Turbine Blade Faults Detection

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Turbine Blades

- Wind turbines are enormous structures, typically with rotor diameters of 75-100 m on top of poles of 100 m height.
- Turbine blades are a distinctive 'aerodynamic' foil shape.
- Blades are expected to last about 20 years but may last only 4-5 years because of faults formation.
- The faults are often de-lamination faults which not easily seen or easy to detect using other means.
- One procedure for fault detection is using 'fatigue loading' with AE (acoustic emission) detection. The faults are 'activated' by twirling the blade and the vibrational response recorded.
- Adam runs laboratory experiments on blades 14.3 m long with artificially introduced faults. He measures the vibrational response and wants to understand the results obtained.

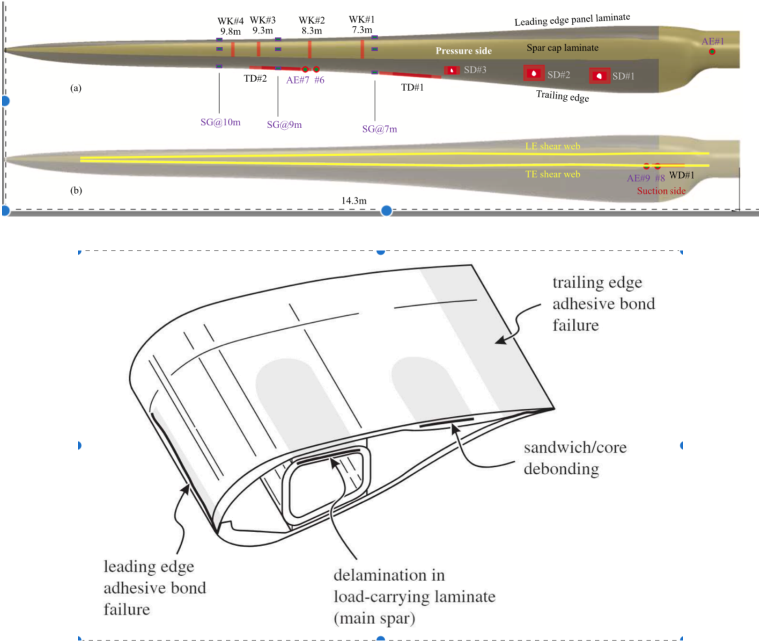


Figure 1: Turbine blade shape and structure

Blade Materials

- A blade is typically constructed using a hollow laminated fibreglass-infused polyester (30% fibre glass) structure, with a sandwich structure near the blade tips.
- The blade is either air filled or a light in-fill is used. Usually there are structural supports running down the blade, see Figure 1.
- Most faults are caused by de-lamination; the adhesive joining layers fails, opening up an 'air filled bubble'. A wrinkle may or may not be seen on the surface, so detecting faults is normally difficult. Wrinkles are also formed during construction.
- Additionally blade flexing may cause a wrinkle to appear and grow and new wrinkles may appear.
- Such faults typically develop between the structural supports (the spar cap), and also near the blade tips.

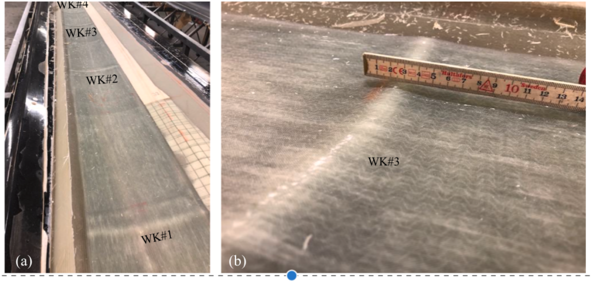


Figure 2: Wrinkles in a turbine blade.

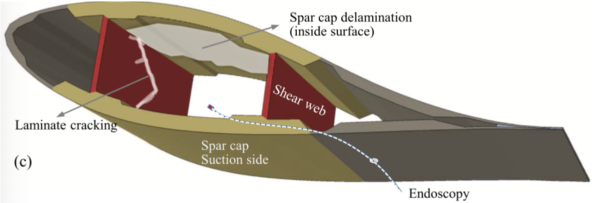


Figure 3: Faults in a blade: Note the de-lamination on the inside of the skin and the structural failure in the strut

Blade Flexing

The longitudinal bending/flexing mode under periodic forcing at $x = 0$ with a free end at $x = L$, is modelled (most simply) by the Euler-Bernoulli equation:

$$EI\, y'''' + \rho \ddot{y} = 0, \text{ with } y(0) = a\cos\omega t,\; y'(0) = 0,\; y''(L) = y'''(L) = 0.,$$

where EI is the flexural rigidity of the blade.

The forced solution (in scaled form with $x = Lx', \omega t = t'$) is

$$y(x', t') = a\cos t' X(x'),$$

where

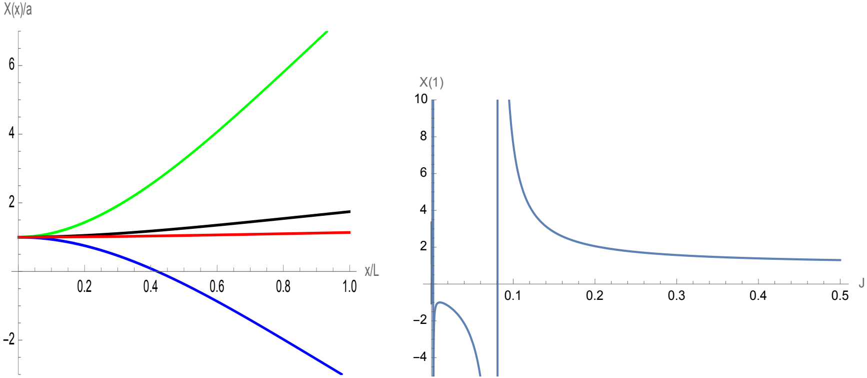
$$X(x') = C_1 \sin(x'/J^{1/4}) + C_2 \cos(x'/J^{1/4}) + C_3 \sinh(x'/J^{1/4}) + C_4 \cosh(x'/J^{1/4});$$

The dimensionless combination

$$J = \frac{EI}{\rho\omega^2 L^4}.$$

determines the extent of flexing. Solution plots are displayed.

Beam flexing: Left: J=0.05 (blue), 0.1 (green), 0.25 (black), 1.0 (red). Right: amplitude of deflection $X(1)$ as a function of J. Note J=0.08 corresponds to the first resonant mode



Note especially that the amplitude of motion increases rapidly as J reduces to the resonant value of 0.08.

Observations

Turbine blades are of very special shape and the above 'beam' model is 'crude', but some general observations can be made based on this model. (Accurate numerical models have been developed).

- The amplitude of motion will increase dramatically as resonance is approached, and J varies like L^4/ω^2; 'tuning' is possible and can be effected by changing L or ω.
- If the aim is to 'fatigue' the experimental blade so as to stimulate faults (see later), then choosing J is the way to go. Furthermore it might be useful to explore the $J < 0.08$ range because the shear stress levels generated are much greater if the second flexing mode is generated; in this mode the two ends of the blade move in opposite directions so shear stress levels will be much greater.

Experimental Observations

Further to the above: Adam's experiments do suggest that the experimental beam needs to moved in a figure eight configuration in order to get 'a fault response'. As indicated earlier such a motion would generate both the longitudinal flexing beam mode and the torsional mode and in fact the energy feed from the (highly energetic) flapping mode to the torsion mode is likely to produce high elastic shear stresses near the surface of the blade. (Note that the above beam model does not attempt to model such effects; a modified Timoshenko model would be better.)
Note also that faults are most likely caused by high frequency modes or transients generated because of a 'mismatch' between blade forcing and natural elastic 'response'; this is a complex problem. It seems likely however, see later, that beam forcing is not the central issue.

Fault detection procedure

- Artificial defects (de-laminations/de-bonding and other) are introduced during (experimental) blade construction; typically a resin slip foil is inserted between layers during construction.
- In between such faults piezoelectric detectors are attached to the surface; (after processing) these measure local displacements. The aim is to detect faults and record their growth.
- Fatigue loading: The blade is 'twirled' (about 2 cycles per sec) so that it 'flaps' in the longitudinal direction and oscillates about the blade axis.
- This complex flexing movement triggers the faults; high frequency ultrasonic *material deformation* stress waves propagate away from the fault (1 kHz or greater). Also incident material deformation waves will be reflected by the fault. This (AE) detection procedure is widely used for fault detection in laminated materials.

Elastic Body Waves

Elastic body deformation waves are of two types: longitudinal/pressure waves (L, P) and transverse/shear (T, S) waves, with **different** wave speeds given by (engineering units)

$$c_l = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}}, \quad c_t = \sqrt{\frac{E}{2\rho(1+\sigma)}},$$

or (scientific units)

$$c_l = \sqrt{\frac{\lambda + 2\mu}{\rho}}, \; c_t = \sqrt{\frac{\mu}{\rho}}.$$

Note that the waves are non-dispersive and that $c_l > c_s$. For materials of interest E=12.0 GPa, ρ= 1.85 10^3 kg/m^3, and assuming $\sigma = 0.3$ we get $c_l = 2.9$ km/sec, c_t=1.6 km/sec.

Interface Effects

Importantly the nature of an elastic wave is changed when it is reflected or refracted, except under very special circumstances. Thus:

- A monochromatic longitudinal wave passing across an interface between two regions with different propagation properties will transmit a transverse wave as well as a longitudinal wave.
- A monochromatic transverse wave incident on a free boundary (vacuum outside) will generate both reflected longitudinal and transverse waves providing the incidence angle is greater than a critical value. If the incidence angle exceeds this critical value then a surface wave (a Rayleigh wave) will result.
- A crack (fault) typically propagates 'with' (a little less than) the Rayleigh wave speed.

Surface and bending waves are linear combinations of L and S body waves with the combination determined by the surface conditions.

Elastic Surface Waves

Elastic Surface Waves (Rayleigh, Love Waves) may be generated when a body wave hits a surface or a crack (a fault).(The incidence angle needs to be less than the critical angle.) The wave travels along the surface with speed approximately $0.9c_t$ (Landau and Lifshitz p 97).
For our materials we get 1.45 km/sec.
Importantly surfaces (including cracks/faults) can 'trap' waves so that much of the elastic energy propagates along the surface.

Bending Waves

Bending waves cause motion at right angles to the surface of beams/rods/plates. They are dispersive and travel with a speed dependent on the 'plate' thickness *h* as well as the wave number k (L and L p101):

$$c_b = (kh)\sqrt{\frac{E}{3\rho(1-\sigma^2)}}$$

Notably these waves are anomalous in that shorter waves travel faster than longer waves, which is unusual.
For our materials and blades $kh = \pi$ which gives the wave speed as approximately 4.6 m/sec.

Observations in Context

- As indicated earlier the body wave composition of an incident wave will change when the wave hits a fault and the resulting wave/s will travel with different speed/s, making detection possible. The received displacement signal will be modulated with its frequency spectrum changed.
- It is likely that surface waves will be generated at a fault so there will be some energy focusing along the fault.
- Shear waves are likely to be highly damped especially because of the composite structure, so detection will be difficult, as indicated by the experimental results.
- The twirling of the blade is likely to result in intermittent wave 'pulses' rather than a continuous signal; the observations above are still relevant.

Speculation

The low frequency, large wave length blade swirling just serves to generate material deformation waves of much higher frequency and small wavelength which either cause fault formation or fault ‘stimulation’. Once formed such faults will slip under excitation thus releasing further elastic energy in the form of propagating elastic waves. It is these waves that are detected.
The waves generated by interaction with the fault will be a different combination of the body waves, propagating with different speed so that there will be changed displacement response as recorded by the detectors.

Conclusions and Suggestions

- This is an important problem and is academically challenging
- Some initial modelling work has been done on the scattering of an incoming shear wave caused by a fault.
- Plastics and composites don't behave like 'pure linear elastic materials. Most importantly they are generally 'lossy' so, frankly, it seems very unlikely that fault detection using elastic waves would work except over small distances, as evidenced by experimental results.
- Experiments need to be performed on blades without faults.

- Much more would be needed to be known concerning the material properties and structure of the blades of interest to proceed further.
- There are too many unknowns here: the blade forcing used is really complex, so it is virtually impossible/not practical to determine either the strength or timing of the source.
- We would guess that the advantage of the present procedure is that it mimics reality but unscrambling the interacting physics is too hard. Even with exact results this would be impossible. It would be useful from the science point of view to set up a simpler experimental configuration (smaller, less expensive, with simpler forcing) to explore the effect of faults in isolation.
- A great deal more time and group/Adam interaction would be required to do this problem justice.