Some criteria for locating sensors in a wind turbine blade

M.Cruz López-de-los-Mozos, Juan A. Mesa[1],
Diego Ruiz-Hernández[2], Carlos Q. Gómez-Muñoz[3]

[1] University of Sevilla
[2] University College for Financial Studies (CUNEF), Madrid
[3] University of Castilla-La Mancha, Ciudad Real

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Outline

Introduction

- Wind energy is one of the best sources of alternative energy. It is a renewable source of energy and does not produce any pollutants or emissions during operation that could harm the environment, other than those required for maintenance.

Wind Farm

- The blade is a critical component in a wind turbine, and its productivity requires high levels of maintainability and safety. In fact, maintenance issues more often occur in the field from leading-edge erosion, weather, and other factors.

Introduction

- Blade maintenance and repair costs are quickly becoming a significant portion of a wind turbine's maintenance cost. Every defect on the surface of a wind blade disrupts its airfoil and reduces overall power production.

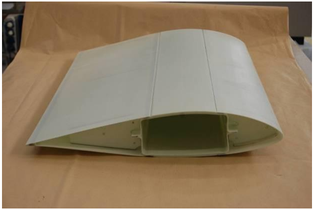
Maintainance of a blade

Damage treated with adhesive tape

Introduction

- A modern blade is made of composite materials (glass fiber, polyester resin and others) in monolithic or sandwich configuration.
- The Nondestructive Testing (NDT) techniques (such as ultrasonic scanning, infrared thermography, X-ray inspection, and others), are useful for detecting hidden damages in composite materials.
- For detecting incipient breakages in the blade surface, the work of Carlos Q. Gómez-Muñoz et al. (University of Castilla-La Mancha) proposes a NDT method, based on using three macro-fiber composite sensors allocated along a blade section to derive a Triangulation Approach.

WIND TURBINE BLADE

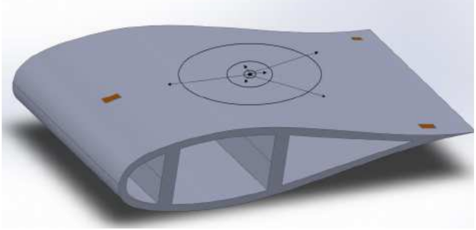


BLADE SECTION

Triangulation approach for locating a fiber breakage

This method (Carlos Q. Gómez-Muñoz et al. (University of Castilla-La Mancha)), can be briefly described as follows:

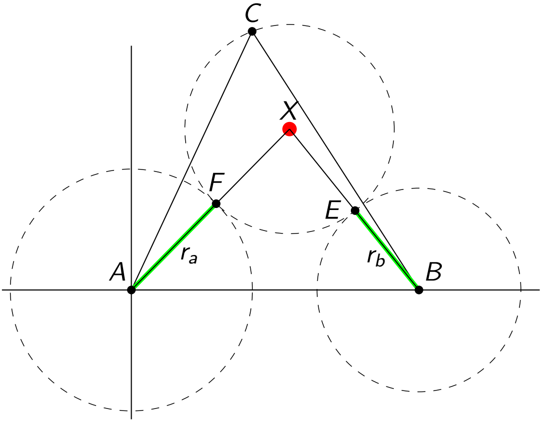
- Three sensors are set in a section of a wind turbine blade, with the aim of detecting a crack on the surface of the blade.



- The acoustic signal emitted by the breaking is first received by the closest sensor, then it is received by the second closest and by the third one, and such receptions have an associated delay time, which is proportional to the Euclidean distance between the points. This gives rise to a triangulation method which leads to a system of nonlinear equations, whose solution is an approximation of the fault.

Triangulation approach for locating a fiber breakage

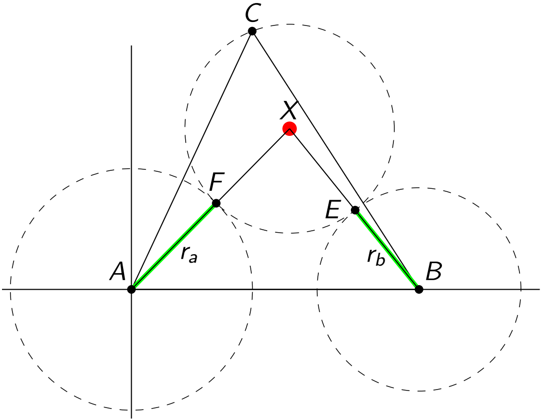
- The blade surface is approximated by a planar surface. First, the method computes the time delays obtained by the excitation of sensors when they receive the acoustic signal from the fault.



- A, B, C: Sensors. X: Fault.
- The propagation velocity v, is obtained experimentally.
- t_{CB}, t_{CA}: Time delays between the excitation of the first sensor C, and the second and third closest sensors B and A. They are computed.
- Obtain:
  $r_b = d(E, B) = v \times t_{CB}$
  $r_a = d(F, A) = v \times t_{CA}$

r_b and r_a are the delays between the excitation of C and the second and third closest sensors B and A, respectively. They are also obtained.

Triangulation approach for locating a fiber breakage



We have:

- Data: A, B, C, r_a, r_b.
- Unknown Variables:

$$X, F, E, \text{ and } r_c = d(X, C)$$

- These variables are obtained by a system of seven nonlinear equations.

- Final result: The approximate position of the acoustic emission X.
- There is no error bounds for this approach.

How should the sensors be located?

There are several open problems dealing with this approach.

From a locational point of view, the problem consists of finding the optimal location of the sensors for detecting faults in the blade surface.

- In a first stage, the aim of this work (still in progress) is to investigate several criteria for locating sensors in a planar surface, under the hypothesis made in the triangulation method.
- The subsequent stages of the research can be focused to generalize the previous settings.

How should the sensors be located?

In order to formulate a model, several questions arise from experimental results obtained in the simulation of the triangulation method in the laboratory:

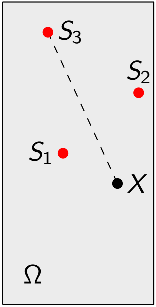
Observations on the triangulation method

- If the distance between sensors is too big, the signal may attenuate or be lost by one sensor (or more).
- Conversely, if the distance between sensors is too small, the reception time of the signal by the different sensors may be indistinguishable.
- Highest accuracy of approximation is obtained for the faults inside the triangle formed by the sensors. Faults that occur outside the triangle can be identified with a cost of accuracy.

Exploring criteria for locating sensors

Elements of the problem:

- We approximate the surface of a blade section by a planar surface Ω. Thus, Ω is a rectangle with side lengths $0 < \ell_1 \leq \ell_2$, and Euclidean distance $d(\cdot, \cdot)$.
- The demand D is the set of points indicating possible damage locations. Initially, we have considered $D = \Omega$, with uniform distribution along Ω.
- Delay times can be measured by Euclidean distances (since the velocity of the acoustic emission does not depend on the direction of propagation).



$$\Sigma = \{S_i, i = 1, \ldots, p\} : \text{ Set of sensors.}$$

$$\forall X \in \Omega, d(X, \Sigma) = \min\{d(X, S_i), i = 1, \ldots, p\}$$

$$\tau(X, \Sigma) = \max\{d(X, S_i), i = 1, \ldots, p\}$$

Exploring criteria for locating sensors

First criterion: with the aim of minimizing the worst distance between the demand points and the furthest sensor. The underlying idea is to minimize the loss of acoustic signal received by the furthest sensor in the worst case.

p-min-max-max criterion.

For $p = 3$, the problem is to find the set Σ of three sensors such that minimizes the maximum distance from the furthest sensor to all points in Ω:

$$\min_{\Sigma \subset \Omega,\ |\Sigma|=3} \max_{X \in \Omega} \tau(X, \Sigma) = \min_{\Sigma \subset \Omega,\ |\Sigma|=3} \max_{X \in \Omega} \left\{ \max_{S_i \in \Sigma} d(X, S_i) \right\}$$

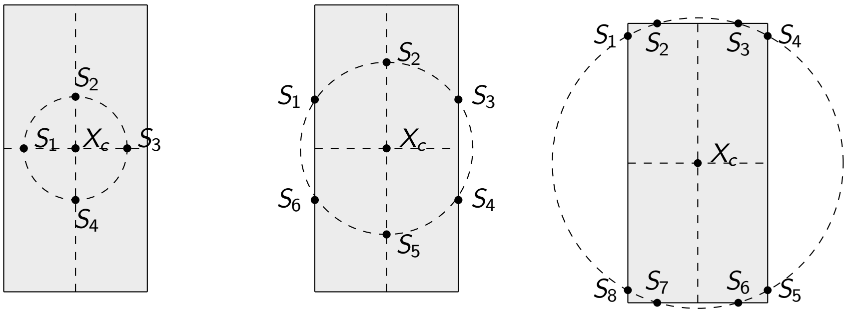
$$\text{s.t.} \quad \min_{S_i, S_j \in \Sigma} d(S_i, S_j) \geq \delta > 0$$

(parameter $\delta > 0$ establishes a minimum distance between sensors.)

Exploring criteria for locating sensors

- Let X_c be the center of the minimum circle containing Ω, and $\overline{C}(X_c;\delta)$ be the circumference with center at X_c and radius δ.
- Let $\overline{C}_\delta$ be the intersection of $\overline{C}(X_c;\delta)$ and both the symmetry edges and the boundary of Ω

Proposition. *There is a solution Σ^* of the problem such that $\Sigma^* \subset \{X_c\} \cup \overline{C}_\delta$.*



$2\delta \le \ell_1$ $\qquad$ $\ell_1 < 2\delta \le \ell_2$ $\qquad$ $\ell_2 < 2\delta$

Caveat: Solutions where the sensors are aligned can be obtained. For example: $\Sigma^* = \{S_1, X_c, S_3\}$ for the left case, $\{S_2, X_c, S_5\}$ for the middle one, etc.

Exploring criteria for locating sensors

Second criterion: The underlying idea is that accuracy of approach improves inside the triangle.
We have also considered a sensors range threshold $T > 0$, meaning that:

If $d(X, S_i) > T$, then S_i does no receive the acoustic signal from X

Maximum area criterion with sensors range threshold

Let $\mathcal{A}(conv(\Sigma))$ be the area of the convex hull of Σ, the set of sensors.
The aim is to find a triangle with maximum area under the range threshold constraint:

$$\max_{\Sigma \subset \Omega, |\Sigma|=3} \quad \mathcal{A}(conv(\Sigma))$$

$$\text{s.t.} \quad d(S_i, X) \leq T, \ \forall X \in \Omega, \ \forall S_i \in \Sigma$$

This constraint can be replaced by the following one:

$$\tau(X, \Sigma) = \max_{S_i \in \Sigma} d(X, S_i) \leq T, \ \forall X \in \Omega$$

Exploring criteria for locating sensors

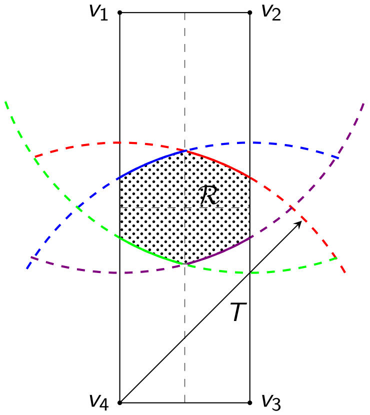
Let $V = \{v_i, i = 1, \dots 4\}$ be the vertex set of Ω, and let $C(v_i; T)$ be the circle with center at v_i and radius T, $i = 1, \dots, 4$.
Let $\mathcal{R}$ be the region of Ω given by the intersection of such circles:

$$\mathcal{R} = \Omega \cap \left(\bigcap_{v_i \in V} C(v_i; T) \right)$$

Lemma.
$\mathcal{R}$ is the feasible region for the problem.

The problem can be written as:

$$\max_{|\Sigma|=3} \quad \mathcal{A}(conv(\Sigma))$$
$$\text{s.t.} \quad \Sigma \subset \mathcal{R}$$



Exploring criteria for locating sensors

- Let $V(\mathcal{R}) = \{Q_i, i \in I\}$ be the vertex set of $\mathcal{R}$ (the breakpoints of its boundary),
- and let $I_{\mathcal{R}} = \{O_i, i = 1, \ldots, 4\}$ be the intersection set of the boundary of $\mathcal{R}$ and the symmetry edges of Ω.

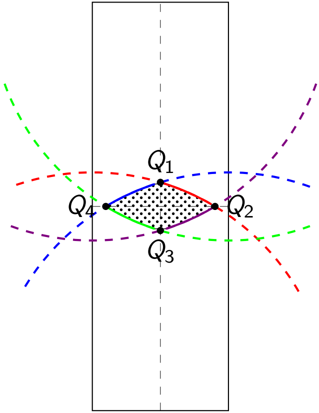
The analysis of the problem is based in a study of cases in order to determine if $V(\mathcal{R}) \cup I_{\mathcal{R}}$ contains some optimal solution.

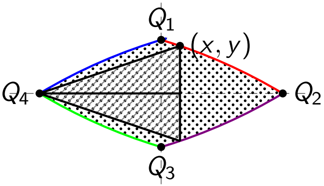
Let 2α be diagonal length of Ω. Omitting both the infeasible and the trivial case, we have considered the following cases:

1. $\alpha < T \leq \sqrt{\ell_1^2 + \ell_2^2/4}$.
2. $\sqrt{\ell_1^2 + \ell_2^2/4} < T \leq \sqrt{\ell_1^2/4 + \ell_2^2}$.
3. $\sqrt{\ell_1^2/4 + \ell_2^2} < T \leq 2\alpha$.

Exploring criteria for locating sensors

Question: Does $V(\mathcal{R}) \cup I_{\mathcal{R}}$ contain some optimal solution? The answer depends on the case.

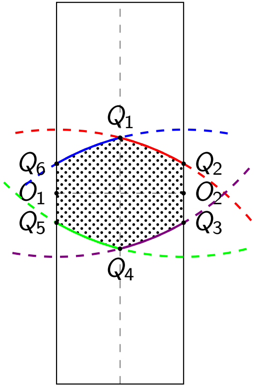


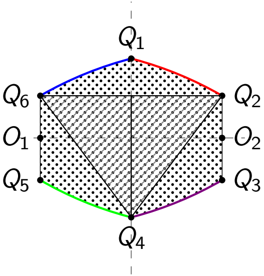


Case 1: No. The solution must be obtained by numerical methods.

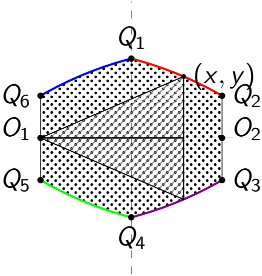
Exploring criteria for locating sensors

Question: Does $V(\mathcal{R}) \cup I_{\mathcal{R}}$ contain some optimal solution?





(a)

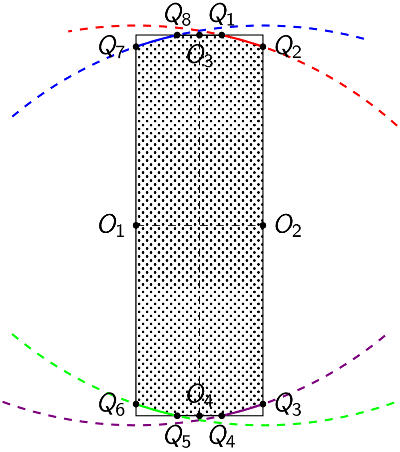


(b)

Case 2: Yes, provided that T holds some sufficient conditions (graphic (a)). Such conditions imply T is near its upper bound.
Otherwise, numerical methods must be apply (graphic (b)).

Exploring criteria for locating sensors

Question: Does $V(\mathcal{R}) \cup I_{\mathcal{R}}$ contain some optimal solution?



Case 3: Yes. Sufficient conditions hold for T.

A different approach: Cooperative cover model

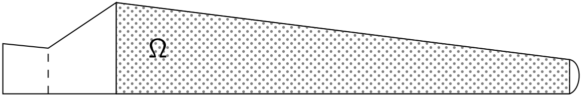
- The area criterion seems more adequate for the requirements of the problem. However, the accuracy of approach worsen for faults outside triangle.
- Using three sensors imply that there are several zones of blade surface outside the triangle. The points in such zones could not be adequately located.
- To avoid this effect, a possible solution is to consider more than three sensors so that each point of the blade is inside some triangle. This can be viewed as a cooperation of the sensors to ensure that each point is covered.

A different approach: Cooperative cover model

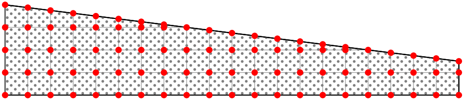
- Paper of Berman, Drezner and Krass (2010): *Cooperative cover location models: The planar case*, provides a theoretical framework for modeling a related problem.
- Literature on Cooperative cover studies models when each demand point receives the sum of the signals from all sources (facilities), and coverage is regarded as ensuring sufficient signal strength.
- The sensor location problem dealing with the Triangular Method presents several requirements not included in the general model.

A different approach: Cooperative cover model

We consider the entire blade surface, and assume that it can be approximated by a trapezoid Ω.
As in the previous problems, $D = \Omega$ is the demand set. Faults are uniformly distributed along Ω, and the velocity of acoustic waves is constant through the surface.



We approach the continuous demand by some discrete set $G \subset \Omega$. In a first stage, we select G as the corner points of a grid defined in Ω.



G: DISCRETE DEMAND SET

A different approach: Cooperative cover model

Let $\Sigma = \{S_i, i = 1, \dots, p\}$ be the set of sensors, where $S_i \in \Omega$ is the unknown location of i-th sensor, $i = 1, \dots, p$.
From the laboratory experiments, the constraints of the previous criteria have been incorporated:

- δ and Δ: Minimum and maximum distance between sensors.

$$0 \leq \delta \leq d(S_i, S_k) \leq \Delta, \ \forall S_i, S_k \in \Sigma$$

- A range threshold $T > 0$, representing the maximum distance so that a sensor receives an acoustic signal emitted by a fault at $X_j \in G$.
- Let N_j be the subset of sensors which are able to receive a signal from X_j:

$$N_j = \{S_i \in \Sigma : \ d(X_j, S_i) \leq T\}$$

- A fault X_j is inside some triangle iif: (i) the signal emitted by X_j is received by at least 3 sensors, and (ii) X_j belongs to the convex hull of N_j.

$$X_j \ \text{ is inside some triangle } \ \text{iif} \ \ |N_j| \geq 3, \ \text{ and } X_j \in Conv(N_j)$$

A different approach: Cooperative cover model

The location problem of sensor cooperative coverage dealing with the triangulation method: Find the minimum number of sensors p, and their locations Σ required to cover the planar surface Ω by means the triangulation method, such that each demand point is inside some triangle:

$$\begin{aligned}
&\min_{|\Sigma|=p} \{p\} \\
&\text{s.t.} \\
&|N_j| \geq 3 && \forall X_j \in G && (1)\\
&X_j \in Conv(N_j) && \forall X_j \in G && (2)\\
&d(S_i, S_k) \geq \delta && \forall S_i, S_k \in \Sigma && (3)\\
&d(S_i, S_k) \leq \Delta && \forall S_i, S_k \in \Sigma && (4)\\
&\Sigma \subset \Omega && && (5)
\end{aligned}$$

- By deleting (2) we obtain a simplified version in which the only requirement is that each X_j is detected by (at least) 3 sensors.

A different approach: Cooperative cover model

Simplified version:

$$\min_{|\Sigma|=p} \{p\}$$

s.t.

$$|N_j| \geq 3 \qquad \forall X_j \in G \qquad (1)$$

$$d(S_i, S_k) \geq \delta \qquad \forall S_i, S_k \in \Sigma \qquad (3)$$

$$d(S_i, S_k) \leq \Delta \qquad \forall S_i, S_k \in \Sigma \qquad (4)$$

$$\Sigma \subset \Omega \qquad (5)$$

This problem is NP-Hard, since the Planar Set Covering Location Problem (NP-Hard) can be obtained as a particular case by assuming $\delta = 0$, $\Delta = \infty$, and replacing (1) by $|N_j| \geq 1$, $\forall X_j \in G$.

A different approach: Cooperative cover model

We now are working in constructing heuristic algorithms for this last problem. The idea is to approach the continuous location space by a discrete set which can be used as an initial location set for the general model.

For the moment we have not finished this phase of research.

Several open questions

Studying the triangular approach under more general assumptions:

- Obtain error bounds.
- The probability distribution of fault's occurrence is not uniform.
- Velocity of acoustic waves depends on the direction of propagation.
- The signal decays over the distance according some non-increasing function.
- Modeling the blade by a nonplanar surface.

Thank you for your attention!

LOGRO

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