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Passive acoustic signal sensing approach to detection of ice on the rotor blades of wind turbines

Eugen Mamontov [1], Viktor Berbyuk [2]

[1] Department of Research and Development
Foundation Chalmers Industrial Technology
SE-412 88 Gothenburg, Sweden
eugen.mamontov@cit.chalmers.se

[2] Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
viktor.berbyuk@chalmers.se

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1 Abstract

In cold seasons, irregular layers of ***atmospheric ice*** (AI) are usually accreted on the ***rotor blades*** of operating ***wind turbines***. For smart, energy-efficient deicing, ice-detection systems should not only ***detect the AI-layer on the blade skin*** (BS) but also provide the "landscape" of the material parameters of this layer over the BS surface. They generally vary in time.

The work considers a ***passive sensing*** with wideness lowpass accelerometers, which: (1) are located at the centers of the mutually non-intersecting low-curvature, *quasi*-***planar*** disk-shaped regions, briefly, ***disks*** on the inner surface of the BS and (2) measure ***acoustic accelerations*** normal to the surface, i.e., the accelerations presenting the differences between the total accelerations and the accelerations of the macroscopic motions of the blade.

The measured accelerations are the material-variable ***signals*** caused by the ***operational load***.

The work deals with these signals only. It develops ***acoustic model and method for identification*** of the AI-layer parameters. The ***model*** is based on the ***third-order acoustic PDEs*** (derived in a previous paper of the authors).

The ***identification method*** can identify the following eight parameters: the thickness • volumetric mass density • bulk and shear moduli • stress-relaxation time (SRT) • porosity • volume and shear viscosities. The method is ***computationally efficient*** and can be suitable for the ***real-time implementation***.

The proposed model and method enrich the scope of structural health monitoring of systems with the identification of material parameters of the thin-layer components.

For ***future research***, the work suggests "smoothing" of the identified-parameter time dependences and calibration of the identification model and method with respect to experimental data.

2 Introduction

A. The BS layer and the accreted on it AI layer present a ***two-layer system***.

B. In the course of the turbine-rotor operation, there appears the ***operational load*** in the two-layer system.

C. The load depends on the acceleration, deceleration, speed of rotation of the rotor, the blade-pitch angle, the weather conditions, and other factors. The load causes the space-time variation of the material, more specifically, ***acoustic variables*** such as strain, stress, displacement, and acceleration.

D. The acoustic variables can reach the levels resulting in ***failures or damages*** of the BS. In order to timely detect and prevent undesirable events, one uses ***structural health monitoring (SHM)***.

E. The SHM of solid components often uses ***passive sensing***, e.g., measurements of the accelerations of the component surfaces by ***accelerometers*** located at the surfaces.

F. Along with this, the operational load generally affects the ***material parameters*** of the AI layers such as the mass density, the elastic moduli, and the stress-relaxation time, and results in their variations in space or time. They in particular depend on the weather conditions.

The ***idea of the present approach*** is development of the model and method for ***identification of the AI-layer material parameters*** from the data measured by the accelerometers in the ***passive***-sensing approach, i.e., similar to the ones used in the SHM methods.

This identification will enable the ***ice-detection systems (IDSs)*** for ***smart, energy-efficient deicing*** because they will provide the parameters indicating the ***quality of the AI layer***.

The identification development should deal with the following ***main features***.

1. The above data are to be the ***acoustic accelerations***, i.e., the differences between the total accelerations and the accelerations of the macroscopic motions of the blade.

2. The accelerometers can be located at ***different points*** on the BS-layer ***inner surface*** only, in spite of the fact that the AI layer is located on the outer surface of the BS.

3. The BS layer is of a ***complex, curvilinear shape*** that, in the course of the rotor operation, varies in space and time (e.g., due to the wind-caused deflections of the blade).

4. The materials of the BS are usually composites, which are viscoelastic solids, i.e., the ones with non-zero SRTs. Moreover, the AI SRT can be in an interval of a few orders. Thus, the model for the two-layer system should be ***applicable at any SRTs***.

5. In order to cover as large fraction of the BS surface as possible, ***the acoustic accelerometers*** should be (1) placed at ***points in the regions of the most probable location of the AI***, thereby forming a ***network***, and (2) ***wirelessly controlled*** because of the blade rotation.

3 Key settings for indentification of the AI-layer material parameters

The main assumptions:

- each of the BS material and the AI is • isotropic, • isothermal, • linear, • homogeneous in the space and time at equilibrium, and • the ratio of the shear modulus of the material to the bulk one is sufficiently small;
- a major part of the space-time-varying operating curvilinear BS with the accreted AI layer can be approximated with a set of mutually non-intersecting ***planar*** disk-shaped cylinders, briefly, ***disks***;
- in each disk, the thicknesses of the BS- and AI-layers, h_s and h, are independent of the location on the disk surface;
- each disk is ***thin*** in the sense that

$$[(h_s + h)/R]^2 << 1 \tag{3.1}$$

where R is the radius of the disk; the radiuses of all disks should be sufficiently small in order to allow the above planar-disk approximation and sufficiently big in order to enable inequality (3.1) for each disk to hold.

At the center of each disk on the inner surface of the BS layer, one attaches a wireless lowpass acoustic accelerometer to measure the acoustic acceleration, which is normal to the surface.

The input data for the model and method for each disk in the thin planar-disk (TPD) approximation

The characteristics in Rows 2–8 and 11 generally dependent on the parameter in Row 1. The characteristics in Rows 1–8 are the same for each disk. They are assumed to be independent of time in each interval comprising any three successive time points (see Row 10). The data in Rows 9 and 10 can be specific to each disk. The data in Row 11 are specific to each disk.

	Notation	Meaning
1	$\overline{T}$	absolute temperature of AI
2	$\overline{\rho}_a$	volumetric mass density of air (see below); it is 1.2 kg/m^3 at sea level
3	$\overline{\rho}_i$	volumetric mass density of a continuous, non-porous AI (see below); it is 916.7 kg/m^3 at zero °C
4	h_s	thickness of the BS layer
5	$\overline{\rho}_s$	volumetric mass density of the BS
6	$\overline{K}_s$	bulk modulus of the BS
7	$\overline{\theta}_s$	stress-relaxation time in the BS
8	$s^*(\overline{\rho})$	dependence of the speed of the bulk acoustic waves in the AI layer (e.g., R.A. Sommerfeld, 1982)
9	N	number of the successive time points, at which the acceleration was measured; $N \geq 4$; this inequality allows to evaluate the third-order time derivatives with the help of finite-difference formulas
10	$t_1, \ldots, t_N$	successive time points, $t_1 < \ldots < t_N$, at which the acceleration values were measured
11	$a_1, \ldots, a_N$	values of acoustic acceleration $a(t)$ at time points t_k, $k = 1, 2, \ldots, N$; value a_k is the one at time point t_k; values a_k, $k = 1, 2, \ldots, N$, correspond to the non-equilibrium component of the *operational-load-caused* stress force in the BS layer normal to the inner surface of the layer.

The ***parameters of the AI layer to be identified*** are the following eight ones:

- the thickness h,
- volumetric mass density $\bar{\rho}$,
- bulk modulus $\bar{K}$,
- SRT $\bar{\theta}$,
- porosity $\bar{\varphi}$ $(0 \le \bar{\varphi} < 1)$,
- volume viscosity $\bar{\eta}$,
- shear modulus $\bar{G}$,
- shear viscosity $\bar{\mu}$.

However, if $\bar{\rho}$, $\bar{K}$, and $\bar{\theta}$ are available, then ***the fifth–eighth parameters*** can be estimated as:

- $\bar{\varphi} = (\bar{\rho}_i - \bar{\rho})/(\bar{\rho}_i - \bar{\rho}_a)$;
- $\bar{\eta} = \bar{K}\,\bar{\theta}$,
- $\bar{G} = [s_T^*(\bar{\rho})]^2/\bar{\rho}$;
- $\bar{\mu} = \bar{G}\,\bar{\theta}$,

respectively, where $s_T^*(\bar{\rho})$ is the $\bar{\rho}$-dependence of the speed of the *transverse* acoustic waves in the AI.

NOTE: Both $s_T^*(\bar{\rho})$ and $s_L^*(\bar{\rho})$, the speed of the *longitudinal* acoustic waves in the AI, are available in *R.A. Sommerfeld, Rev. Geophys. & Space Phys., 20, 1982*. Also, functions $s_L^*(\bar{\rho})$ and $s_T^*(\bar{\rho})$ allow to describe $s^*(\bar{\rho})$, the speed of the *bulk* acoustic waves, with relation

$$s^*(\bar{\rho}) = \sqrt{[s_L^*(\bar{\rho})]^2 - (4/3)[s_T^*(\bar{\rho})]^2}\,. \quad (3.2)$$

Thus, ***it is sufficient to identify*** h**,** $\bar{\rho}$**,** $\bar{K}$***, and*** $\bar{\theta}$ ***only***. As is shown in the paper, the identification originates from the system of the ***two boundary-value problems for the third-order PDEs for the BS and AI layers in one spatial coordinate, which is perpendicular to the layers***.

4 Model and method for indentification of the AI-layer material parameters

For the identification of parameters h, $\bar{\rho}$, $\bar{K}$, and $\bar{\theta}$ associated with any disk in the TPD approximation, the paper derives equation

$$q\left[\bar{\theta}\, d^3 f_1(t)/dt^3 + d^2 f_1(t)/dt^2\right] - 12c\left[[f_0(t) + 2\bar{\theta}\, df_0(t)/dt] - q[f_1(t) + 2\bar{\theta}\, df_1(t)/dt]\right]$$
$$-5\left[\bar{\theta}\, d^3 f_0(t)/dt^3 + d^2 f_0(t)/dt^2\right] = 0, \qquad h > 0, \tag{4.1}$$

where

$$c = (\bar{s}/h)^2 > 0, \tag{4.2}$$

$$q = (\bar{\rho} h)/(\bar{\rho}_s h_s) > 0, \tag{4.3}$$

$$f_0(t) = \bar{\rho}_s\, a(t) + \partial Y_s(0,t)/\partial x, \qquad f_1(t) = \partial Y_s(h_s,t)/\partial x - f_0(t), \tag{4.4}$$

$$\bar{s} = s^*(\bar{\rho}), \qquad \bar{s} = \sqrt{\bar{K}/\bar{\rho}}\,, \tag{4.5}$$

$\bar{s}$ is the speed of the bulk acoustic waves in the AI, and $a(t)$ is the acoustic acceleration measured by the acoustic accelerometer located at the center of the disk.

Importantly, terms $Y_s(0,t)/\partial x$ and $\partial Y_s(h_s,t)/\partial x$ in (4.4) are the functions of the time, which are independent of the AI-layer parameters and determined by the BS-layer parameters only.

- Equation (4.1) is in fact the one for identification of parameters $\bar{\theta}$, c, and q. However, if parameters c and q are available, then parameters $\bar{\rho}$, $\bar{K}$, and h can be determined uniquely. Indeed, as follows from (4.2) and (4.3), $\bar{\rho}\,\bar{s} = (\bar{\rho}_s h_s)\, q\sqrt{c}$. Since the $\bar{\rho}$-dependence in (4.5) monotonically increases, the indicated equality enables one to determine $\bar{\rho}$ as the unique solution of equation

$$\bar{\rho}\,\bar{s}^*(\bar{\rho}) = (\bar{\rho}_s h_s)\, q\sqrt{c}\,. \tag{4.6}$$

As soon as $\bar{\rho}$ is available, $\bar{s}$, $\bar{K}$, and h are calculated with (4.5) and (4.2) or (4.3).

Note that, as follows from the inequality in (4.1), the equation in (4.1) is applicable at all $h > 0$. However, as is shown in the paper, the equation becomes an identity in the limit case as $h \downarrow 0$ and, thus, remains valid in this limit case as well.

- Parameters $\bar{\theta}$, c, and q can be identified with the help of equation (4.1) in different ways. The simplest one is evaluation of them from the system of the three versions of ***nonlinear*** equation (4.1) at three successive time points, say, t_{k-2}, t_{k-1}, and t_k, $k = 3,\ldots,N$, where the time derivatives are replaced with the finite-difference (FD) approximations. This presumes that parameters $\bar{\theta}$, c, and q are t-independent in interval $[t_{k-2}, t_k]$ and, thus, are represented with their values, $\bar{\theta}_k$, c_k, and q_k, specific to this interval. They are determined as the solution of the above system of the three nonlinear equations and present the parameters identified in interval $[t_{k-2}, t_k]$.

Applying this procedure to the intervals corresponding to each of $k = 3, \ldots, N$, one obtains the piecewise-constant t-dependent approximations for the identified AI-layer parameters. These t-dependences include the influence of the operational load upon the parameters.

● In view of the approximate nature of the FD formulas used in the proposed method, the t-dependences can be rather irregular. Consequently, they generally need to be "smoothed" in order to provide the component, which is caused by the operational load rather than the quantitative FD errors. The ***"smoothing" method*** can be a topic for future research.

One more topic for future research is a ***calibration*** of the proposed identification model and method with respect to the related ***experimental data***.

● Systems of ***nonlinear equations***, such as the above one, are usually solved with ***iterative methods***. However, they are difficult to use in the real-time computing because it is not easy to assure unquestionable convergence of the iterations and to choose the initial approximation that directs the iterations to the desirable solution. This presumes intervention of an expert (e.g., a user), which is, however, inappropriate in the real-time mode. Due to that, one can more closely consider ***direct methods***, for example, the one similar to the procedure from the previous work of the authors.

5 Conclusion

- The present work generalizes the approach to a thin single solid layer (of the previous paper of the authors) for the case of a thin ***two-layer system, which comprises the BS and AI layers***. They are assumed to be isotropic and isothermal.
- The work considers a ***passive sensing*** with wireless lowpass ***acoustic accelerometers***, which are (1) located at the centers of the mutually non-intersecting low-curvature disk-shape regions on the inner surface of the BS and (2) measure acoustic ***accelerations*** normal to the surface and caused by the ***operational load***.
- The work develops the acoustic model based on the third-order PDE and the resulting from it method for ***identification*** of the following ***eight parameters*** of the AI-layer: • the thickness • volumetric mass density • bulk and shear moduli • SRT • porosity • volume and shear viscosities. The identification method is ***computationally efficient*** and can be suitable for implementation in the ***real-time*** mode.
- The proposed approach enriches ***structural health monitoring*** of systems with ***identification of material parameters*** of the AI layer necessary for the ***smart deicing***.
- The work also suggests a few directions for ***future research***.

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