Damage localization in a residential-sized wind turbine blade by use of the SDDLV method

2015 J. Phys.: Conf. Ser. 628 012069

(http://iopscience.iop.org/1742-6596/628/1/012069)

Damage localization in a residential-sized wind turbine blade by use of the SDDLV method

R.J. Johansen[1], L.M. Hansen[1], M.D. Ulriksen[1], D. Tcherniak[2] and L. Damkilde[1]

[1]Dept. of Civil Engineering, Aalborg University, Niels Bohrs Vej 8, Esbjerg, Denmark
[2]Brüel & Kjær Sound & Vibration Measurement A/S, Skodsborgvej 307, Nærum, Denmark

E-mail: rjohan10@student.aau.dk, lhanse10@student.aau.dk, mdu@civil.aau.dk, dmitri.tcherniak@bksv.com, lda@civil.aau.dk

Abstract. The stochastic dynamic damage location vector (SDDLV) method has previously proved to facilitate effective damage localization in truss- and plate-like structures. The method is based on interrogating damage-induced changes in transfer function matrices in cases where these matrices cannot be derived explicitly due to unknown input. Instead, vectors from the kernel of the transfer function matrix change are utilized; vectors which are derived on the basis of the system and state-to-output mapping matrices from output-only state-space realizations. The idea is then to convert the kernel vectors associated with the lowest singular values into static pseudo-loads and apply these alternately to an undamaged reference model with known stiffness matrix. By doing so, the stresses in the potentially damaged elements will, theoretically, approach zero. The present paper demonstrates an application of the SDDLV method for localization of structural damages in a cantilevered residential-sized wind turbine blade. The blade was excited by an unmeasured multi-impulse load and the resulting dynamic response was captured through accelerometers mounted along the blade. The static pseudo-loads were applied to a finite element (FE) blade model, which was tuned against the modal parameters of the actual blade. In the experiments, an undamaged blade configuration was analysed along with different damage scenarios, hereby testing the applicability of the SDDLV method.

1. Introduction

Research activities on vibration-based structural health monitoring (SHM) systems for wind turbine blades have been growing rapidly over the last two decades, see, e.g., [1]. The most common approach is to compare collected data from a reference state, which is typically a healthy one, and the current state. The current state is potentially damaged if it differs significantly from the reference state. A typical partition of the damage identification process was suggested in [2] and contains the following four steps: 1) detection, 2) localization, 3) assessment and 4) consequence. There are plenty of well-documented methods for damage detection, see, e.g., [3], thus the present paper concentrates only on the damage localization process.

In [4], Bernal presented the damage location vector (DLV) method, which utilizes the null space of the changes in the flexibility matrix from a pre- and post-damaged structure to locate the damage. The method assumes that the system behaves linearly in both the pre- and post-damaged states. The vectors that form the basis of the null space are designated as DLVs, and they contain usable information about the location of the damage. It is proved in [4] that by applying a DLV as loads to the undamaged structure, the stresses in the damaged elements approach zero.

The DLV method only includes static properties of the system. However, it was lately extended to include the dynamics of the system, namely the dynamic damage location vector (DDLV) method [5]. Here, the dynamics of the system is included by applying the changes in transfer function matrix, instead of changes in flexibility matrix, to obtain the static pseudo-loads [4].

The dynamic version is further extended to an output-only measurements scenario, which is designated as the stochastic dynamic damage location vector (SDDLV) method [6]. Thus far, the SDDLV method has primarily been tested in the context of numerical models of simple truss and frame structures, see, e.g., [6].

In the present paper, the SDDLV method is applied to locate damages in a residential-sized wind turbine blade tested experimentally.

2. Test setup

To demonstrate the applicability of the SDDLV method, experiments are performed on a cantilevered residential-sized wind turbine blade, see figure 1. Specifically, the structural vibration responses are measured for an undamaged and two damaged cases subjected to unmeasured multi-impulse loading conducted by tapping the blade with a pencil. For each case, a state space model, which forms the basis for determination of the pseudo-loads, i.e., SDDLVs, is estimated from the collected acceleration data.

The blade depicted in figure 1 is about 800 mm long and constructed from a composite material, namely carbon-fibre-reinforced polymer. The blade was originally constructed for another project [7], and later modified for the purpose of testing different SHM methods. The blade is separable into two shells, which are assembled by means of 25 bolts along the leading and the trailing edges. Different damage conditions can be examined by untightening one or more bolt(s).

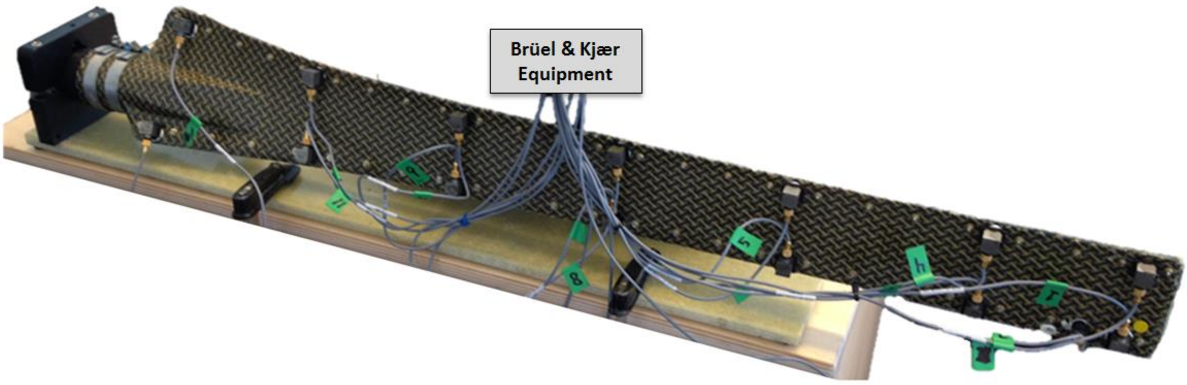

Figure 1. Experimental setup for test on the residential-sized wind turbine blade.

The blade is excited by hitting the structure randomly over the surface in order to simulate operational conditions, i.e., only the output vibrations are collected. The vibrations are captured by use of 14 equally spaced Brüel & Kjær Type 4507-B-004 uniaxial accelerometers along each edge of the blade, as illustrated in figure 1 and figure 2. The accelerometers are mounted, such that they measure perpendicularly to the surface: thus they do not measure in exactly the same direction.

For each experiment, the sampling frequency was set to 8192 Hz, since a sufficiently high sampling frequency is required to ensure that the dynamics of the system is captured properly. The recordings have duration of 200 seconds and are later divided into smaller partitions in order to obtain more than one experiment.

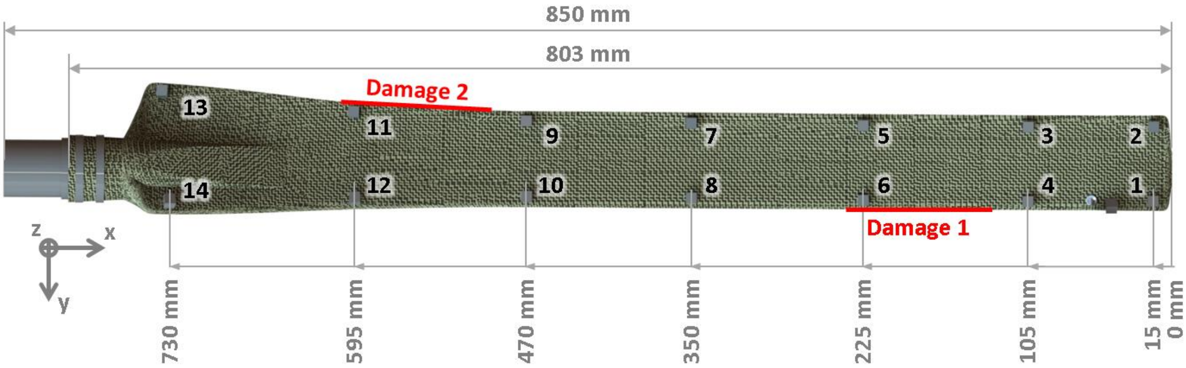

Figure 2. Dimensions of the blade and the locations of the two simulated damages.

The location and size of the two separately simulated areas of damages are shown in figure 2. Both of the damage areas are simulated with three bolts untightened, but kept in the blade to avoid mass changes between the experiments.

3. System identification

System identification techniques are used to mathematically describe the captured acceleration data. In this context, subspace identification is found to be applicable and the fundamental principle of this method is a state-space representation based on the output-only continuous time state-space model, see, e.g., [8].

$$\dot{x}(t) = A_c x(t) + w_k \,, \tag{1}$$

$$y(t) = C_c x(t) + v_k \,, \tag{2}$$

where $A_c \in \mathbb{R}^{n\times n}$ is the state/system matrix for the system containing the dynamic properties, $C_c \in \mathbb{R}^{m\times n}$ is the output matrix, while $x(t) \in \mathbb{R}^n$ and $y(t) \in \mathbb{R}^m$ are the state vector and the output vector. The two last vectors, $w_k \in \mathbb{R}^n$ and $v_k \in \mathbb{R}^m$, are unmeasured stationary noise/disturbances related to the process and the output, respectively. The sizes of the matrices and vectors depends on the order, n, of the state-space model and the number of outputs, m. The system identification is performed using MATLAB System Identification Toolbox, namely using N4SID. For each of the three system states, several state-space models are derived on the basis of different segments of the data. A total of 25 models are derived for each of the two areas of damage and used for estimating a corresponding SDDLV.

4. SDDLV method

The SDDLV method is, as previously declared, based on the change in transfer function matrix for systems where the input is unknown and, as such, the transfer function matrix is inaccessible. Instead, the estimated state matrix and the output matrix are applied to estimate vectors from the kernel of the change in transfer function matrix The transfer function is basically the relation between the output, $Y(s)$, and input, $F(s)$, in the Laplace domain, i.e.,

$$Y(s) = G(s)F(s) \tag{3}$$

where

$$G(s) = C_c(sI - A_c)^{-1}B_c + D_c \,. \tag{4}$$

The input matrix, B_c, and the direct transmission matrix, D_c, are not directly used for the estimation of the SDDLVs, as clarified in the following.

This basic form of the transfer function (4) is not applicable for stochastic systems with output only. In [5], an approach to estimate a fictive input from the state matrix and the output matrix is documented. The idea is to use the fact that there should always be a correlation between the input and the output. The approach ends up in the following:

$$G(s) = R(s)D_c \tag{5}$$

where

$$R(s) = C_c A_c^{-p}(sI - A_c)^{-1} H_p^{\dagger} L \quad , \tag{6}$$

with the value of the exponent $p = 0, 1, 2$, depending on whether the measurements are displacements, velocities or accelerations. The terms estimating a fictive input to the system are defined by

$$H_p = \begin{bmatrix} C_c A_c^{(1-p)} \\ C_c A_c^{(-p)} \end{bmatrix} \tag{7}$$

and

$$L = \begin{bmatrix} I \\ 0 \end{bmatrix} \quad , \tag{8}$$

where the dagger sign in equation (6) designates, that the Moore-Penrose pseudo-inverse is applied to H_p. The direct transmission term D_c is assumed to be a constant, since the 'feedthrough' is assumed to be non-changing and thus not affected from the system properties if damage occurs. The change in transfer function is then proportional to the change in $R(s)$, i.e.,

$$\Delta G(s) \propto \Delta R(s) = R_d(s) - R_u(s)\,. \tag{9}$$

The SDDLVs are found from the quasi-null space of $\Delta R(s)^T$ by singular value decomposition (SVD), hence yielding

$$\Delta R(s)^T = U \Sigma \mathrm{V}^{\mathrm{T}}\,, \tag{10}$$

in which each of the singular values contained in Σ has a corresponding left singular vector in U and a right singular vector in V. The right singular vector associated with the smallest singular value is used as pseudo-loads.

The damage localization is not efficient for all s-values of the quasi-null space of $\Delta R(s)$. Proper ones are selected on the basis of the response characteristics of the system. This information is available when solving an eigenvalue problem of the state matrix. Only the s-value(s) near the poles of the system are selected for the $\Delta R(s)$, hereby introducing a modal truncation of the system. The applied s-values are increased by 1% since studies in context of this paper confirm that the value must be slightly different from the poles of the system, as stated in [5]. A more robust selection may exist and the selection is further discussed by the authors in [9].

5. Finite element model

The pseudo-loads obtained in section 4 are applied to the finite element (FE) model of the blade, in which elements containing stresses approaching zero are potentially damaged according to the (-)DLV approach. The model is based on an approximated 3D CAD geometry and is discretized by equally sized first order shell elements. The FE model is fixed at the blade root, i.e., all displacements and rotations are equal to zero, in order to simulate the clamping mechanism from the experimental setup shown in figure 1. It is calibrated against the first four experimental natural eigenfrequencies and mode shapes obtained from operational modal analysis (OMA) of the undamaged structure, see table 1. The bolts and accelerometers are not included in the model; however, the increased mass is taken into consideration by calibrating the density of the material.

Table 1. Comparison of eigenfrequencies between OMA and calibrated FE model

	Description	OMA [Hz]	Calibrated FE model [Hz]
Mode 1	1st flapwise bending	15.9	16.0
Mode 2	1st edgewise bending	none [a]	48.3
Mode 3	2nd flapwise bending	87.9	88.2
Mode 4	1st torsional	109.0	109.2
Mode 5	3rd flapwise bending	183.3	182.8

[a] *was not found during the experiment.*

As previously mentioned, the accelerations are measured perpendicular to the surface, which consequently defines the direction of the applied pseudo-loads. The local coordinate systems depicted in figure 3 illustrate the perpendicular direction, namely the z-axis, for each of the 14 accelerometer positions. The pseudo-loads are applied over an area corresponding to the size of the accelerometers in order to avoid stress disturbance at the specific positions.

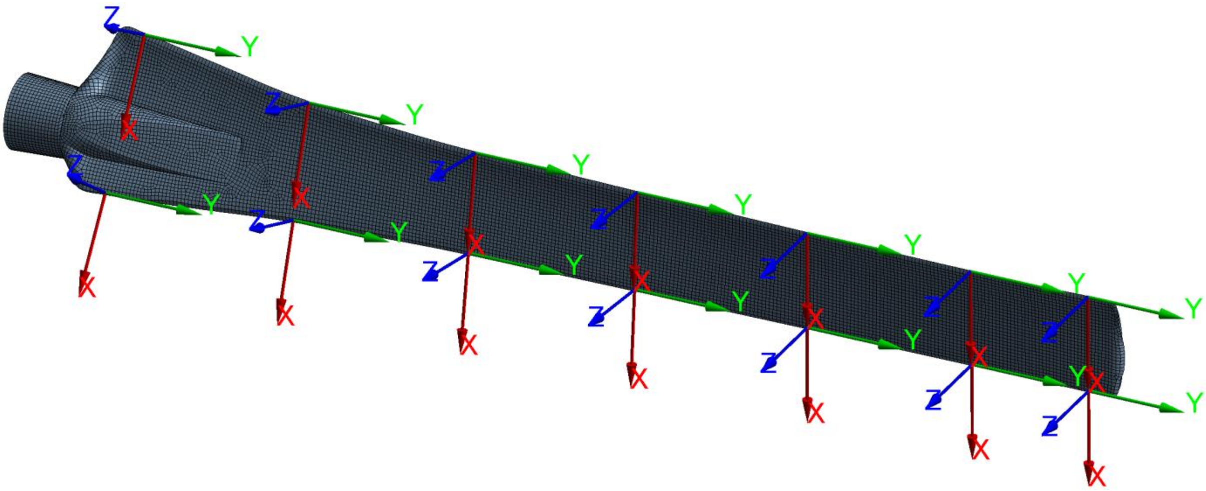

Figure 3. Discretized FE model of the blade and local coordinate systems corresponding to the orientation of the 14 accelerometers.

In the post-processing, the elemental mean von Mises stresses are chosen for locating the damaged area, since this particular stress type contains information from all stress components and is thereby applicable for different load cases, e.g., shearing and bending.

6. Summary of methodological process

A summary of the steps in the damage localization process presented in this paper is outlined in order to make a clear overview of the method before presenting the results.

- Preparation:
  - Collect reference measurements from a healthy state.
  - Perform a system identification of the reference measurements in order to estimate $R_u(s)$.
  - Calibrate an FE model based on experimental modal parameters obtained using OMA.

Journal of Physics: Conference Series **628** (2015) 012069 doi:10.1088/1742-6596/628/1/012069

- Damage localization:
  - Perform system identification of the current measurements in order to estimate $R_d(s)$.
  - Perform SVD on $\Delta R(s)^T$ for a proper s-value in order to estimate the SDDLV.
  - Apply the SDDLV as static pseudo-loads to the calibrated FE model and compute stresses, e.g., von Mises stresses.
  - The stresses approaching zero are identifying damaged location(s).

7. Results

By examining the SDDLV-induced stress fields for the two analysed cases, it is generally found that the global x-directional location of the areas of damage are estimated accurately and consistently, whereas the y-directional location can vary depending on the specific SDDLV applied.

The system identification of the experiments reveals that the poles corresponding to the 2nd and 3rd flapwise bending modes are the most excited and consequently only poles associated with these modes are used to estimate the SDDLV. The s-value used for determination of the SDDLV is taken as the value of the current pole increased by 1 %, as described in section 4.

In figure 4, the stress field from one SDDLV is presented for Damage 1. Here, the damage is located between 560-680 mm from the root at the leading edge, see figure 2. The stress field in figure 4 approaches zero stress in the damaged area, but also at the root and at the tip.

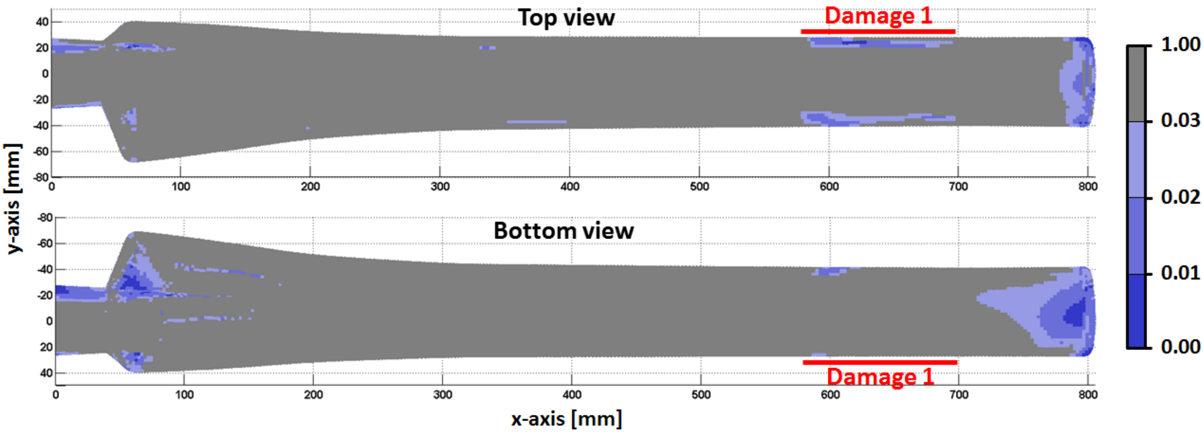

Figure 4. Stress field illustrating the normalized elemental mean von Mises stress for one SDDLV showing the appearance of Damage 1.

These disturbances and lack of precision for localization in the y-direction would most likely disappear if more sensors were used for monitoring the vibrations. The amount and location of this noise are varying for all SDDLVs, but the noise often appears at the tip and root of the blade. The disturbance at the root is understandable, as the geometry is varying more in this area and the number of sensors is small. At the tip, it is clear that noise will appear since the area from sensor 1 and 2 to the end of the blade is only affected a little by the loads applied to the structure.

Examination of SDDLVs for Damage 2 has confirmed many of the observations from Damage 1. Some SDDLVs locate the damage clearly, while others contain mostly noise. Damage 2 is located 180-300 mm from the root at the trailing edge, which defines the maximum damage size based on the same conditions as described for Damage 1. One stress field for Damage 2 is illustrated in figure 5, where the damage is clearly localized, albeit with disturbances at the root and at the tip. In some situations it is hard to distinguish between actual damage and disturbances when observing the stress field for a single SDDLV. However, examination of several SDDLVs has revealed that the damaged location is the only area in which the stresses always approach zero. An informative overview of examined SDDLVs from different operational experiments is listed in table 2. The table, which is based on 25 experiments for each of the two damage scenarios, shows consistency in localization of the damage, even when the disturbance is changing.

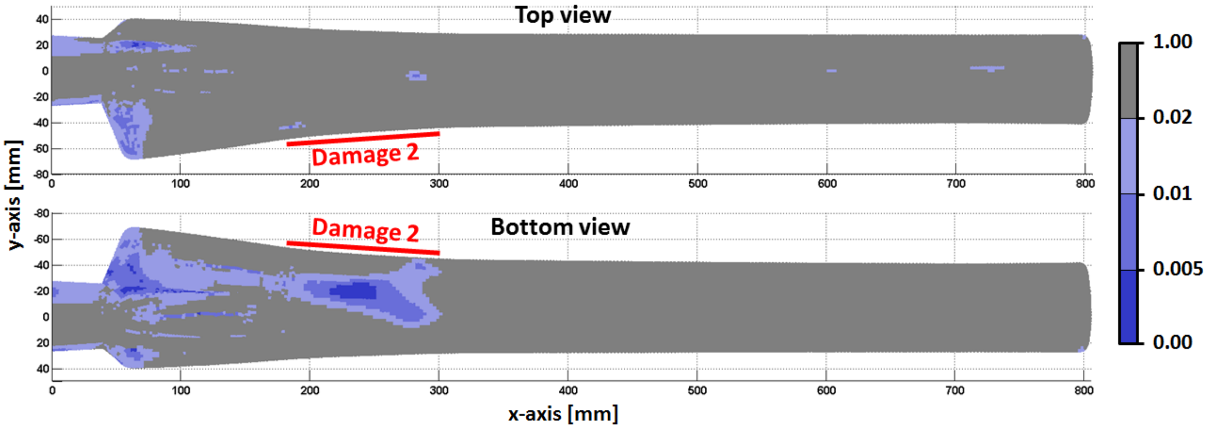

Figure 5. Stress field illustrating the normalized elemental mean von Mises stress for one SDDLV showing the appearance of Damage 2.

Table 2. SDDLV-based damage localization results for two damage types.

	Experiments	Localized		Noise root			Noise tip		
		Yes	No	High	Low	None	High	Low	None
Damage 1	25	23	2	10	8	7	10	3	12
Damage 2	25	25	0	8	10	7	13	0	12

A clear explanation of the varying precision of the SDDLVs throughout the examination of the two areas of damage has not been observed. However, it has been observed that SDDLVs based on s-values corresponding to the second flapwise bending mode and the third flapwise bending mode yield less stress disturbance than those for the remaining identified blade modes for Damage 1 and Damage 2, respectively. It has been noticed during OMA, that these two modes are excited significantly better than other higher modes.

From the experiments visualized in figure 4 and figure 5 and the results listed in table 2, it is clear that the stresses in the damaged areas approach zero, while the zero stresses elsewhere occur rather randomly. This observation suggests that one way of reducing the level of disturbance, in order to separate damages from noise, is to apply a statistical evaluation on a large set of stress fields obtained from different SDDLVs. This is treated in [9].

8. Conclusion

The presented paper deals with localization of damage in a residential-sized wind turbine blade by use of the SDDLV method. The method employs the vectors from the quasi-null space of the damage-induced change in transfer function matrix as static pseudo-loads, which are applied to a known model of the undamaged system. The damage is then, suggestively, found at locations where the stresses are approaching zero.

The SDDLV method is demonstrated as capable of locating different areas of damage on both the leading and trailing edges of the blade. The stress field generally approaches zero in the location of the damage. However, noise is, in most cases, present, making it difficult to obtain unambiguous localization. The disturbances primarily appear at the tip and at the root of the blade; thus a way to reduce these noise contributions could be to apply a statistical approach in which several SDDLV-induced stress fields are evaluated in a combined manner. This is a part of future research activities.

Further future research activities will deal with the selection of s-value(s). In the present study, it has been set to be a 1 % increment of the s-value corresponding to the consistently identified pole. This procedure has been chosen somewhat randomly, and it could therefore be an interesting study to apply different s-values around the pole of interest in order to see, if any general approach can be established for the choice of s-values, hereby increasing the reliability and robustness of the SDDLV method.

9. Acknowledgement

The experimental part of the project was supported by the EUDP (Danish Energy Technology Development and Demonstration Programme) grant 64011-0084 ”Predictive Structure Health monitoring of Wind Turbines”. The authors also acknowledge Robert Flemming Mikkelsen who provided the blade for the experiments.

10. References

[1] Ciang C C *et al* 2008 Structural health monitoring for a wind turbine system a review of damage detection methods *Meas. Sci. Technol.* **19** 122001
[2] Rytter A 1993 Vibration based inspection of civil engineering structures Ph.D. Thesis Aalborg University Denmark
[3] Farrar C R *et al* 2001 Vibration-based structural damage identification *Philosophical Transactions: Mathematical, Physical and Engineering Sciences* **359** 131-149
[4] Bernal D 2002 Load vectors for damage localization *J. Eng. Mech.* **128** 7-14
[5] Bernal D 2007 Damage localization from the null space of the transfer matrix *AIAA Journal* **45** 374-381
[6] Bernal D 2010 Load vectors for damage location in systems identified from operational loads *J. Eng. Mech.* **136** 31-39
[7] Bottoli F and Pignatti L 2001 Design and processing of structural components in biocomposite materials rotor blade for wind turbine cars M.Sc. Thesis Risø DTU
[8] Van Overschee P and Moor B L R 1996 Subspace identification for linear systems theory implementation applications Kluwer academic publishers
[9] Hansen L M *el al* 2015 Statistical evaluation of characteristic SDDLV-induced stress resultants to discriminate between damaged and undamaged elements *Submitted to 11th International Conference on Damage Assessment of Structures*