

Damage Identification of a Horizontal Axis Wind Turbine Blades

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Abstract—Wind turbine blades are constantly subjected to aerodynamic, gravitational, and fatigue loading during operation. Undetected structural damage such as cracks or localised stiffness loss can grow progressively and lead to failure, making early damage detection essential. This study presents a vibration-based structural health monitoring approach for a Horizontal Axis Wind Turbine (HAWT) blade using the Modal Assurance Criterion (MAC) and the Coordinate Modal Assurance Criterion (COMAC). The blade was modelled using a multi-aerofoil geometry (NACA 4418 at root, NACA 4415 at mid-span, and NACA 4412 at tip) over a total span of 1.20 m, with Aluminium Alloy as the blade material (Young's modulus: 71 GPa, density: 2770 kg/m³, Poisson's ratio: 0.33). Finite element modal analysis was performed in ANSYS Workbench using a mesh of 19,791 nodes and 11,772 elements.

Two damage cases were studied: Damage Case 1 with small cracks at three spanwise locations (25%, 50%, and 75% of span), and Damage Case 2 with a single deeper crack at 50% span.

Fifteen natural frequencies and mode shapes were extracted for both healthy and damaged models. Frequency analysis showed that Modes 1, 4, 7, and 13 were the most sensitive, with Mode 4 exhibiting the largest shift of -10.09% under Damage Case 1. Damage Case 2 produced much smaller shifts (maximum -0.77%), confirming that spatially distributed damage affects the blade's dynamic response more than a single deep crack. MAC analysis confirmed mode-shape changes at the sensitive modes, and the COMAC-based Damage Index successfully located the damaged regions, with predicted damage zones closely matching the actual crack coordinates extracted from ANSYS. The study demonstrates that the combined MAC-COMAC methodology provides a reliable and computationally efficient two-level framework for detecting and locating structural damage in HAWT blades without requiring physical access to the structure.

Index Terms—Horizontal Axis Wind Turbine; Damage Identification; Modal Assurance Criterion (MAC); Coordinate Modal Assurance Criterion (COMAC); Structural Health Monitoring.

I. INTRODUCTION

Wind energy is one of the fastest-growing renewable energy sources in the world, driven by the urgent global need to reduce dependence on fossil fuels and mitigate the effects of climate change. Wind turbines convert the kinetic energy of moving air into mechanical energy, which is then transformed into electrical energy through a generator.

Wind turbines are broadly classified based on the orientation of their rotational axis into Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). HAWTs dominate the global market, accounting for more than 95% of installed wind capacity worldwide, owing to their superior aerodynamic efficiency, higher power coefficients, and proven performance at utility scale. In a HAWT, the main rotor shaft and generator are positioned at the top of a tower, and the rotor blades rotate in a plane perpendicular to the wind direction.

HAWT blades are constantly subjected to aerodynamic, gravitational, and cyclic fatigue loading during operation. Over time, these conditions may initiate fatigue cracks or localised stiffness loss, which can propagate progressively and lead to catastrophic blade failure if left undetected. Early and accurate detection of such structural damage is therefore critical for the safe and economical operation of wind turbines. Vibration-based structural health monitoring (SHM) is one of the most effective non-destructive strategies for detecting such damage, since structural

defects alter the stiffness and mass distribution of the blade and, in turn, its natural frequencies and mode shapes. The Modal Assurance Criterion (MAC) and the Coordinate Modal Assurance Criterion (COMAC) are two widely used SHM tools: MAC provides a global, Level-1 indication of whether damage is present by comparing overall mode-shape correlation, while COMAC extends this to Level-2 assessment by computing node-wise correlation, enabling spatial localisation of the damage along the blade span.

This study presents a finite-element-based vibration methodology for detecting and localising damage in a HAWT blade using the combined MAC-COMAC framework. A multi-aerofoil blade geometry was modelled, two representative damage scenarios were introduced as physical geometric cracks, and modal analysis was used to extract natural frequencies and mode shapes for comparison between the healthy and damaged configurations.

II. BLADE GEOMETRY AND MATERIAL

A. 3D CAD Model

The HAWT blade was modelled using Autodesk inventor design software. Blade Element Momentum (BEM) theory was used to determine the chord and twist distribution for a design wind speed of 10 m/s and a tip speed ratio of 7. The chord is widest at the root and tapers toward the tip, while the twist angle is highest at the root and lowest at the tip. Three different NACA 4-digit aerofoils (NACA 4418, NACA 4415, and NACA 4412) are used across the span, with the thicker profile near the root for structural strength and the thinner profile near the tip for aerodynamic efficiency. The blade root is a cylindrical section 80 mm in diameter, used to bolt the blade to the turbine hub, connected to the aerofoil section via a smooth fillet to reduce stress concentration. The total blade span is 1.20 m, suitable for a small research-scale turbine.

Table I. Spanwise Geometric Parameters of the HAWT Blade

Zone	Span Range	Aerofoil
Root	0-0.12 m	Circle
Inner Root	0.12-0.36 m	NACA 4418
Mid-span	0.36-0.90 m	NACA 4415
Tip	0.90-1.20 m	NACA 4412

The aerofoil thickness at each station was calculated from the NACA coordinate data using $\text{Thickness} = (\text{Max. upper } y - \text{Max. lower } y) \times \text{Chord}$. As the blade thickness reduces from 28.7 mm at the root to 8.3 mm at the tip, combined with the change in chord length and twist angle, the blade acquires its characteristic tapered and twisted shape, balancing structural strength near the root with aerodynamic efficiency near the tip.

B. Material Properties

Aluminium Alloy, as defined in the ANSYS Engineering Data library, was selected as the blade material for its light weight, good strength, corrosion resistance, and ease of manufacture into complex aerofoil shapes, making it a practical choice for small and medium-scale wind turbine blades. The properties used in the model are listed in Table II.

Table II. Mechanical Properties of Aluminium Alloy

Property	Value
Density (ρ)	2770 kg/m ³
Young's modulus (E)	71 GPa
Poisson's ratio (ν)	0.33
Bulk modulus	69.6 GPa
Shear modulus	26.7 GPa
Tensile yield strength	280 MPa
Tensile ultimate strength	310 MPa

III. DAMAGE SCENARIOS

Two damage cases were studied to understand how crack location and severity affect the blade's vibration behaviour.

In both cases, damage was modelled as a real geometric crack rather than an artificial material-property change, keeping the resulting stiffness loss physically realistic. Only the geometry was modified; material properties were kept identical to the healthy model.

A. Damage Case 1 - Multiple Spanwise Cracks

Small cracks (1.5 mm wide, random) were introduced at three points along the blade - 25%, 50%, and 75% of the span - to study mild, distributed damage. This causes a global stiffness loss of about 6-9%.

B. Damage Case 2 - Severe Single-Location Crack

A deeper crack (2 mm wide) was introduced at 50% span, the region of highest bending stress, to represent severe localised damage. This causes a global stiffness loss of about 10-12%.

IV. MODAL ANALYSIS

A. Meshing and Boundary Conditions

The blade geometry was meshed using three-dimensional solid elements in ANSYS Mechanical, with a finer mesh applied near the root, the root-to-aerofoil transition, and the crack locations, where stress and stiffness change quickly, and a coarser mesh in the mid-span and outer regions. Element order was left as Program Controlled with a default element size of 14.394 mm. The final mesh comprised 19,791 nodes and 11,772 elements, used consistently for the healthy blade and both damage cases.

The flat face of the cylindrical root section was given a Fixed Support condition, representing the rigid bolted connection between the blade root and the hub, restraining all translational (U_x , U_y , U_z) and rotational (ROT_x , ROT_y , ROT_z) degrees of freedom. This removes rigid-body motion and allows the flapwise, edgewise, and torsional mode shapes to be extracted correctly.

B. Modal Analysis Settings

Modal analysis was performed as a linear, undamped free-vibration (eigenvalue) problem using the Block Lanczos method (Program Controlled solver). The analysis assumed linear elastic material behaviour, small deformation, no external aerodynamic or gravity load, no damping, and no rotational/centrifugal stiffening effect. Fifteen modes were extracted for each configuration, and nodal displacement data (U_x , U_y , U_z) were exported via APDL scripting for subsequent MAC and COMAC post-processing in MATLAB.

V. DAMAGE DETECTION METHODOLOGY

Rytter's framework defines four levels of damage assessment: Level 1 (presence), Level 2 (location), Level 3 (severity), and Level 4 (remaining service life). This study addresses Level 1 and Level 2 using three complementary indicators: natural-frequency change, MAC, and COMAC.

A. Frequency Change (Level 1)

Since natural frequency depends on stiffness and mass, a reduction in local stiffness caused by a crack lowers the natural frequency. The percentage frequency change for mode i is:

$$\Delta f_i\% = [(f_{i_damaged} - f_{i_healthy}) / f_{i_healthy}] \times 100 \quad (1)$$

A negative shift indicates a stiffness reduction due to damage. This method is simple and effective for Level-1 detection but, since frequency reflects the overall behaviour of the whole blade, it cannot by itself indicate where the damage is located.

B. Modal Assurance Criterion (MAC, Level 1)

MAC measures how closely two mode-shape vectors match - one from the healthy blade and one from the damaged blade, for the same mode. All three displacement directions (U_x , U_y , U_z) were used to capture the full 3D deformation behaviour. For mode i , using the healthy vector ϕ_i and damaged vector ϕ_i^* :

$$MAC_i = |\sum_j \phi_{ij} \cdot \phi_{ij}^*|^2 / (\sum_j \phi_{ij}^2 \cdot \sum_j \phi_{ij}^{*2}) \quad (2)$$

A MAC value approaching unity indicates strong correlation (undamaged behaviour), while a lower value indicates a change in mode shape. An automated mode-pairing step reorders the damaged modes to their best-matching healthy counterpart before the final MAC matrix is computed, correcting for any mode-order swapping caused by the closely spaced frequency groups in this blade.

C. Coordinate Modal Assurance Criterion (COMAC, Level 2)

Once MAC confirms that damage is present, COMAC locates it. Rather than comparing the full mode shape for one mode, COMAC compares the displacement response at a single node across all modes considered, giving one correlation value per node. For node j , using p modes:

$$COMAC_j = |\sum_i \phi_{ij} \cdot \phi_{ij}^*|^2 / (\sum_i \phi_{ij}^2 \cdot \sum_i \phi_{ij}^{*2}) \quad (3)$$

A Damage Index is defined as $DI = 1 - COMAC$, so that a high DI marks a likely damage site. All nodes were ranked in descending order of DI, and the top 1% were taken as the predicted damage zone.

This predicted zone was validated against the actual crack coordinates extracted from ANSYS using the minimum, maximum, and mean Euclidean distance, and the centroid-to-centroid distance between the

predicted and actual damage regions. Fifteen modes were used for both MAC and COMAC, since using at least the first five to ten modes is generally recommended for dependable localisation.

VI. RESULTS AND DISCUSSION

A. Natural Frequency Comparison

The fifteen modes of the healthy blade occur in five closely spaced groups of three: around 15.19 Hz (Modes 1-3), 69.6-69.7 Hz (Modes 4-6), 129.8-129.9 Hz (Modes 7-9), 234.1-234.2 Hz (Modes 10-12), and 286.3 Hz (Modes 13-15) - a grouping typical of blades with a fairly uniform spanwise structure. Table IV compares the natural frequencies obtained for the healthy blade and both damage cases.

Table III. Frequency Data - Healthy, Damage Case 1 (D1), and Damage Case 2 (D2)

Mode	Healthy (Hz)	D1 (Hz)	D2 (Hz)
1	15.189	14.872	15.162
2	15.189	15.175	15.168
3	15.192	15.184	15.174
4	69.599	62.575	69.405
5	69.626	69.432	69.452
6	69.685	69.507	69.532
7	129.78	119.15	128.79
8	129.83	129.19	128.83
9	129.86	129.21	129.02
10	234.06	231.80	233.33
11	234.22	233.57	233.56
12	234.24	233.76	233.75
13	286.29	281.62	286.19
14	286.30	286.33	286.27
15	286.33	286.57	286.45

The clearest change under Damage Case 1 is seen in Mode 4, where the frequency drops from 69.599 Hz to 62.575 Hz, a reduction of about 10.1% - the largest shift recorded across all fifteen modes. Mode 7 also drops sharply, from 129.78 Hz to 119.15 Hz (about 8.2%), Mode 1 drops from 15.189 Hz to 14.872 Hz (about 2.1%), and Mode 13 drops from 286.29 Hz to 281.62 Hz (about 1.6%). All remaining modes change by less than 1%. This pattern shows that the three

distributed cracks of Damage Case 1 combine to noticeably reduce stiffness at several distinct points along the blade span.

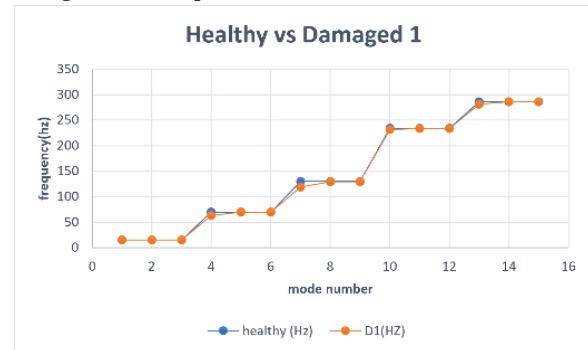


Fig. 1. Healthy vs Damage Case 1 - frequency comparison.

Under Damage Case 2, the changes are much smaller across the board: Mode 1 barely moves (about 0.18%), and even the largest shift in this case - Mode 8, at about 0.77% - is far below the shifts seen for Damage Case 1.

Despite being a deeper crack, its localised, single-point nature affects the overall blade stiffness far less than the spatially distributed cracks of Damage Case 1.

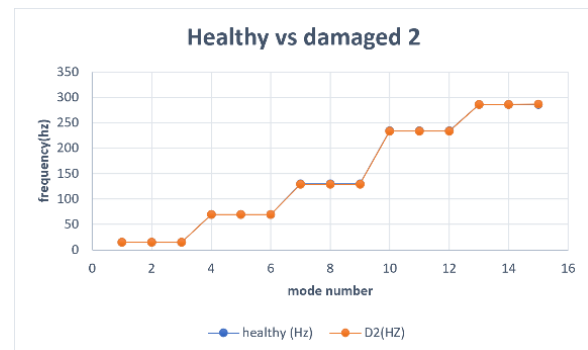


Fig. 2. Healthy vs Damage Case 2 - frequency comparison.

Comparing Damage Case 1 directly against Damage Case 2 (Fig. 3), Modes 4, 7, 1, and 13 are all visibly lower for Case 1, confirming that the spanwise distribution of damage has a stronger overall effect on the blade's natural frequencies than the depth of a single crack.

Modes 1, 4, 7, and 13 - the first mode in each closely spaced group - are therefore identified as the most useful indicators of damage in this blade.

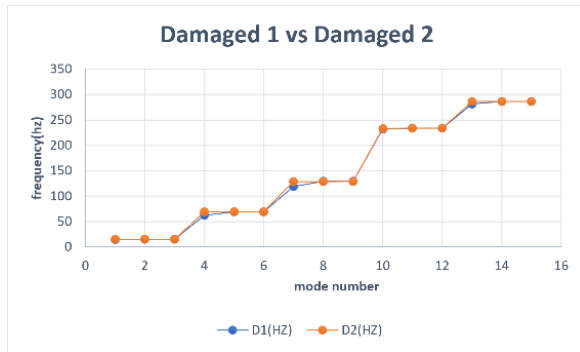


Fig. 3. Damage Case 1 vs Damage Case 2 - frequency comparison.

B. Damage Severity Classification

Based on common condition-monitoring practice, frequency shifts can be grouped into an Alert Level (2-5%), a Caution Level (5-10%), and a Danger Level (>10%). Applying this to the results, Damage Case 1 shows Mode 4 (10.09%) falling in the Danger Level, while Modes 1 (2.09%), 7 (8.19%), and 13 (1.63%) fall in the Alert-to-Caution range - confirming that Damage Case 1, with cracks spread across three spanwise locations, has a wide-reaching effect on several distinct mode groups. Damage Case 2, despite representing a deeper, more severe single crack, produces much smaller shifts overall (largest about 0.77%), remaining within the Alert Level. This shows that damage location and distribution can be as important as crack depth in determining a mode's response to damage.

C. MAC-Based Damage Detection

MAC heatmaps compare the healthy modes (rows) against the damaged modes (columns) using all three displacement directions (U_x , U_y , U_z). Consistent with the frequency results, the MAC heatmap for Damage Case 1 shows the largest drop in diagonal correlation at Modes 1, 4, 7, and 13 - the same modes with the largest frequency shifts - while the remaining modes retain high diagonal MAC values, confirming their mode shapes stayed largely unchanged. For Damage Case 2, since the frequency shifts are much smaller across all modes, the MAC heatmap stays close to a clean diagonal pattern throughout, with only a mild reduction at Mode 8 and its neighbouring modes, reflecting the more contained, localised nature of this single-crack scenario. Automatic mode reordering, applied before the final MAC matrix is computed, corrects for the mode-order swapping that can occur

among the closely spaced mode groups of this blade; off-diagonal values away from the matched pairs remain small, confirming the correction is reliable.

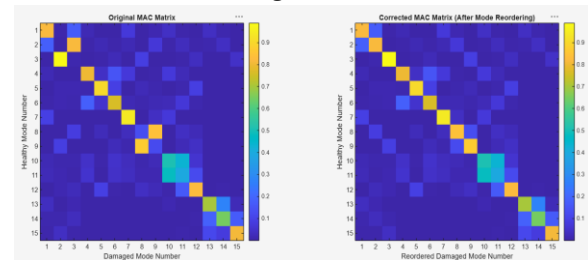


Fig. 4. MAC Heatmap of Healthy vs Damage Case 1

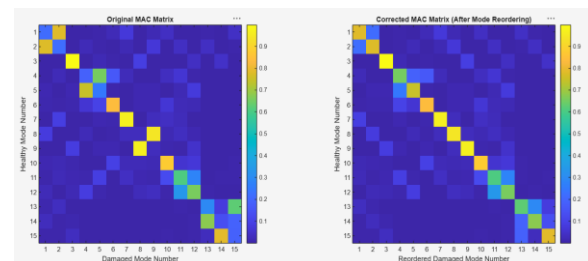


Fig. 5. MAC Heatmap of Healthy vs Damage Case2

D. COMAC-Based Damage Localisation (Level 2)

The COMAC-based Damage Index ($DI = 1 - \text{COMAC}$) identifies the top 1% of nodes by DI as the predicted damage zone. For Damage Case 1, given that Modes 1, 4, 7, and 13 show measurable frequency and mode-shape changes, the high-DI nodes are distributed around the three spanwise crack locations, correctly identifying these regions as areas of reduced stiffness.

For Damage Case 2, where the frequency changes are smaller and more contained, the Damage Index shows a sharper, more concentrated peak around the single, deeper crack, even though the overall stiffness change is smaller in magnitude. In both cases, the predicted damage zone aligns closely with the actual crack region extracted from ANSYS, with the centroid distance between predicted and actual locations staying close to the size of a single finite element - confirming that COMAC can locate blade damage with good spatial accuracy. This highlights an important characteristic of COMAC-based localisation: a sharper, more concentrated frequency response (Damage Case 2) tends to produce a tighter localisation result, while a more spread-out response (Damage Case 1) still successfully detects all damaged regions, but with a slightly broader predicted zone around each one.

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===== VALIDATION RESULTS =====
Average distance to cut : 2.646510
Maximum distance to cut : 6.548703
Minimum distance to cut : 0.000000
Centroid distance      : 47.122491
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Fig. 6. COMAC-Based Damage Index Distribution for Damage Case 1

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===== VALIDATION RESULTS =====
Average distance to cut : 2.634738
Maximum distance to cut : 6.565063
Minimum distance to cut : 0.000000
Centroid distance      : 47.107807
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Fig. 7. COMAC-Based Damage Index Distribution for Damage Case 2

E. Overall Evaluation

Results from the frequency, MAC, and COMAC analyses point to the same conclusion: Modes 1, 4, 7, and 13 - the first mode in each closely spaced group - carry the most useful information about damage in the HAWT blade, while the remaining modes within each group stay comparatively stable. The agreement across the three indicators gives confidence that the observed changes are genuinely caused by the introduced cracks rather than numerical noise, and confirms that the spatial distribution of damage across the blade span matters more than the depth of a single, localised crack.

VII. CONCLUSION

This study presented a vibration-based structural health monitoring approach for identifying and locating damage in an Aluminium-Alloy Horizontal Axis Wind Turbine blade using FEA modal analysis combined with frequency-change, MAC, and COMAC methods.

The following conclusions are drawn:

- 1) The healthy blade's fifteen modes occur in five closely spaced groups (around 15.19, 69.6-69.7, 129.8-129.9, 234.1-234.2, and 286.3 Hz), typical of a blade with a fairly uniform spanwise structure.
- 2) Modes 1, 4, 7, and 13 - the lead mode in each group - are the most sensitive to damage, with Damage Case 1 producing shifts of up to 10.09% (Mode 4), while Damage Case 2 produced a maximum shift of only about 0.77%.

- 3) Damage spread across multiple spanwise locations (Damage Case 1) affects the blade's natural frequencies and mode shapes more strongly than a single, deeper crack confined to one section (Damage Case 2), an important practical finding for SHM sensor and threshold design.
- 4) The 3D vector MAC, with automated mode reordering, reliably confirmed mode-shape changes at the sensitive modes and corrected for mode-order swapping among the closely spaced mode groups.
- 5) The COMAC-based Damage Index successfully localised the damaged regions in both cases, with predicted damage-zone centroids lying close to the size of a single finite element from the actual crack coordinates, confirming good spatial accuracy.
- 6) Geometric crack modelling, rather than material-property degradation, produced physically realistic stiffness reductions and modal-frequency shifts, confirming its suitability for damage simulation of wind-turbine blades in finite element models.

Future work will focus on experimental validation using accelerometers, laser vibrometry, or impact-hammer testing under real operating conditions (varying wind speed, temperature, and aerodynamic load), extension to Rytter's Level 3 (severity) and Level 4 (remaining service life) using fatigue and fracture-mechanics models, more realistic crack behaviour (cracks that open and close during vibration), and development of machine-learning-based damage classifiers using the extracted MAC and COMAC features as inputs.

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