Robotic deployment of stabilized shearography unit for wind turbine blade inspection

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Abstract. A wind turbine blade inspection system called Winspector has been developed by a European consortium to automate the in-situ non-destructive testing of wind blades. A robot platform is winched up a wind turbine tower to reach a blade locked into a 90-degree pitch angle. The blade region to be inspected is reached by a combination of an extension ladder and a 5-axis robot arm to place an end-effector onto the blade surface. The end-effector is critical to the success of the shearography technique used to detect subsurface defects when the blade is experiencing inevitable out-of-plane, in-plane, and root-to-tip vibrations. The paper describes the development of the end-effector which carries the shearography unit and ensures (with passive compliance and design based on analysis of aerodynamic blade shapes) that the unit remains at a constant distance from blade surface in the presence of blade vibrations. The system has been tested with three separate field trials in a wind farm near Athens in Greece. Sub-surface defect detection with shearography has been successfully demonstrated.

Keywords: Robotic in-situ inspection of wind blades, Measurement of wind blade vibrations, Shearography NDT of wind blades

1 Introduction

1.1 The need to inspect wind turbine blades

Annual wind power installations in Europe increased from 3.2 GW in 2000, to 11.8 GW in 2014. At the end of 2014 the total installed capacity in the EU reached 128.8 GW [1] and 370 GW globally [2].

There are currently more than 700,000 wind turbine blades in operation, with approximately 243,600 wind turbine blades within the EU [3]. Given that an average of 3,800 blade failures occur annually, attributed to poor maintenance [4], costing between £70,000 and £700,000 each, preventative inspection every 3-4 months and maintenance every 6 months is necessary.

1726 accidents have been reported from 1970 to May 2015 with fatalities accounting for 45% of the total number [5]. There is a clear market need to develop automated inspection techniques that can meet the requirements of inspecting wind turbine installations so that structural failures and catastrophic consequences can be avoided.

1.2 Automation of the non-destructive testing (NDT) of wind turbine blades

A solution to this problem is to utilize specially designed robot platforms that can climb WT towers, reach the blade and test wind turbine blades on site with non-contact non-destructive testing (NDT) methods. Systems to automate the NDT of wind turbine blades are in early stages of development with RadBlad [6] using robots to climb up a WT tower to reach a stationary wind turbine blade and use x-ray radiography to scan the blades. Another development [7] uses a climbing robot with permanent magnet adhesion to carry a long arm that can reach wind turbine blades. Other approaches [8-11] place a climbing robot carrying a shearography system directly on to a wind turbine blade using a crane.

2 The Winspector system

The Winspector project was funded by the European H2020 Fast Track to Innovation program [12] with WRS Marine in the Netherlands leading the project and Gamesa (Spain) and Iberdrola (Spain) providing wind turbine blade data and access to testing facilities. Winspector consists of a wheeled robotic platform developed by project partner Innora (Greece), see Fig. 1. The wheeled platform adheres to the wind turbine tower with two magnet systems at the top and bottom of the platform. A ladder arm is rotated to reach outwards towards a wind turbine blade. A five-axis robot arm (two prismatic joints, three rotational joints) mounted at the end of the ladder deploys the Digital Shearography Unit. The Shearography Unit is contained within an end-effector frame, termed the Shearography Unit Holder. The shearography unit was developed by project partner TWI (UK) while the Shearography Unit Holder was developed by London South Bank University (UK). The robot platform carries a winching system that uses two wire ropes from the nacelle to obtain up/down vertical motion of the robot.

The following sections describe the development of some aspects of the Winspector system with particular focus on overcoming problems caused by blade vibrations/oscillations due to wind effects and blade construction materials.

2.1 Development of the Winspector robot

The prototype was developed for the middle range of the Gamesa family of wind turbines, G9x series. The design was optimized to be able to develop three sizes of this robot, targeting smaller or bigger wind turbines with respect to the G9x, with a tower height ranging from 50m to 150m.

A combination of climbing platform, ladder, robot arm and end-effector deploys the shearography equipment at a desired position along the blade chord while maintaining a steady distance of the shearography unit from the blade (despite blade movement due to wind gusts, etc.) and always at a normal orientation to the blade surface, see Fig. 2. The Winspector robot is designed to position the shearography system on both sides of a wind turbine blade while the wind turbine blade is stopped at a pitch angle of 90°.

The end-effector, comprising of the Shearography Unit Holder and laser/optical unit is attached to the wind turbine blade surface during inspection.

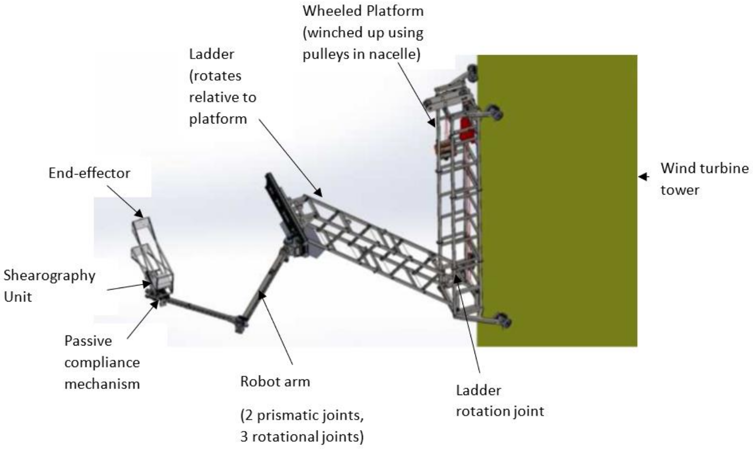

Fig. 1. Winspector robot

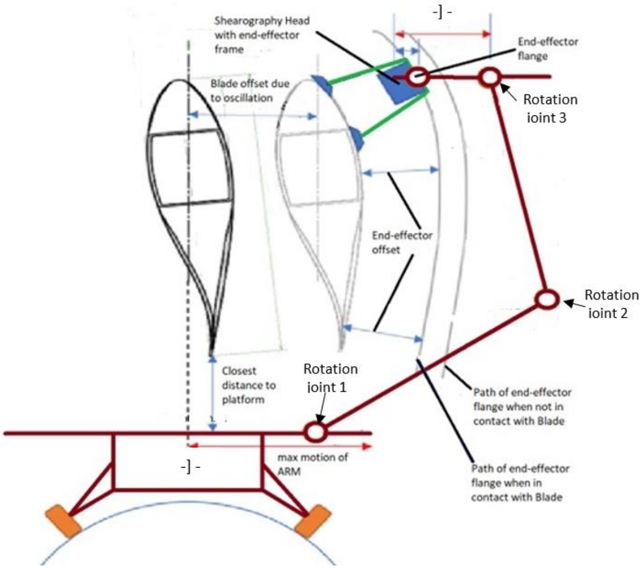

Fig. 2. Winspector schematic, platform, robot arm, end-effector with blade stopped at 90° pitch

This paper focusses on design of the end-effector and compliance mechanisms which are critical to enabling the shearography to detect blade flaws when the blade is vibrating in three dimensions.

2.2 The Winspector shearography system

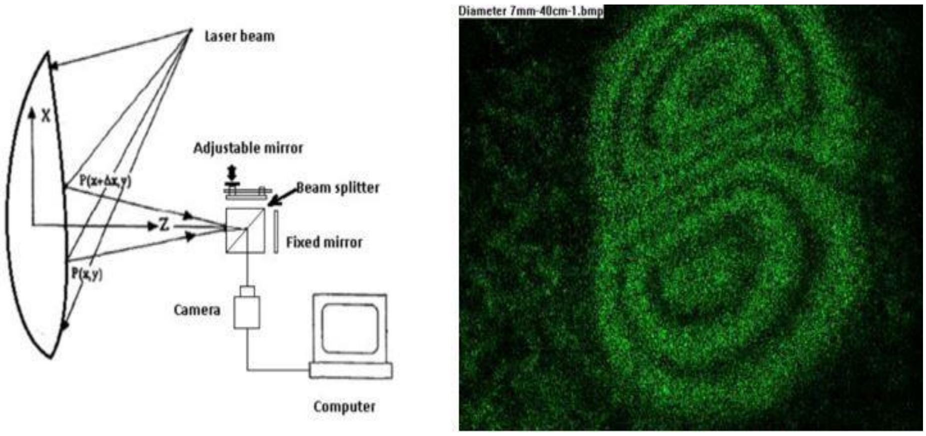

Fig. 3. Shearography system with a typical bull's eye fringe pattern indicating a subsurface defect

On-site shearography, a high-resolution inspection technique that can identify sub-surface defects, offers early detection of areas of risk to prevent costly blade failure incidents. A high-quality inspection carried out in-situ by examining up to 100 m2 /hour, will reduce downtime by 25% and eliminate the need of other thorough techniques which require the dismantling of the blades and transfer to workshops.

The Winspector NDT system (Fig.3), developed by project partner TWI Ltd (UK), is a shearography system that can inspect composite wind turbine blades. The critical defects found in composite wind turbine blades include cracks, voids, disbonds, delaminations, and impact damage [11]. As a rule of thumb, the minimal characteristic dimension of a defect is equivalent to its depth (the distance from the surface of the material). For a volumetric defect such as a void, the characteristic dimension is the diameter of the defect. For a planar or linear defect such as a delamination or a crack, the characteristic dimension is much complex to quantify since the effect of the defect on the surface deformation is highly dependent on the orientation of the defect.

The technique measures and qualifies both large and small complex geometries quickly and efficiently, yielding near real-time results. A thermal pulse is applied to the inspected part of the blade, distribution of the stress on the tested area is recorded using a shearing image interferometer, included in the digital shearography camera. By analyzing the derivatives of the stress distribution, any discontinuities are observed, thus every critical defect is revealed.

The single shearography camera is capable of detecting surface and sub-surface anomalies as small as 3 nm and scan the blade with an efficiency of up to 130m^2 per hour. A wind turbine can be inspected within a day on average.

2.3 Design of end-effector to enable shearography in the presence of 3-D blade vibration

Shearography offers the advantage of non-contact inspection with the Shearography Unit (SU) deployed at one meter from the blade. However, vibration of the blade caused by wind creates a relative motion between the blade and the shearography system which renders the inspection data invalid. To overcome this motion of the blade, an end-effector was developed to place and firmly attach the shearography system to the blade with sufficient passive compliance in the system to enable the SU and blade to move together. Blade oscillation data was gathered from a wind turbine representative of the targeted market, to design and dimension the whole robotic system.

The end-effector is composed of the following main components:

- Shearography Unit Holder holds the shearography unit and uses suction cups to attach to the surface of the blade.
- A mechanism to keep the Shearography Unit Holder connected to the rest of the robot climbing up the wind tower for the duration of the inspection session.
- A passive compliance mechanism between the Shearography Unit Holder and the robot arm that allows the Shearography Unit Holder and hence the Shearography Unit to remain stationary with respect to the vibrating blade.
- A control and communication system that ensures the correct sequence of steps are followed for inspection.

For the design and implementation of the mechanical and control system of the end-effector, the oscillation of a blade was characterized which would be representative of the targeted population of wind turbines and under inspection conditions. This characterization enables the design and dimensioning of the Shearography Holder Unit (SUH) and defines the specifications of the control system for the end-effector as well as the manipulator of the robot climbing up the wind tower.

Characterization of the oscillation on a Gamesa G90 (2MW) Wind Turbine.

The amplitude and frequency of the oscillation of large onshore wind turbine blades was measured directly on the surface of the blade and under maintenance/inspection conditions. The deflection of the blade was measured at three different radii (distance from the nacelle along the surface of the blade). The chosen wind turbine was a G90 (2MW) located in Barchín del Hoyo (Spain) wind farm.

The conditions of the test were representative of an inspection session, with the blade stationary at the four possible pitch angles used in a G90 blade, test lasting for about four hours, wind speed at the farm was between 1 and 6 m/s, being within the 10 m/s maximum wind speed allowed for safety reasons for inspection and maintenance work on site.

Real-time data on the oscillation of the blade was obtained using three IMU sensors (NGIMU, X-IO Technologies) placed on the upper shell near the root of the blade (radius R=3000mm), near the middle of the blade (R=22500mm), and near the tip of the blade (R=44500mm).

Deflection of the blade.

.From the collected data of the variation of the pitch, roll and yaw angles of the IMU sensor, the deflection of the blade at the three selected radii was calculated. The pitch, roll and yaw angles of the IMU sensor correspond to the three axes of rotation of the sensor:

- X axis, which corresponds to the axis from the tip to the root along the length of the blade.
- Y axis, which corresponds to the out of plane axis, that is, the movement of the blade towards and away from the wind tower.
- Z axis, which corresponds to the in-plane axis, that is, the movement of the blade along the plane defined by the surface of the blade.

Fig. 4 shows the data on deflection for the three radii, the four pitch angles of the blade and the entire duration of the test. The out of plane and in-plane deflection are of a comparable magnitude while the deflection along the X axis of the sensor is much smaller – this is the case for the measurement taken near the middle and the tip of the blade; near the root the deflection along the three axes are of a comparable magnitude (see Fig. 4). The maximum deflection calculated from the measurements on a G90 blade is 2.6mm near the root, 9.6mm near the middle, and 94.3mm near the tip. Therefore, the maximum deflection caused by the wind to be expected on a G90 blade under inspection conditions is approximately 100mm.

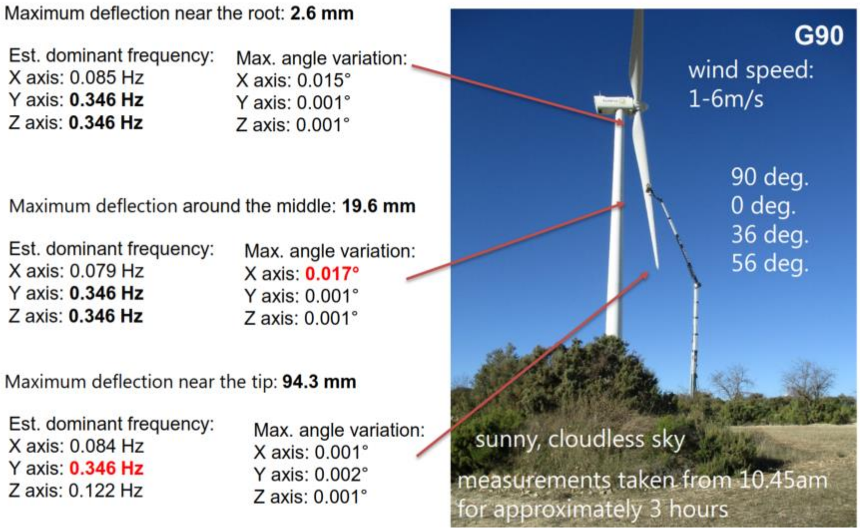

Fig. 4. Deflection of blade near the root, middle and tip of G90 blade calculated from experimental data for pitch angles of (90°, 0°, 36° 56°), around the three directions of rotation.

The estimated dominant frequency, calculated from experimental data on a G90 blade for each axis and each radius of the blade is summarized in Table 1, the dominant frequency of blade under inspection conditions is approximately 0.35Hz.

Table 1. Estimated dominant frequency calculated from experimental data on a G90 blade for each of the three radii considered and each axis of rotation.

Axis	Position along the blade		
	ROOT (R=3000mm)	MIDDLE (R = 22,500 mm)	TIP (R = 44,500mm)
X (tip to root)	0.085 Hz	0.029 Hz	0.084 Hz
Y (out of plane)	0.346 Hz	0.346 Hz	0.346 Hz
Z(in plane)	0.346 Hz	0.346 Hz	0.122 Hz

Table 2. Maximum angle variation directly measured for each radius considered on a G90 blade and each direction of rotation.

Axis	Position along the blade		
	ROOT (R=3000mm)	MIDDLE (R = 22,500 mm)	TIP (R = 44,500mm)
X (tip to root)	0.015°	0.017°	0.001°
Y (out of plane)	0.001°	0.001°	0.002°
Z (in plane)	0.001°	0.001°	0.001°

The maximum angle variation measured by the sensors at each location along the blade is one hundredth of a degree. This means that the end-effector looking at the area of inspection (a circle of 0.5m diameter) will hardly notice any change of orientation of the blade due to the wind. The end-effector will see the area of inspection getting closer and away and moving from left to right by as much as 100mm as previously shown.

Curvature of Gamesa's G90 blade.

Data provided by Gamesa for the G90 wind turbine blade was used to determine whether the footprint of the Shearography Holder Unit (SUH) (the area between the three pairs of suction cups) will be small enough to allow the suction cups to attach to the blade surface along the length of a blade (from its root to tip) and between the leading edge and the trailing edge of the blade. Figure 5 shows how the blade thickness is measured. Defining the longitudinal blade curvature as the radius of the blade surface from the blade root to its tip and the transversal curvature as the radius of the blade from its leading edge to its trailing edge. The transversal curvature is the radius of the surface across the chord. The radius changes depending on blade thickness, with blade thickness being higher at the root of a blade (small radius) and becoming thinner towards the tip (large radius). If the suction cups are too far apart, either longitudinally or transversally, they might not be able to attach to some areas of the blade as the compliance on the cups might not be able to adapt to the relative change of curvature between cups.

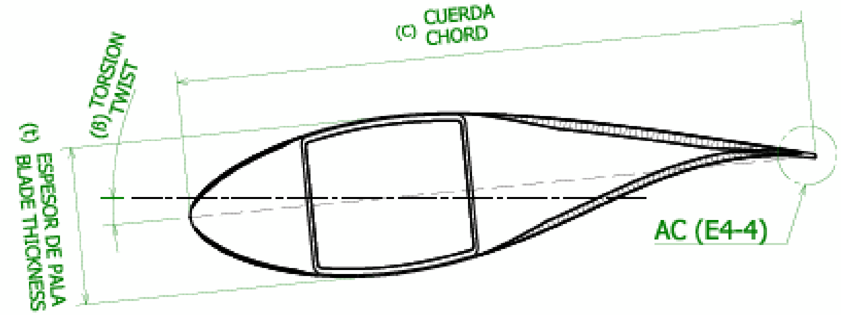

Fig. 5. Profile of Gamesa G90 blade. Note that the distance along the cross section of the blade is called its chord. The torsion line divides the profile in two sides, top and bottom.

3 Design of the end-effector to stabilize shearography

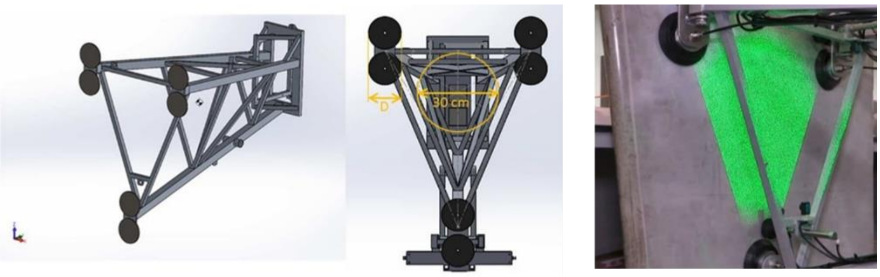

Fig. 6. (Left) Frame design of end-effector with arrangement of suction cups. (Middle) Front view shows the circle limiting the inspection area. (Right) Shearography laser imaging area.

Fig. 6 shows the design of the end-effector. The pyramid-like end-effector structure is attached to a wind blade surface with suction cups located at the three vertices of a triangle. The shearography unit is placed at the top end of the pyramid so that its laser projection area is between the three triangle vertices and its optics have clear access to a measurement area within a circle of 30 cm diameter with its center at the optics focal point, as shown in Fig. 6, middle image. At each attachment vertex two suction cups aligned along the vertical, z axis, establish the connection between the end-effector and the wind blade. As the curvature of the blade is mainly along the chord (x axis), with vertical alignment of the suction cups we minimize its footprint along x direction and maximize the area of the blade we can inspect. The suction cups above the center of gravity of the end-effector will be in traction and the ones bellow will be in compression, meaning that more suction pressure is required at the upper part. To place the end-effector in the most stable configuration to withstand its own weight, the triangular base has been oriented pointing downwards.

The three-point contact configuration improves the stability and the rigidity of the end-effector when it is subjected to crosswinds or other side forces. The connection used in the two upper vertices has one-degree of freedom – z rotation, allowing for the suction cups to locally adjust to the blade curvature. This has the advantage that it is easier to attach the end-effector to the wind blade.

The end-effector structure was analyzed with the Finite Element Method (FEM) to perform: 1) Static Load Analysis; and 2) Modal Analysis. Suction cups and shearography unit were modelled with simplified versions that retain the most relevant geometrical dimensions and weight of the original components. Fig. 7 shows the end-effector geometry, as well as the connections and boundary conditions for FEM. Fixed support condition applied to the suction cups at the bottom. Free z-rotation condition applied to the two connections between the frame and the suction cups.

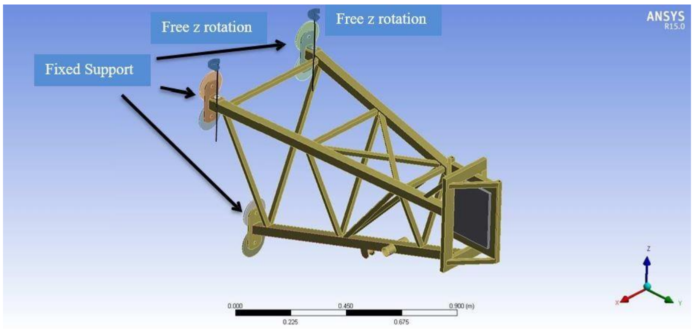

Fig. 7. Boundary conditions and connections for FEM analysis

Results from the FEM analysis showed the deformation in the x direction of the end-effector when submitted to 30N force in the x and y direction at the connection point with the compliant base. Additionally, also considered was the effect of the end-effector weight (190N). The maximum absolute value of the deformation is 0.079 mm.

The maximum absolute value of the deformation in the y direction is 0.021mm. According to these results the maximum deformations are observed for the x (maximum of 0.079mm), and z (maximum of 0.078mm) directions, with the y direction showing the smallest deformation, with a maximum of 0.012mm. The total deformation accounts for a maximum of 0.1mm. In all these cases the maximum deformation falls below the maximum acceptable of 0.5mm, meaning that the end-effector is rigid enough to cope with forces in all three direction.

Modal Analysis.

Considering that the blade is an oscillatory body and that the end-effector will be attached to it, it is important to ensure that the last is not excited at its natural/resonant frequency. If such a scenario would occur, not only would the measurements be compromised but also the integrity of the whole system, which could raise some safety issues. It is therefore important to estimate the resonant modes associated to the end-effector and ensure that these are far from the oscillations imposed by the wind blade. Additionally, evaluating a structure based on its resonant frequencies can be very helpful to optimize the relation between rigidity and weight. To evaluate the resonant frequencies of the end-effector a modal analysis was performed. The characterization of the oscillations of a wind blade type G90 determined that the dominant frequencies are between 0.085 Hz and 0.346 Hz - for wind conditions between 1 and 6 m/s with 10 m/s being the maximum allowed for inspection. Considering that lowest resonant frequency for the end-effector is 58.77 Hz and the highest dominant frequency of excitation is below 0.5 Hz, the oscillations are not expected to compromise the end-effector performance.

End-effector Compliance Support.

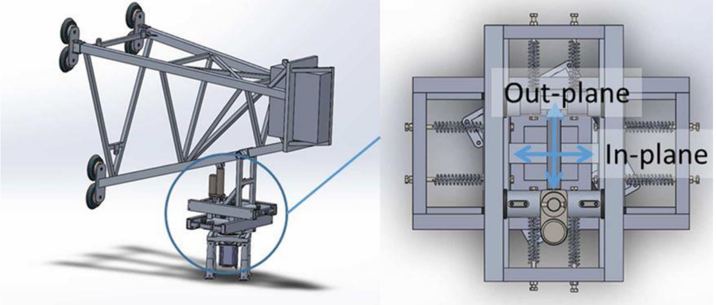

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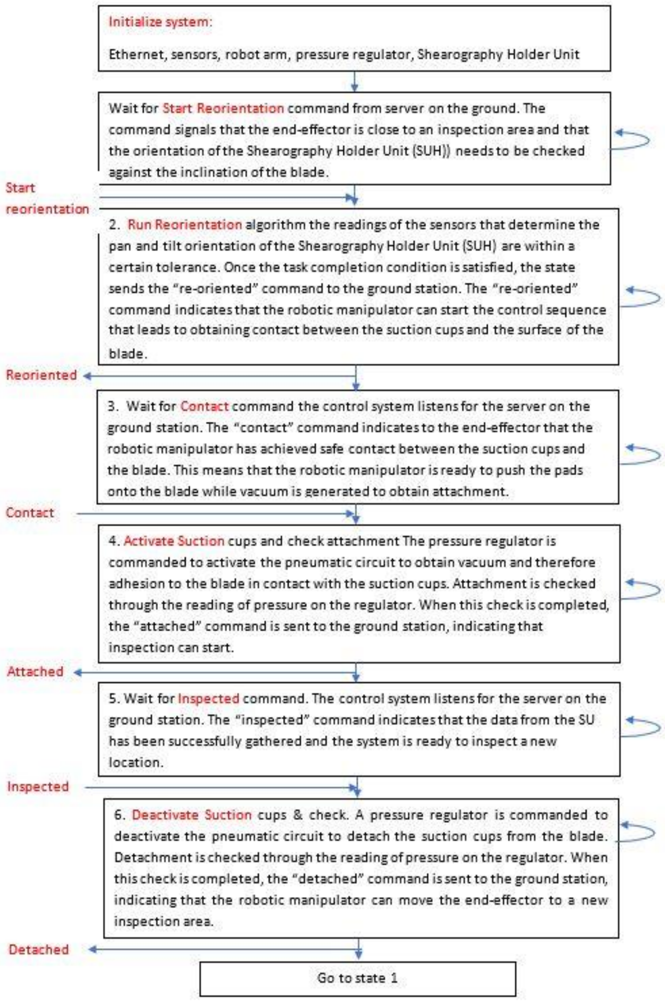
Fig. 8. Compliant connection of two sliding platforms showing the sliding platforms for the in-plane and out-plane oscillations. Springs in the sliding platforms center the end-effector.

Fig. 8 shows the end-effector and a detailed view from the top of the compliant connection which consists of two sliding platforms, one aligned with the blade in-plane direction and the other with the out-plane direction, which are centered by a set of springs shown in Fig. 8. These extension springs are pre-loaded by adjusting a set of screws attaching them to the sliding platform. When extended, within the expected oscillation limits (3 cm), the force of the spring applied to the end-effector should be around 30 N, as considered in the static analysis. The fact that the force of the spring must be limited implies that an auxiliary method is needed to guarantee a steady position of the end-effector during the deployment phase. To this end, a compressed air braking system is built into each of the sliding parts to hold the end-effector steady during its deployment. The air brakes are released after the end-effector is attached to the blade.

Control, power and communication system for the end-effector.

A control system was implemented to orientate the Shearography Holder Unit (SUH) to match the inclination of the blade surface. Distance sensors on the end-effector calculate the pan and tilt angles required to align the end-effector to the blade at an inspection site. The five-axis robot arm performs the required orientation before presenting the end-effector suction cups to the blade for attachment. A passive compliance mechanism between the end-effector and the robot arm ensures that the end-effector remains attached to the blade despite the maximum measured amplitude of blade vibrations.



Initialize system:

Ethernet, sensors, robot arm, pressure regulator, Shearography Holder Unit

Wait for Start Reorientation command from server on the ground. The command signals that the end-effector is close to an inspection area and that the orientation of the Shearography Holder Unit (SUH)) needs to be checked against the inclination of the blade.

2. Run Reorientation algorithm the readings of the sensors that determine the pan and tilt orientation of the Shearography Holder Unit (SUH) are within a certain tolerance. Once the task completion condition is satisfied, the state sends the “re-oriented” command to the ground station. The “re-oriented” command indicates that the robotic manipulator can start the control sequence that leads to obtaining contact between the suction cups and the surface of the blade.

3. Wait for Contact command the control system listens for the server on the ground station. The “contact” command indicates to the end-effector that the robotic manipulator has achieved safe contact between the suction cups and the blade. This means that the robotic manipulator is ready to push the pads onto the blade while vacuum is generated to obtain attachment.

4. Activate Suction cups and check attachment The pressure regulator is commanded to activate the pneumatic circuit to obtain vacuum and therefore adhesion to the blade in contact with the suction cups. Attachment is checked through the reading of pressure on the regulator. When this check is completed, the “attached” command is sent to the ground station, indicating that inspection can start.

5. Wait for Inspected command. The control system listens for the server on the ground station. The “inspected” command indicates that the data from the SU has been successfully gathered and the system is ready to inspect a new location.

6. Deactivate Suction cups & check. A pressure regulator is commanded to deactivate the pneumatic circuit to detach the suction cups from the blade. Detachment is checked through the reading of pressure on the regulator. When this check is completed, the “detached” command is sent to the ground station, indicating that the robotic manipulator can move the end-effector to a new inspection area.

Go to state 1

Fig. 9. State chart to control the Winspector system

The state machine of overall control system of the end-effector is described in Fig. 9. An error-handling state (not shown) manages all contingencies that might happen during the control sequence. This state is accessible from and can communicate with all states of the machine as well as the ground station via Ethernet.

4 Field trials in Greece

Capabilities of WInspector were first tested in laboratory environments. Three separate field trials were conducted at the Centre for Renewable Energy Systems (CRES) wind farm near Athens, Greece. At the first trial, a problem identified was related to the attachment of the climber to the tower with the magnet system on the platform scratching the tower paintwork and not providing sufficient adhesion to remain attached. It was difficult to manhandle the system to bring it to the base of a tower and put it on to the tower.

The magnet system was modified by using stronger permanent magnets and in-creasing the air gap between the magnets and tower surface. A second field trial was conducted with no problems attaching the platform and winching it up the tower. Adverse weather conditions with wind speeds exceeding 8 m/s at times gave very limited time to collect data from the shearography inspection. Three 100-second-long video clips of laser speckle images were collected but there was some doubt about the capability of the heating set-up to thermally stress the blade. Data processing was performed by careful image subtraction to see some shearography fringes but with poor fringe contrast. However, this was still considered a breakthrough for shearography (operated in bad weather conditions) to move from essentially a laboratory technique to a field technique operating in the sky.

A third and final field trial was carried out in May 2019 at the CRES wind farm. Experience with deployment of the system in the previous two trials resulted in faster and more assured placement of the system on the tower. Thermal stressing with a powerful heat gun and covering the end-effector with a black curtain to eliminate background daylight interference, clearer shearography speckle videos and fringe patterns were obtained that demonstrated that shearography could be used for on-site blade inspection in the presence of blade vibrations. Fig. 10 shows Winspector under-going trials on a wind turbine blade. A shearography image obtained on site is shown on the right with a defect marked with a red circle.

Fig. 10. Field trials. Manhandling of the platform into place at the bottom of the tower; winching it up; end-effector attached to the blade to perform shearography; RHS: A fringe pattern indicating defect (circled red) found in the blade.

5 Conclusions

Winspector is an innovative remotely controlled robotic NDT system for on-site WTB inspection. Three field trial demonstrations at the CRES wind farm in Greece have shown that shearography stabilized with the end-effector can overcome the effect of blade vibrations that would otherwise result in no useful shearography data. To our knowledge, this is the first time that shearography is proved to be working remotely on a wind tower blade.

6 Acknowledgements

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