Research article

Climbing ring robot for inspection of offshore wind turbines

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Abstract

Purpose – Structural integrity inspection of offshore wind turbine blades poses problems of gaining access to the blades, danger to human operatives and large costs of removing a blade and transporting it off-shore for inspection. The purpose of this paper is to show that a climbing robot that can perform *in situ* blade inspection with micro/nano focus computed axial X-ray tomography is a solution to find defects in the thickest blade sections and reduce the cost of inspection.

Design/methodology/approach – The weight of such an inspection system will be high, typically 200 kg and cross sectional scanner dimensions of 1×2 m to envelope a blade. The design of a climbing ring robot that completely encircles a turbine tower, typically 3 m in diameter, will provide the best means of climbing with this payload. Because of the development costs of such a huge robot, the optimal design path is to first prototype a small scale model.

Findings – First results on such a model are described and from its performance the load carrying capabilities of a full scale version computed. The robot is able to climb either straight up or down, or with a spiralling motion, or rotate around the circumference at the same height. Furthermore, the design is entirely modular thus enabling easy on-site assembly of the robot.

Originality/value – A climbing robot with high payload and versatile motion capability, with adhesive forces between the robot and climbing surface provided entirely by mechanical means rather than by vacuum suction or magnetic force, making the system much safer and easier to manipulate.

Keywords Robotics, Turbines, Offshore construction works, Image scanners, Prototypes

Paper type Research paper

1. Introduction

The largest wind turbines planned for the future will generate 5 MW and involve fibre reinforced composite (FRP) blades up to 100 m in length. These blades will be subject to enormous stresses, especially in storm conditions in offshore locations. At the same time, the use of FRP in safety critical structures located in such extreme environments is relatively new and it is likely that structural defects of a previously unknown nature may arise. Effective regular inspection for structural integrity inspection is thus essential.

An automated on-site inspection solution with the blades remaining on their axles is desirable to avoid the costs of dismantling the blades and moving them to an onshore inspection laboratory. Robotic deployment is also desirable to avoid dangers to manual operatives and the costs of using manual operatives in such dangerous activities. For robotic deployment, the non-destructive inspection instrument needs to be transported to every part of the turbine blades in order to achieve 100 per cent volume inspection coverage (European CRAFT project CONCEPT-INSPECT, 2006).

Concerning the method of inspection, using real time photon detectors, X-rays can penetrate the thickest sections of FRP blades but conventional through transmission radiography (TTR) alone would produce results that are very difficult to interpret. In computerized tomography (CT) images (i.e X-ray absorption maps) of any cross section of the object under inspection, orthogonal to the X-ray direction, can be obtained. So images of all defects in the cross section are displayed without mutual overlap (unlike TTR) and obviously the defect images will thus be of much higher contrast than corresponding images in TTR. One way is to take multiple real time TTR radiographs at smaller angular intervals ranging through 180 degrees, after digitisation of such data commercial software packages exist to routinely convert such data sets into CT images.

This paper describes results on a prototype scale model, which will be scaled up to carry the X-ray source and detector.

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Industrial Robot: An International Journal
36/4 (2009) 326–330

[DOI 10.1108/01439910910957075]

The support of the European Commission under project COOP-CT-2006-032949 is gratefully acknowledged, and Nueva Granada Military University of Colombia for sponsoring the PhD of Leon Rodriguez.

Industrial Robot: An International Journal
Volume 36 · Number 4 · 2009 · 326–330

2. Requirements and defects to be scanned

Wind farms on land are located in remote areas; access to site is always suitable for mobile plant, and some roads only consist of two thin gravel paths. Some fence sections have to be removed for larger vehicles. The ground at the bottom of the wind turbines is uneven. Some sites have a policy that any damage to the ground due to crane pads is re-seeded. It is possible on most sites to get lifting platforms close to the blades operating off the site roads.

Some wind farms are located offshore and this leads to the possibility of more adverse conditions and unstable working platforms and reduced resource availability onsite.

The wind turbine blades (WTB) can be fixed in the 6 o'clock position, not all positions are able to be locked into but these may be attainable if a safe working practice can be agreed with the site. When stopped the blades can flex in high wind but no working in height must be undertaken in high winds (>12 m/s).

Traditionally, the material used to construct WTB is glass reinforced plastic (GRP), the fibre properties of GRP are determined by manufacturing process, ingredient chemistry and coatings. The fibres range in diameter of 3.5-24 μm and are made primarily up of silica sand (50 per cent), metal oxides and other ingredients can be present. E-glass is the most common form of fibreglass, making up 90 per cent of all glass-reinforced plastics. E-glass is an excellent electrical insulator and its chemical make up is mostly silicon oxide (50 per cent), aluminium oxides, boron, calcium, limestone, boric acid and clay.

3. Types of defects

Some wind farms have been in operation for around ten years, the inspection techniques that are presently in use are remote visual inspections at various timescales and at specific times due to local environmental changes and the use of conditional monitoring techniques.

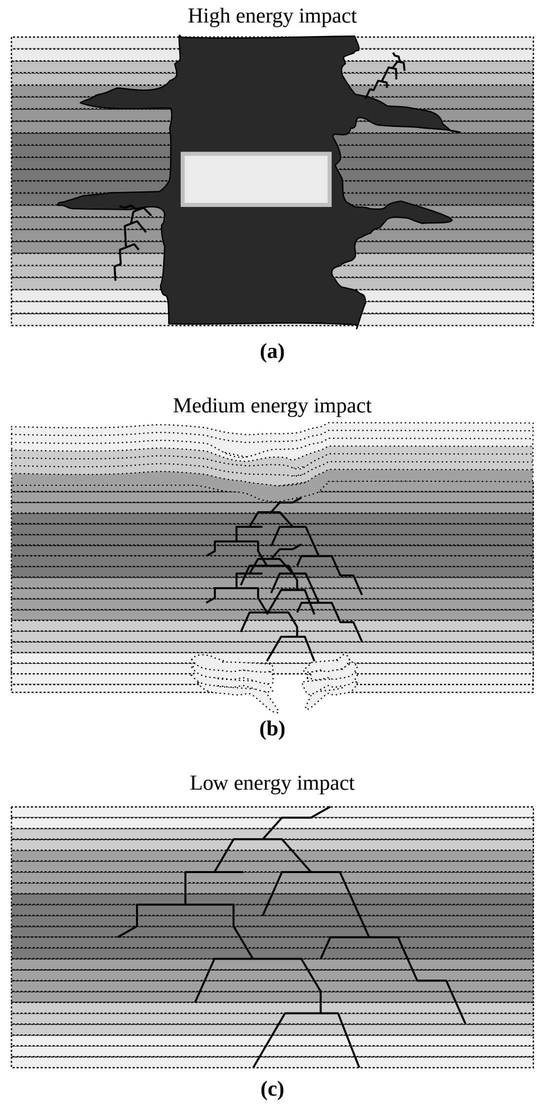
Wind turbine blade sizes vary and blade failures have been reported, blades/blade sections have been reported to have been thrown up to 400 m after failure.

While a metal structure will show a "dent" or "ding" after being damaged, a composite structure may show no visible signs of damage, and yet may have delaminated plies or other damage within.

Impact energy affects the visibility, as well as the severity, of damage in composite structures. High and medium energy impacts, while severe, are easy to detect. Low energy impacts can easily cause "hidden" damage. Figure 1 shows typical assessment damage to composites.

The biggest numbers of incidents found were due to blade failure. "Blade failure" can arise from a number of possible sources, and results in either whole blades or pieces of blade being thrown from the turbine. A total of 98 separate incidences were found: nine incidents were reported in 2005 and seven in 2006 to date. There is therefore a need for an effective inspection technique for the projected higher usage of wind power. Pieces of blade are documented as travelling over 400 m, typically from much smaller turbines than those proposed for use today. In Germany, blade pieces have gone through the roofs and walls of nearby buildings.

Figure 1 Typical damages in wind turbines



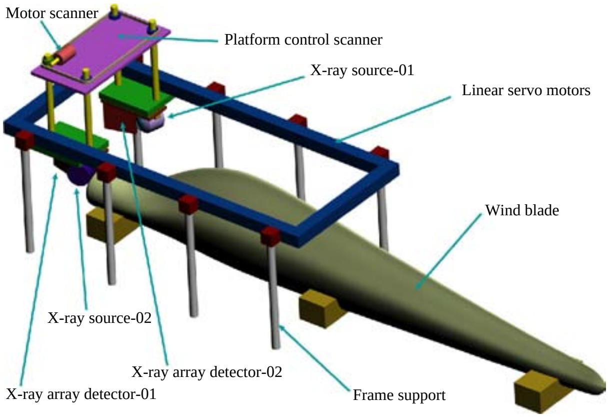
4. Specification of the CONCEPT prototype tomography scanner

A portable NDT scanning system is required to detected internal defects in the wind turbine using X-ray tomography technology. In tomography, images in the form of spatial X-ray absorption maps of two-dimensional sections of a test object are produced and three-dimension absorption maps are then reconstructed from successive two-dimensional tomography images.

Several options are considered for a scanner configuration that can allow X-ray tomographic imaging to be carried out on wind turbine blade without take them out of service. A wind generator is an enormous steel tower with about 45 m separating the hub or centre of rotation and the end of a wind blade and about 150 m in length.

Figure 2 shows what could be described as a traditional method of scanning a wind turbine just after manufacture. It consists of a Cartesian scanner in which the source and

Figure 2 Conceptual design of scanning automated system (laboratory based system)



detector array move relatively to the blade in two orthogonal directions, one direction being parallel to the blade axis. This method can be considered the most obvious option for scanning the blade at periodic inspections, but it requires repeatedly to be dismounted from its tower and them moved to a NDT facility for examination exam, a process which is very expensive and carries a high risk of further damage to the blade during transport.

In-situ tomography inspection can be carried out without having to construct a rotation mechanism because the rotation of a blade round its longitudinal axis used for pitch adjustments can be exploited. Altogether there will need to be three orthogonal axes of movement, a vertical motion of a climbing robot combined with two orthogonal linear movements of a source – detector scanner. The image resolution will depend on the range through which the blades can be rotated, the narrower the range, the lower the resolution. However, in view of the additional complexity that would be introduced by adding external rotation mechanisms, the possibilities of using blade rotation needs to be considered seriously.

Figures 3 and 4 show a "ring" climbing robot with a payload capability allowing it to climb around the cylindrical tower and scan the blades *in situ.* The climbing robot can carry a heavy payload of the full NDT equipment and control system. The robot is a ring system which itself can divide the forces around the tower; this robot can be developed by several modular frames to decrease the diameter from 4.5 to 3 m as the robot climbs from the bottom of the tower to the top.

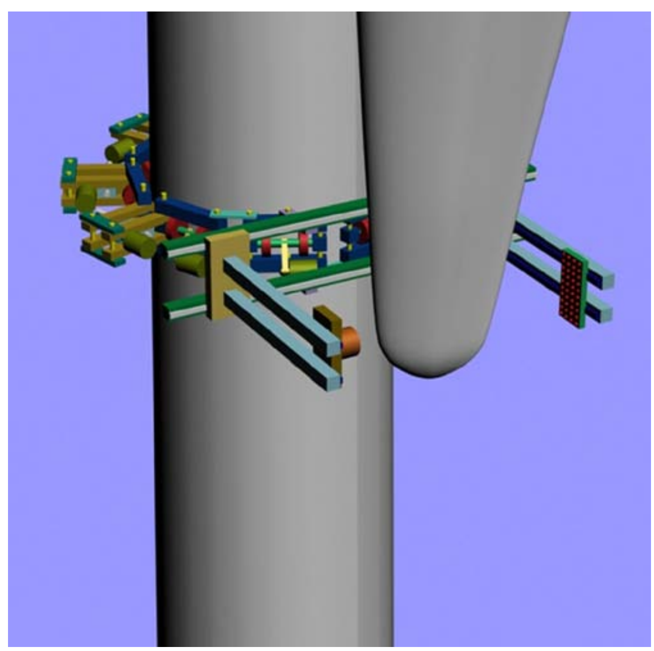
The system has a Cartesian scanning arm on one of its side to be able to scan the blades.

A possible inspection procedure could be to climb the robot to the top of the tower, move the X-ray source and the array detector to defined the home position, get NDT data on this first position, rotate the blade "pitch" to second angle in order to obtain new NDT results, move the robot to a new position to obtain new results along the blade from different angles.

Figure 5 shows another option of for the climbing vehicle. This is a wall climbing robot with permanent magnet adhesive forces. It has been found through design experience on several projects (Bridge 2007; Chen *et al.* 1999) that these magnetic

Figure 3 Ring Climbing Robot with mobile NDT scan

Figure 4 Ring climbing robot with mobile NDT scan, tomographic scanner is obtained by exploiting the rotation capability of the blade along its long axis



systems can create a 600 kg force over an area of ferromagnetic steel wall about the size of an A4 sheet (0.3 × 0.3 m). Approximate calculations show that the robot could have a 100 kg payload.

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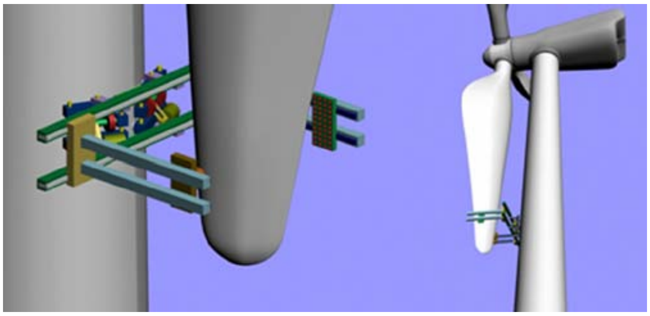
Volume 36 · Number 4 · 2009 · 326–330

Figure 5 Wall climbing robot with mobile NDT scan and permanent magnets



A final option is to dispense with a climbing robot and deploy the Cartesian scanner via a crane or cherry picker. This might be a preferred option if such equipment happened to be available at the test site. However, if all equipment needed to be transported to a given test tower in a given farm, this would be an unsatisfactory option as the overall equipment bulk would clearly be much greater than would be the case using a climbing robot.

Overall, the use of climbing robots, if they can achieve the desired payload specification, is a much more satisfactory solution. For example, the transport of a robot and scanner by sea to an offshore turbine would require far less cargo space than a crane or cherry picker capable of reaching to the top of a 100 or 200 m tower.

5. Climbing robot prototype

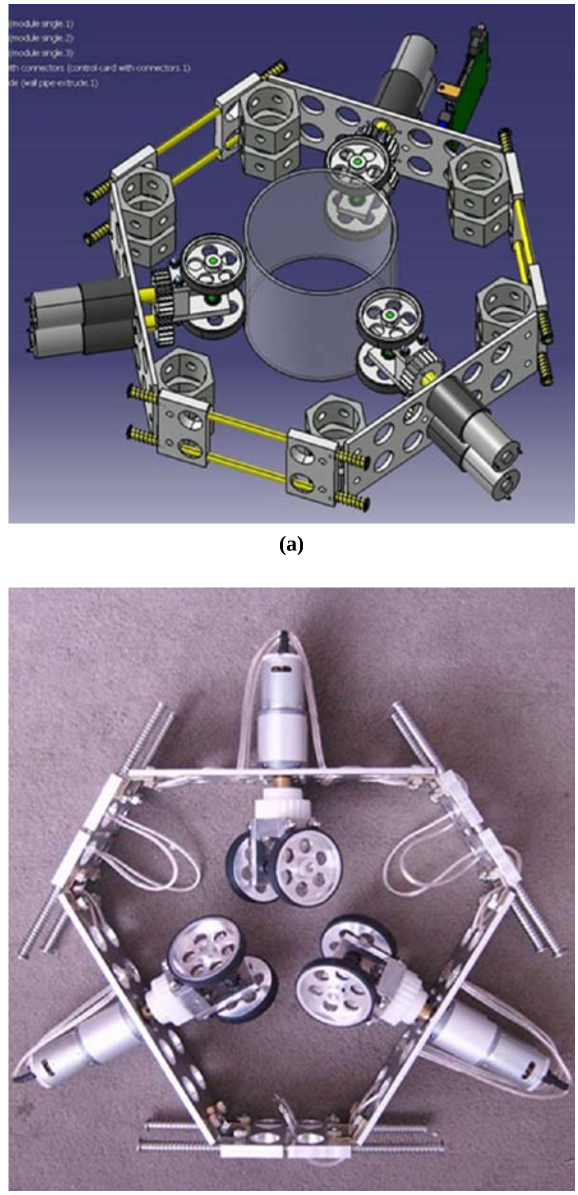
Figure 6(a) and (b) show a design drawing and its physical realisation of the prototype of a novel "ring" climbing robot with a payload capability allowing it to climb up the cylindrical tower and scan the blades *in situ* with a Cartesian scanning arm. The key innovation is that the adhesive forces between the robot and climbing surface are provided entirely by mechanical means rather than by using the usual methods of vacuum suction, air vortex or magnetic force, making the system much cheaper and easier to manipulate.

The prototype has three modules which are completely identical and can be easily joined together to climb on any tube. The robot is placed around the tower and it uses spring forces to grip it. The wind turbine tower has a tapering radius. It is envisaged that active force control will be required to adapt to changing radius on real towers but this method has not been used in the scaled prototype.

Each module uses two motors, one to drive the wheels and the other to turn the angle of the wheel to face in different directions which means that the robot can either climb along the tube, see Figure 7(a), or with a certain pitch angle it can spiral around the tube, Figure 7(b), or if the wheel is turned through 90 degrees then the robot will not climb but it will rotate around the tube at the same spot, Figure 7(c).

The prototype has been built to a linear scale of 1:10 (for both the robot and test pipe) and tested successfully performing the three types of motion, i.e. up/down, spiral, and rotation on the spot. The robot weight is 3 kg, the payload capacity is 2 kg with a safety factor of two and maximum speeds of climbing and circumferential motions are 10 m/min. In the full scale model the cross sectional area over which adhesive forces between the wheels and turbine tower could be developed would increase by a factor of 100 (assuming the wheel widths and diameters to be scaled up by a factor of ten and the payload capacity can thus be potentially increases in the same proportion to about 200 kg, the target figure. However, if necessary, adhesion forces can always be augmented in the full scale design by the inclusion of a number of rare earth magnet arrays.

Figure 6 Pipe Climbing Robot prototype



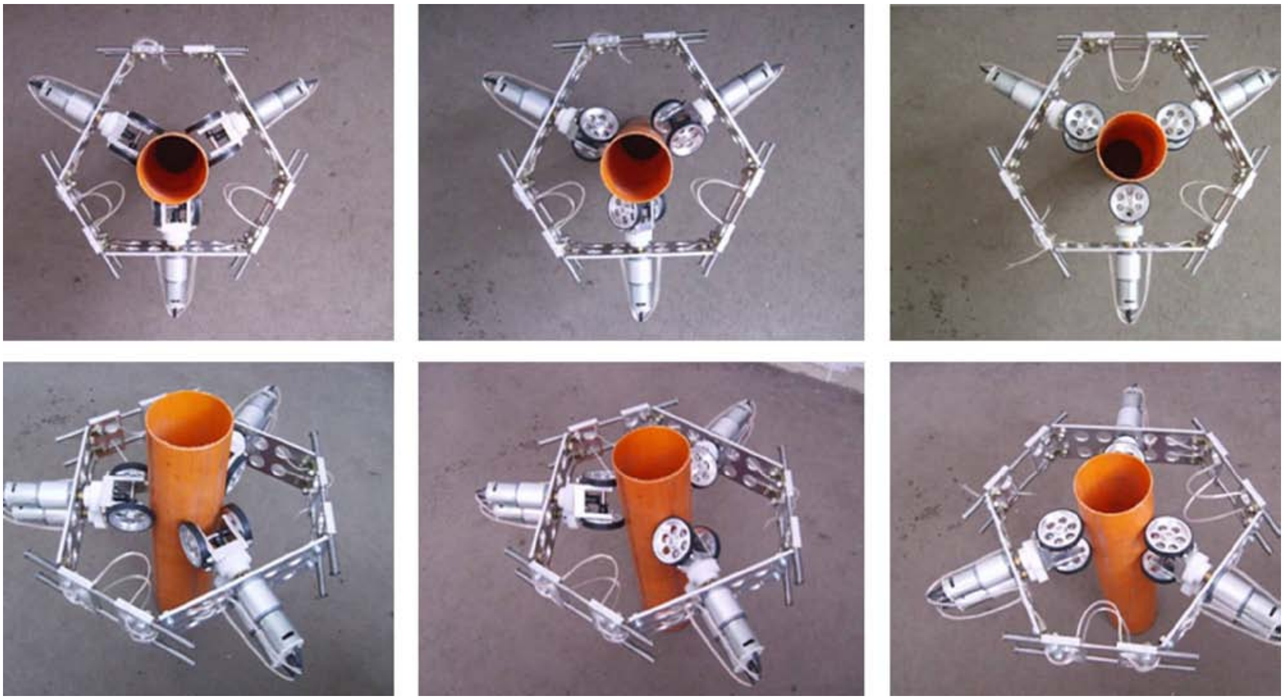
(a)

(b)

6. Conclusion

A ring climbing robot prototype has been developed to provide access to wind turbine blades. The small scale prototype has

Figure 7 Prototype design in small scale of wind turbine climbing robot. (a) Straight up/down motion, (b) spiralling motion and (c) circumferential motion at the same tower height



(a) (b) (c)

demonstrated that the robot has the ability to adapt to the tapering diameter of the tower as it climbs, provide a payload capability that should scale up to be able to meet the target payload capability of 200 kg, and provide a motion capability to inspect around all the tower circumference.

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