Robotics and Computer–Integrated Manufacturing 49 (2018) 134–142

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Profile tracking with ultrasonic alignment for automatic Non-destructive testing of complex structures

Xiao Zhen[a,*], You Yong[b], Xu Chun Guang[a], Xiao Ding Guo[a], Liu Fang Fang[a], Li Xin Liang[a]

[a] School of Mechanical Engineering, Beijing Institute of Technology, Beijing, 100081, China
[b] Zhuhai Campus, Beijing Institute of Technology, Zhuhai, 519000, China

ARTICLE INFO

Keywords:
Quaternion
Matrix transform
Coordinate conversion
Ultrasonic alignment
Robotic scanning trajectory

ABSTRACT

Micro-defects located on complex geometrical structures are difficult to inspect using traditional non-destructive testing (NDT) equipment, especially for those aerospace components that have obvious variation of thickness. This is because the tracking of the profile of the test surface cannot usually satisfy the requirements of high-accuracy measurement so that the inspection results are inaccurate. In this paper, an industrial robot is used as an auxiliary test method to realize the inspection scanning motion. Matrix transformation of the robotic orientation is proposed to investigate the correct spatial relationship between the specimen and the ultrasonic probe, based on the mathematical models of coordinate conversion between the user frame and the robotic tool frame. The ultrasonic waves reflected by the test surface were used to find and represent the character of the defects in the specimen. Moreover, robotic orientation is calibrated by the ultrasonic alignment method based on the quaternion algorithm, so the robot can adjust the orientation of the tool frame to satisfy the ultrasonic incident angle constraints, and the precision of robotic trajectory is enhanced compared to that of other NDT methods. Our experimental results verified the accuracy of robotic scanning trajectory while the defect character can be captured from the ultrasonic echo waves. If the proposed approach is used, the trajectory error is no more than 0.275 mm with respect to the test specimen. Signals collected from echo waves can be transformed into ultrasonic images and the integrity of the specimen is evaluated based on those signals. In addition, the distribution of defects in the specimen was shown with a higher resolution of 0.15 mm derived from the distance between the adjacent points, if the robotic orientation is correct at each point in the scanning trajectory.

1. Introduction

Profile tracking is crucial to the evaluation of integrity and metal fatigue for complex structures with large curvature, but the precision of the scanning trajectory using traditional non-destructive testing (NDT) methods does not meet the ultrasonic constraints owing to trajectory error. Specially, if the beam axis of the probe cannot be guaranteed to stay normal to the test surface, the ultrasonic incident angles will not be constant and the test results are usually inaccurate when the constraints of NDT application have not been followed as expected [1]. In this case, non-destructive evaluation (NDE) of the test object cannot reveal the distribution of defects.

Several methods have been proposed to inspect specimens with curved surface and have been implemented for last two decades [2]. Semi-automated inspection systems using both mobile and fixed robotic platforms have been developed to inspect specimens with noncomplex shapes (plates, cylinders or cones) and typically specific machines, such as linear manipulators, are used to inspect identically shaped specimens [3–5]. However, these tests cannot identify micro-defects in complex specimens because the positional accuracy of probe is outside the permitted errors range, especially for small-scale specimens, which are sensitive to errors. Additionally, using the traditional semi-automated inspection approaches produces a low precision trajectory bottleneck in industrial application and this limitation provides the fundamental motivation for the development of automatic inspection methods.

Some applications using robotic arms in the NDT field have been published during the last few years and there is growing interest in using such emerging automatic solutions from many manufacturers within the aerospace sector [6–8]. Owing to its superiority in terms of high repeatability, ease of operation, and accessibility to areas where manual inspection is not practical [9], industrial robots are suitable for inspecting specimens with complex shapes [10,11].

However, there are some key challenges to overcome in the industrial application of robotic NDT systems. First, specimens are usually designed to be identical, but they will exhibit significant deviations from the Computer-Aided Design (CAD) geometric models. This presents a

* Corresponding author.
E-mail address: shawzhen86@gmail.com (X. Zhen).

http://dx.doi.org/10.1016/j.rcim.2017.06.007
Received 27 April 2016; Received in revised form 20 May 2017; Accepted 27 June 2017
Available online 3 July 2017
0736-5845/

challenge for precision NDT measurement deployment which must be flexible enough to accommodate these manufacturing issues [12]. Second, when the probe/specimen is grasped by the robot manipulator, the orientation accuracy of the robotic trajectory is reduced as a result of assembly error. Traditional measuring instruments perform poorly underwater, so, a new approach is needed to calibrate the orientation of the robot and the position of the probe/specimen should be precisely identified by the robot manipulator, considering that there is a clear relationship between the work-piece coordinates and the robotic tool frame [13]. Third, the scanning trajectory strategy should be taken into consideration when it comes to surfaces with large curvature [14–16]. Based on the practical experience that ultrasonic waves with gently varying amplitude are easier to be capture with a high-speed scanning motion, the robot's trajectory planning should be optimized so that the scanning motion is as effective as possible [17–19]. It is necessary to improve the positioning accuracy of the robot manipulator by profile tracking of the test surface because the ultrasonic NDE results are affected by the robotic scanning trajectory during automatic inspection [20–22].

Messay et al. [10] described an analytical approach to calibrate industrial manipulators based on the Denavit-Hartenberg kinematic model. However, in this method the precision of the robotic end effector is decided by the radial measurements from the calibration points, so it could not adapted for use on complex surfaces. Summan et al. [12] evaluated the use of Bayesian filtering for NDE applications. Multiple positional sensing data were used to calibrate the robotic trajectory, and the extended Kalman filter was selected to improve the accuracy of the trajectory estimates. Sattar et al. [19] used eddy-current inspection techniques to assess the quality of defect data. Permanent magnet adhesion was used to obtain a secure contact and adjust the robotic arm; this approach requires the probe to be in contact with the test object.

In this paper, a robotic NDT system is constructed, in which the test object is grasped by the manipulator in order to track the calibration points with high precision. Moreover, with the aid of ultrasonic distance measurement and echo signals in the time domain, the integrity of the specimen can be evaluated with greater accuracy than the results obtained using other traditional approaches, such as tracked using a geometry measuring instrument. The precision of the robotic trajectory was high enough, usually no more than 0.275 mm when the robotic reference coordinates were ascertained, and this was achieved by aligning the calibration points to the beam axis of the probe. Furthermore, based on ultrasonic signals read from the data acquisition card and the corresponding discrete points located on the test surface, transformed from the real-time position data of trajectory points that were synchronously acquired from the robot manipulator, the character of the defects in the specimen can be represented as an ultrasonic C-scan image. Then, the magnitude and distribution of the defects can be derived from the test image.

This paper proposes a new calibration method with ultrasonic alignment to obtain the correct position and orientation of a robot manipulator during automatic inspection. Considering that the beam axis of the probe coincides with the normal vector of a discrete point located on the test surface if ultrasonic time-domain reflectometry is used, then the acoustic wave energy attenuation is limited so the detection precision is guaranteed and the resolution of flaws is no more than 0.15 mm, which is more accurate than results obtained using the traditional calibration methods. Moreover, profile tracking of the test specimen is carried out with an allowed tolerance of incident angle, which has a huge impact on the stability of the ultrasonic echo. The angle can be adjusted according to the real-time ultrasonic echo signals and the proposed algorithm, which transforms the orientation of discrete points on the test surface to the trajectory of robotic end effector for NDT application.

In Section 2, we propose a mathematical model for coordinate conversion between the robotic tool frame and the user frame where the probe is fixed, then the errors between the planned points and the reached points deduced from the angle encoders are calculated. In Section 3, the robotic trajectory is verified using the proposed ultrasonic alignment while the robotic tool coordinates were easy to define and calibrate with the aid of ultrasonic signals, and the deflection angles were concluded based on the feature signals of the ultrasonic echo waves. In Section 4, as a practical application, turbine blades with varying thickness were analyzed using the proposed approach and the characteristics of the defects in the specimen were evaluated according to the pulse echo. Consequently, the proposed approach to calibrate the robotic trajectory with ultrasonic alignment can be widely used in large-scale industrial production.

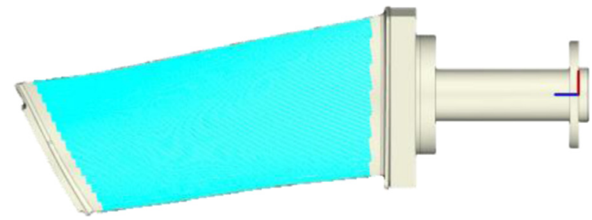

Fig. 1. Discrete points located on the test surface of the blade's CAD model.

2. Approaches to robotic trajectory planning for NDT applications

Although industrial robots have good positioning accuracy, the error between the point of the planned trajectory and the actual trajectory exceeds the value allowed by the ultrasonic NDT requirements. Therefore, the robotic scanning trajectory should be calculated using a mathematical matrix transformation. If the position and orientation of the robotic trajectory were inaccurate or inconsistent during automatic detection, the character of the defects in the specimen may determined incorrectly and some distortion may appear in the ultrasonic image. Hence, it is necessary to calibrate the robotic trajectory for high resolution of testing results.

2.1. Profile tracking of the test specimen

Profile tracking is crucial to the robotic scanning trajectory, especially for test specimens with curved surfaces and irregular shapes, which are difficult to calibrate and to ensure that the normal vector of the test surface coincides with the beam axis of the probe using traditional approaches. With the aid of a CAD model and machining simulation of the test specimen using computer-aided manufacturing (CAM) technology, discrete points can be extracted from the model and used to compute the robotic trajectory according to the matrix transform algorithm. As shown in Fig. 1, the test surface is covered by the green point cloud, and the position data measured from the work-piece coordinates can be transformed to an equivalent form based on the robotic reference tool frame. In this case, the robot manipulator can identify the instructions.

An approach for coordinate conversion between the work-piece coordinate and the robotic tool frame is proposed to obtain the robotic scanning trajectory. The position and orientation of the robot manipulator can be adjusted with the aid of the ultrasonic alignment. First, the robotic trajectory was monitored and recorded according to the real-time position information encoded by the angle encoders, then it was transmitted to the computer via the In/Out interface of the robot controller. Second, the error can be evaluated in real-time based on the feature signals of ultrasonic A-scan waves; the deflection angles of the robot end effectors and the position error of the tool coordinates can be determined with the aid of Matlab compiler and Visual studio software. Third, trajectory errors can be reduced and eliminated if the compensation of the deflection angles is taken into consideration and the robotic trajectory is re-planned; the computational process is finished in the C#.Net compiler and the robotic inspection motion is carried out under the instructions written by VAL3. Finally, during the automatic inspection, the corresponding ultrasonic A-scan waveform is stable and undis-