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Calculation of the robot trajectory for the optimum directional orientation of fibre placement in the manufacture of composite profile frames

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ABSTRACT

This article deals with theissue of calculating the trajectory of the end-effector of an industrial robot in the manufacture of composites. In the introduction to the article we describe the basic approaches used in the manufacture of composites. Robots are used to define the winding orientation of carbon fibre strands on an uneven polyurethane 3D core. The core is attached to the robot-end-effector and is led through a fibre-processing head according to a suitably defined robot trajectory during dry carbon fibre winding on the core. The model of a passage of the polyurethane core through a fibre-processing head is described in the article. The placement of the fibre-processing head is defined in the basic Euclidean coordinate system E_3 of the robot. The core is specified in the local coordinates of the Euclidean coordinate system E_3, the origin of this local system is in the robot-end-effector. The positioning of the local system in the basic system of the robot is entered using the "tool centre point" of the robot. A matrix calculus is used when calculating the trajectory robot-end-effector to determine the desired passage of the core through the fibre-processing head. Gradually, the required rotation and translation matrices of the local coordinate system of the robot-end-effector relative to the basic system are calculated and subsequently the Euler angles of rotation are determined corresponding to the transformation matrices. This is used to determine the sequence of values of the "tool centre point" for defining the desired trajectory of the robot-end-effector. The calculation for the trajectory was programmed in the Delphi development environment. The article also solves practical tasks of the polyurethane core passage through the fibre-processing head. The calculations of the trajectory of the robot-end-effector were used as input values for the graphic software simulator and at the same time winding of carbon strands on the polyurethane core was verified for the calculated trajectory of the robot-end-effector in the experimental laboratory.

1. Introduction

Currently, the use of composite materials in various productions is significantly increasing. Composites often replace traditional materials such as steel, iron, wood, etc. The most important advantages of composites are their high strength, flexibility, light weight, long life and minimum maintenance requirements. Composites are synergistic materials which are formed by the interaction of a carrier component (fibre reinforcement) and a resin (binder of the reinforcement). The structural parameters of the composite (especially the type of matrix, the geometric shape of the profile, the type of fibre, and the winding direction) are determined according to the estimated load. Various procedures have been developed for the production of composites for special applications (such as in the aviation industry [1–3]). One widely-used production technology is the "filament winding technique" [4], which involves winding of fibres on the surface of the core of the produced composite (for example support frames for large plastic products, which improve the mechanical properties of these products). Industrial robots are increasingly being used for the application of this technology and they brings a significant reduction in production time and costs of the composite production [5,6]. Robots wind the fibres on the surface of the core using a fibre-processing head. The core can be fastened to the robot-end-effector and a force/torque sensor unit can be placed between the fibre-processing head and the end-effector for monitoring the quality of the winding [5]. The issue of the temperature of the wound fibre is also often solved at the same time.

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Determination of the trajectory of the robot arm is a complex task that is not always optimally resolved when winding the strands of fibres (so-called roving) [7,8]. Knowledge of differential geometry is often used [9], and the time optimization of the passage of the robot-end-effector by the given trajectory is also dealt with in several cases [10]. CAD-based modelling [5] and simulation software tools are often used to determine the trajectory of the robot-end-effector. In principle, the fibre strands can be placed on a core with any type of surface and shape. Therefore, composites can be produced for any type of core, which is usually made of a low-density material such as polyurethane foam and then coated with a knitted fabric made of carbon, glass, aramid or basalt fibres. This type of composite is primarily used in the manufacture of complex components and frames in the aerospace, aviation, and automotive industry and also currently in construction and environmental engineering.

One of the possible methods for producing the composites is to stretch the fabric from the fibres on a core with an arbitrary geometry. However, if the core of the composite is a closed 3D frame or a frame with a complicated 3D shape or several layers of the fibre strands are wound simultaneously on the core, then this method is not suitable. In such cases, the method of dry winding of endless fibre strands on a core geometry using rotation fibre-processing heads is often used for the production of the composite. This method provides full control over the placement, laying direction, and the amount of fibres on the core as well as the homogeneity of the fibre structure. The final composite is obtained after dry winding of the required layers of strands on the core by injection of the resin to the mould using heat and pressure.

The objective of this article is to study and mathematically describe the real-time process of winding three layers of carbon strands on a 3D formed core with a circular cross-section. We will also discuss the fibre-processing head, which is based on the original prototype of a rotating guide line, on which the endless fibres are placed circumferentially (Fig. 1), as well as the final design which uses three guide lines, on which twelve coils with the carbon strands are uniformly placed circumferentially. Each guide line provides the winding of a single layer of carbon strands.

The described rotating guide lines have the same internal radius, a common central axis and are located on parallel planes. The fibre-processing head is firmly placed in the workspace of the robot and its coordinates are specified in the basic coordinate system of the KR16-2 robot (the robot and the KRC4 control unit are supplied by KUKA GmbH). The polyurethane core is firmly fixed to the robot-end-effector by an auxiliary structure (Fig. 1). During the winding of the core the central longitudinal axis of the core passes preferably parallel to the central axis of the head and as close as possible to the centres of the two outer rotating guide lines of the fibre-processing head based on the movement of the robot-end-effector. The passage of the core through the fibre-processing head takes place based on a fixed trajectory of the robot-end-effector. For the sake of simplicity we assume a constant speed of movement of the end-effector throughout the article. When addressing the issue of direct kinematics we used the theoretical knowledge included in [11–13]. We tested several design solutions for the working head. The resultant structure used in this article counts with a fixed central guide line (longitudinal fibres) and a rotation guide line on both sides (Fig. 2). Because the position of the fibre-processing head in the workspace of the robot is fixed and cannot rotate with the central line the required position of the longitudinal fibres on the surface of the wound core can only be met by suitably turning the core. When the core passes through the fibre-processing head strands are successively wound on the surface of the core at a targeted angle (positive fibre orientation e.g. 45°) relative to the common axis of the rotation guide line and in the direction of the movement of the core using the first rotation guide line. A second static line allows the fibres to be placed in a longitudinal direction (fibre orientation 0° to the direction of movement) and the third rotational line subsequently winds the strands at a negative orientation angle – e.g. 45°. For a comparison of the constructions of the rotation heads (head with one line, head with three lines) see Figs. 1 and 2. The principle of the winding solution is shown in Fig. 3.

The individual chapters describe the compilation of the mathematical model for calculating the trajectory of the robot for the optimum directional orientation of the fibre placement during the manufacture of a composite profile frame. We use the model to calculate the rotation and translation of the local coordinate system of the robot-end-effector relative to the basic coordinate system of the robot as the fibre processing head passes through the core. The calculations of the trajectory of the robot (programmed in the Delphi development environment) were tested in an OfficeLite simulator and a KUKA.SimPro robot movement graphic simulator (both simulation tools were supplied by KUKA GmbH). Subsequently, the calculations of the passage of the fibre-processing head through the core were verified in the experimental laboratory (Fig. 2). The company KUKA GmbH offers users several specific software tools, such as the modules KUKALaserTech (used for welding and laser cutting) and KUKAPlastTech (used to synchronize the movement of the robot and injection moulding machines during the production of plastic moulds). These modules add new commands and tools to the control system of the robot, which helps the programmer to determine the required trajectory. The Denavit–Hartenberg method is often used to determine the trajectory of the robot (see e.g. [14]). However, the modules offered by KUKA GmbH and other manufacturers of industrial robots are generally unsuitable for describing the specific production needs of the optimum directional orientation of fibre winding on the resulting composite profile of an arbitrary core. The software typically offered includes support in the areas of welding, pressing, cutting, packing or gluing during the manufacture of the product.

The trajectory of the robot during the winding of the core can be defined using a discrete set of points. This procedure is relatively challenging due to the need to set the correct axis rotation of the effector's coordinate system. In addition, any change in the position of the fibre-processing head in the basic coordinate system requires a new trajectory of the robot-end-effector to be set. If the user of the industrial robot does not have an appropriate software module which supports the programming of the desired trajectory of the robot-end-effector, then he often enters the robot trajectory manually. However, this requires practical experience and the technique is time-consuming (usually it is necessary to repeatedly enter the trajectories in order to find a satisfactory one). In addition, the trajectory obtained by such a procedure is not usually the best one. The most appropriate trajectory is then selected from all the trajectories obtained. However, this approach is not suitable for determining the exact trajectory of the robot-end-effector or for example for optimizing the trajectory of the required winding on a core. A schematic representation of the experimental laboratory and the simulation environment for winding strands of fibres on a polyurethane core with an arbitrary geometry is shown in Fig. 4.

2. Studies and assumptions of fibre winding for the optimal design of the composite profile

Before defining the robot trajectory calculation for fibre winding for the optimal production of the composite profile, it is important to determine the optimal placement angle and the directional arrangement of the fibres. Theoretically, the greatest