DESIGN OF COMPOSITE FRAMES USED IN AGRICULTURAL MACHINERY

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Abstract
At present, composite materials are increasingly used in agricultural machinery. The light weight, long lifespan and minimal maintenance of composites are among the main reasons for their use in agricultural machinery. Frame composites are often produced for the needs of agriculture. The production technology of these composites is based on the winding of fibres (from carbon or glass) on a frame (usually from polyurethane). A fibre-processing head and industrial robot are used in the production of composite frame. This paper describes the calculation of an appropriate off-line trajectory of the industrial robot during the passage of frame through the fibre-processing head. The described mathematical model of the winding process and matrix calculus are used to calculate suitable robot trajectory.

Key words: *composite; fibre-processing head; industrial robot; mathematical model; software implementation.*

INTRODUCTION

At present, composites are increasingly replacing classic materials (such as iron, steel, aluminium, wood) in industrial production. The main advantages of using composite materials are their low weight (75% lighter than steel and 30% lighter than aluminium), strength, flexibility, weather and corrosion resistance, minimal maintenance, long life span (see (*Gay & Hoa, 2007*), (*Petrů et al., 2015*)). Composites offer an attractive ratio of material properties-to-production costs. The use of composite materials is currently most widespread in the aerospace and automotive industries. However, composites are also currently well-established in other areas. A significant sector in the use of composites is production of agricultural machinery. In addition to the general advantages of composites the use of composites in the production of agricultural machinery makes it possible to achieve special cargo space shapes. The agricultural machine also causes less pressure on arable land due to its lower weight when using composites. Specifically, the use of composite frames is significant in the production of tractors, grain harvesters, various agricultural cultivators etc. In particular, composite frames are often used to reinforce the chassis and driver's cab of agricultural machinery. Composite frames can also be used to reinforce cargo space, cab doors and various covers of machines.
The article is focused on the technology of composite frame production using a fibre-processing head and an industrial robot. All experimental tests were performed at a robotic workplace (see Fig. 1). The fibre-processing head (see Fig. 2 on the left) is fixed in the robot workspace and the frame is fastened to the end-point of the robot (robot-end-effector, REE, see Fig. 2 in the middle and Fig. 3 on the left).
The closed composite frame shown in Fig. 3 on the left is used to attach the side window in the tractor cab. The paper presents a mathematical model of the winding of fibres on a frame. The use of matrix calculus (especially matrices of rotations and translations) allows us to find a suitable trajectory of REE when passing the frame through the fibre-processing head. Calculation of robot trajectory is programmed in the Delphi development environment.

MATERIALS AND METHODS

We describe a mathematical fibre winding model to calculate a suitable REE trajectory during the passage of the frame through the fibre-processing head. The winding technology is implemented on the basis of the use of the fibre-processing head and an industrial robot. The fibre-processing head consists of three guide lines, each of which has ten coils with carbon or glass fibres (see Fig. 3 on the right). The composite frame passes through the fibre-processing head and three layers of fibres are gradually wound on the surface of the frame. The first rotating guide line winds fibres under angle $\pi/4$, the middle guide is static and winds the second layer of fibres under angle 0 (placement of the fibres in a longitudinal direction). The second rotating outer guide line winds the fibres under angle $-\pi/4$. The winding process is shown in Fig. 2 on the left (fibre-processing head contains three guide lines). The passage of the frame through the fibre-processing head should be orthogonal to the guide lines and the frame should be go through the head as near the centre of the guide lines as possible. In this way, the correct winding angles and the homogeneity of the fibre windings are ensured. We need to determinate the appropriate trajectory of the REE to meet the above conditions.

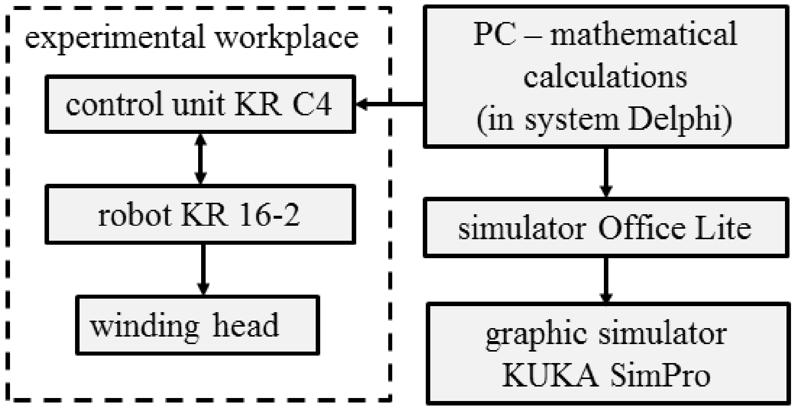

Fig. 1 Schematic representation of the experimental robotic workplace.

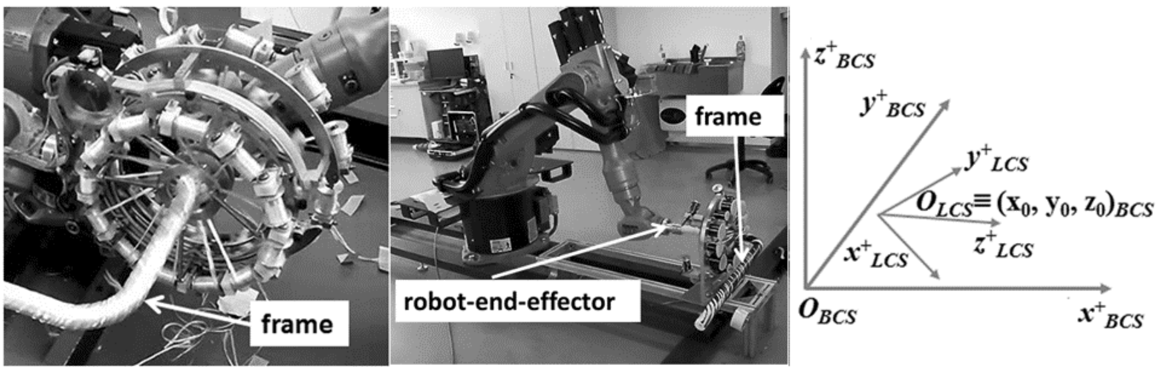

Fig. 2 Example of fibre-processing head with three guide lines (on the left); industrial robot with frame fastened in the end-effector, fibre-processing head contains only one guide line (in the middle) and basic coordinate system (BCS) of the robot and local coordinate system (LCS) of REE (on the right).

Industrial robot workspace in our model is defined by the base right-handed Euclidean coordinate system E_3 (BCS, see Fig. 2 on the right). Description of location and orientation of individual subjects in the robot workspace is made in BCS. Subsequently, we determine the local right-handed Euclidean coordinate system E_3 (LCS, see Fig. 2 on the right). This system describes location and orientation of REE towards BCS. In the following text, we will label the vectors and points with coordinates in BCS with the subscript $_{BCS}$ and vectors and points with coordinates in LCS with the subscript $_{LCS}$.

1/ Robot activity control

The robot central unit controls all working activities of the industrial robot (see Fig. 2 in the middle) using instructions through the REE. The location and orientation of the REE relative to BCS is defined by the position of LCS relative to BCS. The LCS origin is positioned in the REE. The actual position of the LCS with regard to the BCS is determined by six parameters listed in the tool-centre-point (TCP), where $TCP = (x, y, z, a, b, c)$. The first three parameters specify the coordinates of the origin of the LCS in regard to the BCS. The last three values a, b and c specify the angle of the rotation of the LCS around the axis *z*, *y*, and *x* with regard to the BCS.

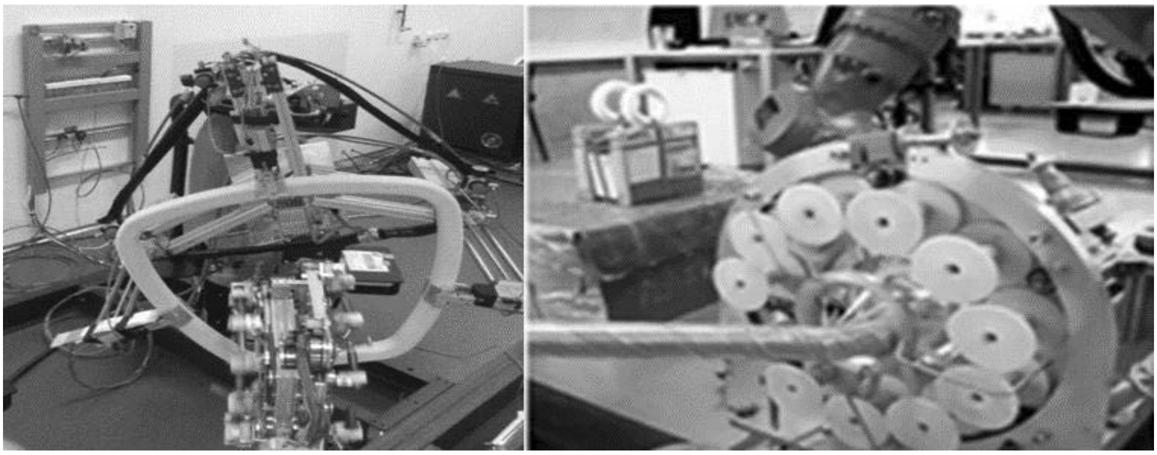

Fig. 3 Industrial robot with connected polyurethane frame and fibre-processing head (on the left) and guide line of fibre-processing head with ten coils with fibres (on the right).

2/ Fibre-processing head representation

The fibre-processing head is fixed in the working space of the robot. Each of the three guide lines of the head has ten coils with carbon fibres (see Fig. 3 on the right). These fibres are gradually wound onto the frame. Individual components of the head are described in BCS. The first outer rotating guide line is presented by circle $k1$ with the centre $S1_{BCS}$ and the second outer rotating guide line by circle $k2$ with the centre $S2_{BCS}$ (see Fig. 4 on the right). The second outer rotating guide line is presented by circle $k2$ with the centre $S2_{BCS}$. The static middle guide line (enables the placement of the fibres in a longitudinal direction) need not be considered in the model. The circles $k1$ and $k2$ have an identical radius r_{CIRCLE}. Centres $S1_{BCS}$ and $S2_{BCS}$ lie on the axis s of the fibre-processing head.

The centre of the fibre-processing head is represented by point H_{BCS}. Unit vector $\mathbf{h1}_{BCS}$ indicates the direction of the passage of the frame through the head. Vectors $\mathbf{h1}_{BCS}$ and $\mathbf{h2}_{BCS}$ are orthogonal. Point H_{BCS} together with vectors $\mathbf{h1}_{BCS}$ and $\mathbf{h2}_{BCS}$ allow us to calculate a REE trajectory when the frame passes through the head.

3/ Composite frame representation

The composite frame has a circular cross-section. The frame can be described by its central axis o and radius $\mathbf{r}_{TUBE}$ ($r_{\text{CIRCLE}} > r_{TUBE}$). An example of a vertical section of a polyurethane frame composed of two perpendicular arms is shown in the Fig. 4 on the left. The central axis o is defined in the LCS (of the REE) by a discrete set of points $B(i)_{LCS}$ and the unit tangent vectors $\mathbf{b1}(i)_{LCS}$ at those points, $1 \le i \le N$. In addition, the unit vector $\mathbf{b}2(i)_{LCS}$ ($1 \le i \le N$) lies in the plane orthogonal to the vector $\mathbf{b1}(i)$. The points $B(i)_{LCS}$ and vectors $\mathbf{b1}(i)_{LCS}$, $\mathbf{b}2(i)_{LCS}$ are prescribed by a composite designer to ensure passage of the frame through the fibre processing head. The variable l represents the distance between point $B(1)_{LCS}$ and a point on the axis o (see Fig. 4 on the left).

4/ Calculation of REE trajectory

We describe the main idea of REE trajectory calculation. A detailed calculation procedure is given in (*Martinec et al., 2015*). Recall that frame is fastened to the REE. We calculate REE trajectory that ensures the gradual passage of the axis o of the frame through the centre H_{BCS} of the fibre-processing head (see Fig. 5) in the desired direction $\mathbf{h1}_{BCS}$ (and by this way passage frame through head).

The frame's initial point of passage is $B(1)_{LCS}$ and the end point is $B(N)_{LCS}$ (for example see Fig. 4 on the left, end point is $B(106)_{LCS}$).

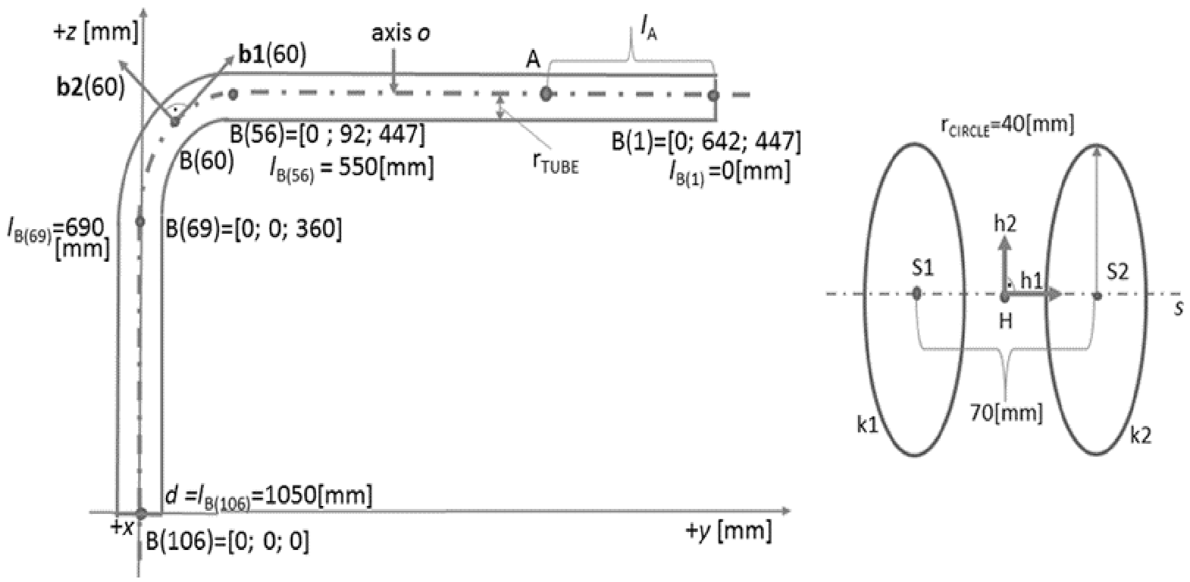

Fig. 4 Example of a vertical section through a composite frame composed of two perpendicular arms (on the left) and two outer rotating guide lines $k1$ and $k2$ of fibre-processing head specified in BCS (on the right).

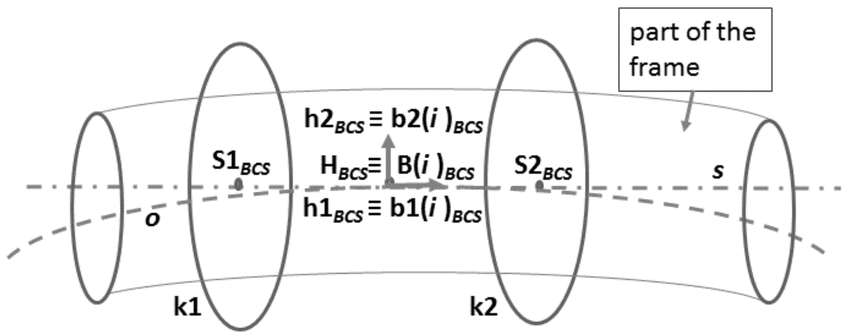

Fig. 5 Schematic representation of the composite frame passing through the fibre-processing head.

We need to find such TCP_i for each i ($1 \le i \le N$) that the following relations are valid (see Fig. 5)

$$B(i)_{BCS} \equiv H_{BCS}, \; \mathbf{b1}(i)_{BCS} \equiv \mathbf{h1}_{BCS}, \mathbf{b2}(i)_{BCS} \equiv \mathbf{h2}_{BCS}. \tag{1}$$

It means that the two orthogonal vectors and their common initial point originally defined in the LCS are in the same position in the BCS as the two fixed orthogonal vectors and their common initial point specified in the BCS. The location and orientation of the REE in BCS in the *i*-th step of the passage of the frame through the fibre processing head are uniquely determined by the relation (1). The identification of vectors $\mathbf{b2}(i)_{BCS}$ and $\mathbf{h2}_{BCS}$ allows the performance of the necessary rotation of the frame around the tangent of the axis o at point $B(i)_{BCS}$ when the point $B(i)_{BCS}$ is identified with centre of the head H_{BCS}. We calculate the transformation matrix $\mathbf{T}_i$ from LCS to BCS for the *i*-th step of passage of the frame through the fibre processing head. The transformation matrix $\mathbf{T}_i$ is generally the product of the translation matrix $\mathbf{L}_i$ and the rotation matrix $\mathbf{Q}_i$, i.e.

$$\mathbf{T}_i = \mathbf{L}_i \cdot \mathbf{Q}_i. \tag{2}$$

Validity of relation (1) is reached by applying matrix $\mathbf{T}_i$ in relation (2) to LCS, i.e. then $H_{BCS} \equiv B(i)_{BCS} = \mathbf{T}_i \, B(i)_{LCS}$, $\mathbf{h1}_{BCS} \equiv \mathbf{b1}(i)_{BCS} = \mathbf{T}_i \, \mathbf{b1}(i)_{LCS}$ and $\mathbf{h2}_{BCS} \equiv \mathbf{b2}(i)_{BCS} = \mathbf{T}_i \, \mathbf{b2}(i)_{LCS}$ is true.

Calculation of translation matrix $\mathbf{L}_i$ and rotation matrix $\mathbf{Q}_i$ in relation (1) is made using matrix calculus (in more detail see (*Sciavicco & Siciliano, 2004*), (*Martinec et al*., *2015*)). Rotation matrix $\mathbf{Q}_i$ can be written in the form (see (*Martinec et al*., *2015*))

$$\mathbf{Q}_i = \mathbf{Rot}(z, a_i) \cdot \mathbf{Rot}(y, b_i) \cdot \mathbf{Rot}(x, c_i), \tag{3}$$

where $\mathbf{Rot}(z, a)$ is the orthogonal matrix of rotation of LCS around axis z by angle a, $\mathbf{Rot}(y, b)$ orthogonal matrix of rotation of LCS around axis y by angle b and $\mathbf{Rot}(x, c)$ orthogonal matrix of rotation of LCS around axis x by angle c (the so-called Euler angles of matrix $\mathbf{Q}_i$).
Now, we can determine $TCP_i = (x_i, y_i, z_i, a_i, b_i, c_i)$, where parameters x_i, y_i and z_i define translation of the REE and are determined by matrix $\mathbf{L}_i$ in relation (2) and the last three parameters a_i, b_i and c_i are given by relation (3) (in more detail see (*Martinec* et *al*., *2015*)).

RESULTS AND DISCUSSION

The procedure described in paragraph 4/ of previous chapter is used to calculate the sequence TCP_i (for $1 \le i \le N$) on an external PC. Then we enter the calculated set of TCP_i into the robot's control unit. Subsequently, the robot creates by its commands a continuous trajectory of the REE allowing the passage of the frame through the fibre-processing head. The robot's control unit creates the REE trajectory on the principle of linear interpolation or using of cubic splines of the parameters included in TCP_i ($1 \le i \le N$).
The quality of the produced composite frame depends primarily on the quality of the frame itself (often created from polyurethane) and on the quality of wound fibres (usually from carbon or glass). However, keeping the correct angles and homogeneity of the filaments on the frame are also very important for the quality of composite frame. Traditional procedures of composite frames manufacturing based on the manual skills of technicians are labour-intensive and time-consuming. In addition, it is difficult to maintain the correct winding angles of fibres on the frame during manual processing. One of the possible approaches used to produce composite frames is to stretch the fabric from the fibres on a frame. However, if the frame has a complicated 3D shape or if the frame is closed, then this approach is difficult to use. In such cases, the method of winding of endless fibre strands on a frame geometry using rotary fibre-processing head is suitable for use.
Note that using two industrial robots in the production of composite frame can also be used in the case of a closed frame (see Fig. 6). A composite frame is connected to the first robot and during the winding process the composite frame is fastened to the second robot.
Described approach to REE trajectory definition is significantly more effective than the teach-in method. The principle of this method is that the technician finds a suitable trajectory based on repeated use of the robot control panel called the "teach pendant".

CONCLUSIONS

This article describes the procedure of calculating the 3D trajectory of REE of an industrial robot during the manufacturing of a frame composite. This described computational procedure in the article allows us to determine the appropriate off-line REE trajectory based on the use of a mathematical model of winding process and matrix calculus.
Suppliers of industrial robots currently offer specific software tools facilitating control of the REE for specific tasks of the industrial robot (e.g., laser cutting, welding, pressing, packing). But these tools are not applicable for our problem.
Procedure of off-line calculation of REE trajectory described in the article is completely independent of the industrial robot type and software tool of robot unit. Therefore, the described algorithm can be applied to any industrial robot and any manufacturing process.
The procedure for determining the optimized REE trajectory in the winding process can be obtained by modifying the described algorithm in this article (see (*Mlýnek et al*., *2018*). In contrast, the teach-in method is practically unusable finding the optimal trajectory.

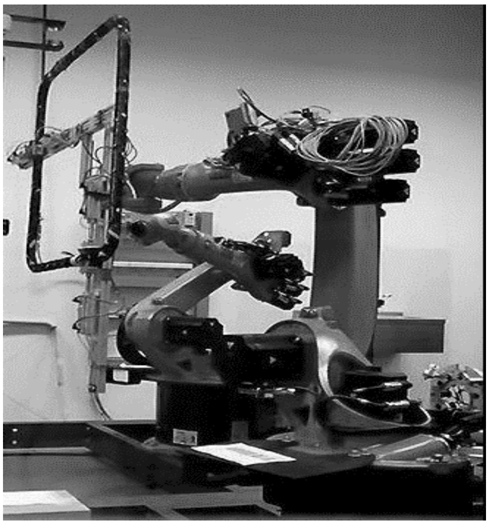

Fig. 6 Cooperation of two industrial robots in the production of closed composite frame.

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