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Research paper

Design and analysis of a metamorphic mechanism for automated fibre placement

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ABSTRACT

Automated fibre placement (AFP) integrates the functions of fibre feeding, transmission, clamping, restarting, cutting, heating, and compacting, which is characterised by multiple degrees-of-freedom, multiple drives, constraints, and strong coupling. To simplify the complexity of mechanical structures, a metamorphic design to achieve above functions is introduced in this study based on the relationship of the motion sequence and constraints in the effort to realise sequential motions. Furthermore, the variable topological structures and the mobility of this mechanism are analysed in different phases of the operation, and a kinematics model is proposed to reveal the dynamic performance. Specifically, a mechanical model is presented for convenient analysis of the transformation of phases. The global optimisation process is then introduced using global and other configuration optimisers that ultimately obtain global optimisation results. Corresponding simulation results demonstrate that the proposed mechanism can effectively realise stable operation.

1. Introduction

Composite materials have been successfully applied in automotive and aerospace industries since the 1960s [1]. Compared with traditional materials, such as alloy steel, iron, and aluminium, composite materials have considerable lightweight and high-performance advantages, such as their increased specific strength, modulus, and corrosion resistance [2]. The conventional manufacturing patterns are time-consuming and labour-intensive in instances where material is laid onto a complex shape until the AFP (automated fibre placement) is developed [3]. The processing concept for AFP was first proposed in the late 1970s, and was adopted to overcome the disadvantages of the fibre winding process. It also provides the capacity to substitute the manual lay-up [4]. A typical robotic AFP system includes an AFP head and an industrial robot. Each fibre tow of AFP first passes through the guider and tension control subsystem and through the cutting, clamping, and restarting subsystems (which are combined and known as the CCR unit). These fibre tows are finally laid onto the mould surface along a predefined path by the heating and compacting device, with high efficiency, high quality, and lower production costs. Few companies and institutions have designed and manufactured innovative contributions to the AFP [4–15]. Boeing Company first proposed and developed AFP prototype ‘AVSD’ in the mid-1980s, which basically achieved the functions of cutting restarting and compacting [12]. Meanwhile, Cincinnati Machine (CM) was also heavily dedicated to FP development. CM produced a commercialized AFP machine tool VIPER 1200 in 1989, and CCR unit is driven by three cylinders and multi-link mechanisms [5]. ADC Acquisition Company designed a multi-directional tape laying apparatus in 2007 and its CCR units

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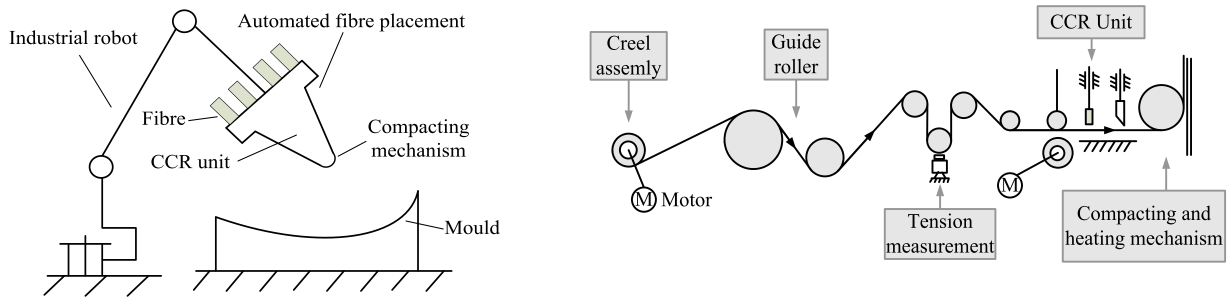

Fig. 1. Automated fibre placement system.

are arranged symmetrically on both sides [6]. Researchers in CM devised a drive roll assembly in AFP to accomplish the functions of clamping and cutting but the clearance zone of drive roll limits the minimum time interval between each motions of clamping and cutting [8]. Researchers in Boeing Company provided a simplified device for maintaining fibre tension [14]. Researchers of Electroimpact Inc. combined optical encoders with modular automated fibre placement head technology to achieve high precision with few thought for the structural improvement [13]. Berend et al. [10] exhibited a new approach for AFP system and its compaction unit is suitable for producing complex-curved structures. The aforementioned AFP systems usually contain multiple degrees-of-freedom, multiple drives to satisfy functional requirements, and complex constraints. Particularly, the CCR unit as the core function of AFP system, has received less attention and traditional design method would increase inertia and volume of the AFP system which consequently limit complex control system and the laying precision.

Currently, many new types of mechanisms have been developed to overcome the disadvantages of the conventional mechanism. Among them, metamorphic mechanisms that can perform multiple tasks with the minimum number of actuators provide a novel way to simplify the complexity of the modular AFP system and directly increase the laying speed and moulding precision. Many scholars have proposed the fundamental principles and improved potential applications. Dai and Jones [16] introduced and analysed the mobility of metamorphic mechanisms in applications. Chiou and Kota [17] demonstrated a synthesis methodology based on the matrix representation, which was successfully adopted for function design generating mechanisms. Yang et al. [18] presented the explicit mapping relations between topological structures and position and orientation characteristics. Subsequently, Yan et al. [19–21] also proposed and improved the configuration synthesis method of the mechanism. Li and Dai [22] proposed a structural synthesis method for single-driven metamorphic mechanisms based on augmented Assur groups. Li et al. [23] then developed a method by integrating the Assur groups and extended the adjacency matrix. Additionally, they [24] presented a task-based configuration synthesis method to derive constraint types and structures. Zhang et al. [25] introduced a special classification approach of constraints based on the multiconfiguration characteristic. Regarding the application of metamorphic mechanisms, Ding and Li [26] designed a type of deployable/retractable mechanism using a friction self-locking/unlocking unit, which can be expanded and retracted along a line. Xu et al. [27] subsequently designed a metamorphic mechanism unit which was capable of sequence deployment and retraction. These realisations of metamorphic mechanisms were based on the variable kinematic joints whose types or moving directions could be transformed in the process of continuous movement.

In this study, we proposed a metamorphic mechanism based on the variable kinematic joints for CCR unit and it can effectively simplify the AFP system. Considering movement sequence, the planar mechanism is synthesized to achieve functional requirements. The outline of the paper is organized as follows. In Section 2, the requirement analysis of CCR unit and the use of variable kinematic joints is presented. Section 3 designs a metamorphic mechanism, which can execute multiple missions with one actuator. The kinematic model is established and mechanical property is analysed in Section 4. In Section 5, the global optimisation method is proposed and a case study and simulation are also presented.

2. Mechanical design principle

2.1. Analysis of requirements and movement sequence

Compared with the traditional winding system, the AFP process is more compatible with laying reinforcement fibre onto a complex structures, such as the case of a tapered shape. Each tow of the AFP head can be individually controlled to stop, cut, and restart. These tows are finally used to form a band of material and laid onto the mould surface with low tension and compaction pressure, as shown in Fig. 1. During the laying process of the material, each tow spreads with material at its respective speed, and the material bandwidth, defined as the width of the composite band, can be changed by multiple, individually controlled CCR units. Specifically, the maximum width B of the composite band is

$$B = l \times n \tag{1}$$