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Elastic buckling analysis of webs transported through rollers with misalignment

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ABSTRACT

Emerging flexible electronics industries, such as solar cells and RFID tags manufactures, adopt the roll-to-roll (R2R) technology to improve their production efficiency. However, the flexible webs used in these fields wrinkle easily due to their tiny thickness and complex structure. Moreover, the webs are easily buckled if the rollers are misaligned. Therefore, it is desired to introduce an efficient method which can help to determine the critical buckling conditions of the webs when there is misalignment of rolls during their production. The current research presents a model based on the Kirchhoff plates buckling theory to determine the critical buckling misalignment and tension for webs transported through misaligned rollers. Webs are modeled as tensioned Timoshenko beams to obtain their stress distributions. The critical buckling conditions are calculated using the Galerkin method in the current research. Results indicate that the calculated critical conditions are close to the practical ones considering the parabolic variation of shear stress and the linear variation of bending stress. The results also indicate that the critical misalignment increases with the increase of the span ratio and tension, and critical misalignment decreases with the increase of the elastic modulus and web width. Moreover, the critical tension increases as the thickness and elastic modulus increases. The presented model provides a useful method to design and maintain R2R equipment.

1. Introduction

The R2R technology is widely used in many industries due to its high efficiency and low production cost. In recent years, newly emerging industrial fields such as flexible electronics, RFID and fuel cells [1–5] are adopting this efficient technology to meet the requirement of massive production. However, there is a significant change in trend that, webs used in these fields have very small thickness and complex structures. This trend causes the webs buckle easily. Buckling, or "troughs" are the out-plane displacement of webs between rollers. The troughs can induce distorted and erroneous patterns, reduce the accuracy of manufacturing, degrade the performance of devices, and can even interrupt the whole manufacturing process, as illustrated in Fig. 1. Web troughs can be caused by various factors including roller misalignment, imperfect roller profile, non-uniform tension, and uneven web cross-section. Roller misalignment is one of the most significant factors. Roller misalignment generates compressive stress in webs, and causes troughs to appear. Troughs can be avoided directly by reducing the roller misalignment or indirectly by increasing the applied global tension. However, over high precision of roller parallelism can increase the cost of R2R equipment greatly and an overlarge tension may even break the web. Therefore, it is necessary to clarify the relationships among the critical roller misalignment, applied tension and parameters of webs, while designing a new R2R system and determining the processing parameters to avoid troughs.

Generally, the instability problem of tensioned webs can be solved by two theories. The first one is the tension field theory, which assumes that the web has no bending stiffness. A web buckles when a compressive stress arises in it. The tension filed theory offers a convenient criterion of the critical load for many engineering cases. For example, the required tension to avoid buckling for webs with roller misalignment can be determined based on beam theory [6]. However, the tension field theory ignores the bending stiffness of webs, thus the obtained critical buckling load is always less than the actual value. The second method is the plates buckling theory, which considers the webs as plates with small bending stiffness. According to the plates buckling theory, webs can resist small compressive loads. However, a web buckles instantaneously when the compressive stress exceeds a certain critical value. On the basis of the plates buckling theory, and by making use of the energy methods or numerical methods such as finite element

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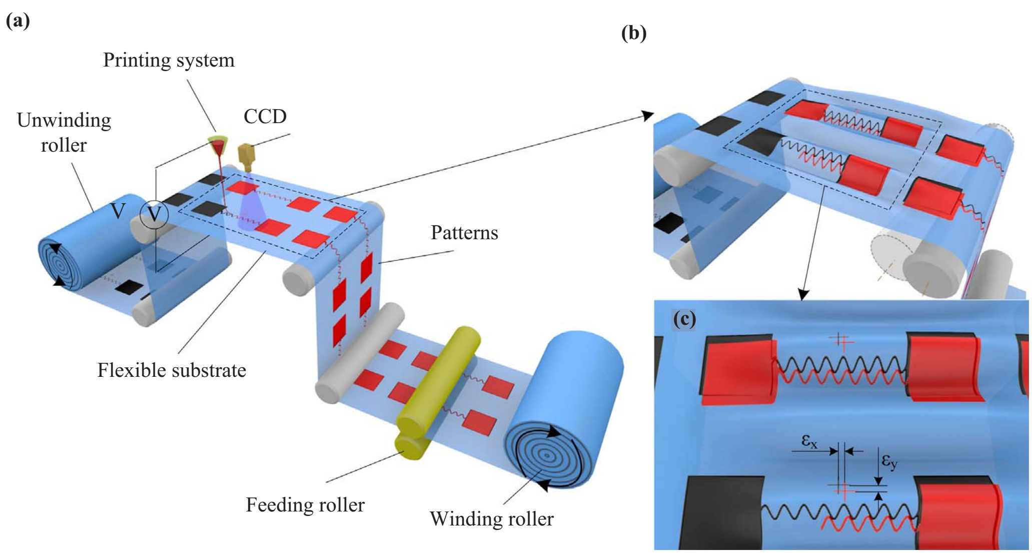

Fig. 1. Schematic diagrams of a R2R system and buckling. (a) A typical R2R system compatible with flexible electronics: the printing system adds new patterns on the existing ones. (b) Buckling of a web when rollers are misaligned. (c) The new patterns distortion and mismatching of the existing patterns after buckling.

analysis (FEA), many buckling analyses of webs subjected to global tension have been carried out in literature. For example, Lin [7] and Kim [8,9] studied the critical buckling loads of webs with all edges simply supported and subjected to non-uniform tension. Cerda [10,11] studied the instability problem of webs with two opposite edges clamped and subjected to uniform tension. All these studies used energy methods to determine the critical buckling loads. Some other buckling problems with more complicated conditions were solved with the assistance of FEA, such as webs with a hole [12,13], webs transported through rollers with misalignment or webs with non-uniform profile [14,15].

The boundary conditions of webs transported through misaligned rollers were first studied systematically by Shelton [16–18]. In his studies, webs were modeled as Euler beams, and the "Normal Entrance Law" was proposed to determine the boundary conditions. After that, the stress distribution in the web could be obtained. Furthermore, based on Shelton's studies, many other buckling analyses of webs have been presented in literature. For example, a series of studies were carried out by researchers in the Web Handling Research Center of USA. Good et al. [19,20] presented a buckle prediction model for isotropic and anisotropic webs with roller misalignment and compared the predicted results with the measured data. Hashimoto [21] proposed a model to predict the relationship among speed, tension, and critical misalignment angles with experimental characterization. Beisel [22] studied the buckling phenomenon caused by the imperfect structure of rollers, such as coin or concave profile of rollers. Moreover, Good and Beisel [23,24] used the biaxial loaded plates buckling criterion to study the buckling of the web caused by the misalignment of the roller.

However, in most of previous studies on the buckling caused by roller misalignment, such as Good and Beisel [23,24], webs were modeled as plates subjected to uniform biaxial loads, which did not conform to the practical stress distributions in the webs. The actual stress distribution is similar to that of a beam subjected to shear forces. Both the normal and shear stress vary significantly. When considering the maximum or average of shear stress on the boundary as the equivalent load, and considering uniform stress distribution, the critical buckle conditions do not conform to the actual ones. Thus it is necessary to take into account the variations of normal and shear stresses when calculating the accurate critical condition.

In the current research work, a theoretical calculating process for the elastic buckling of webs transported through a pair of misaligned rollers, by making use of the plate buckling theory, is presented. First, the stress distribution of webs is determined by using the Timoshenko beam theory. Then, the critical buckling loads are calculated based on the Kirchhoff plates buckling theory and the Galerkin method under the small strain assumption. Subsequently, an iteration procedure is carried out to determine the critical misaligned angle and tension. The obtained critical misaligned angles of the downstream roller under the given tension were compared with the existing solutions in the literature. Moreover, the influences of geometric parameters and material properties on the critical misalignment were also investigated in current study. Finally, the correlation between the required critical tension and the material properties were obtained by the same method, which can be used to determine the operation tension of R2R equipment.

2. Mechanical modeling and solution strategy

In this section, the buckling problem of webs is simplified and defined. Then as traditional buckling analysis, the stress distribution of webs, which determine the critical buckling loads, is calculated at first. Later, the buckling problem is converted into the classic eigenvalue problem and solved using the Galerkin method to obtain the critical conditions.

2.1. Definition of the problem

The instability problem of webs caused by misaligned roller is illustrated in Fig. 2. An isotropic web is transported through two rollers, with a length of a, a width of b and a tension load of T_0. If the downstream roller j is not parallel to the upstream roller i, a shear force arises

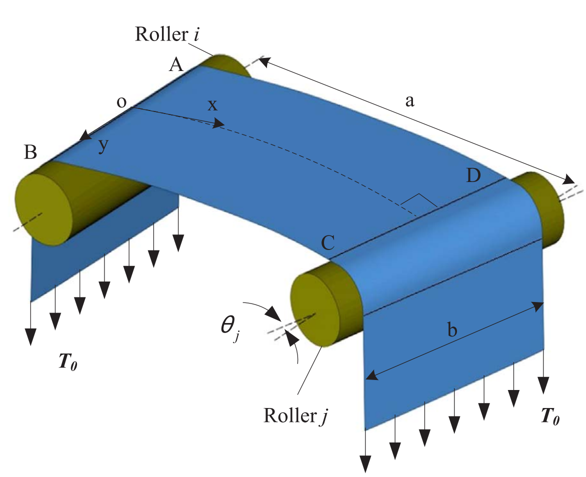

Fig. 2. Schematic diagram of a web with roller misalignment.

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