Mechanism and Machine Theory 122 (2018) 75–85

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Short communication

Precise tension control of a dancer with a reduced-order observer for roll-to-roll manufacturing systems

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ARTICLE INFO

Article history:
Received 6 February 2017
Revised 11 December 2017
Accepted 13 December 2017

Keywords:
Dancer
Printing
Printed electronics reduced-order observer
Roll-to-roll
Tension

ABSTRACT

Precise tension control is critical to guaranteeing the specific functionality and topography of printed layers from roll-to-roll (R2R) printing systems. This is because the tension disturbance of substrate affects the surface energy, which determines the geometry of a printed circuit. Dancer systems are used to attenuate tension disturbances by the motion of the dancer roll. The angle of the dancer rod is measured by a potentiometer, and feedback control with an adjacent driven roller is used to maintain the dancer roll in an equilibrium position. However, the dynamic tension regulation of the dancer has not been verified through a dynamic analysis on the position of the dancer roll and tension disturbance. In this study, a mathematical model of the dancer was summarized, and the dynamic characteristics were analyzed to investigate the motion of the dancer roll and tension. The tension regulation performance was found to deteriorate in the certain frequency range. Because the dynamic response of dancer position does not correlate well with the tension; particularly magnitude difference between tension and dancer position began to increase in bode plot. So, a well-known reduced-order observer was employed to estimate and control the tension disturbance over a wide frequency range.

1. Introduction

Recently, roll-to-roll (R2R) printing technology has attracted attention for its applicability to manufacturing flexible electronic devices such as radio frequency identification (RFID), organic thin film transistors (OTFTs), organic light-emitting diodes (OLEDs), sensors, and others [1,2]. In contrast to conventional production methods for electronics such as photolithography, printing technology is an additive process, which enables patterns to be directly written on flexible substrates. Thus, it is an environmentally friendly process. In addition, R2R printing is suitable for high-throughput and large-area processing on cost-effective flexible polymer substrates or metal foils [3,4]. The gravure, inkjet, and offset are employed for additive patterning in the R2R process [5–7].

The R2R printing system fabricates printed patterns by unwinding, infeeding, printing, drying, sintering, outfeeding, and rewinding [8]. In addition, adhesive coating and lamination can be used as supplements for multilayered production. The tension of the substrate during the printing process has a deep influence on the pattern quality. Disturbances to the tension of the substrate due to infeeding are a major source of machine-directional registration error in multi-layer printing systems

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https://doi.org/10.1016/j.mechmachtheory.2017.12.012

Nomenclature

l_u	upstream span length of the dancer, m
l_{u0}	upstream span length of the dancer at steady state, m
l_d	downstream span length of the dancer, m
l_{d0}	downstream span length of the dancer at steady state, m
l_1	rod length of the hinge to the cylinder, m
l_2	rod length of the hinge to the dancer roll, m
θ	angle of the dancer arm
E	Young's modulus, N/m^2
r_d	radius of the idle dancer roll, m
J_d	moment of inertia of the idle dancer roll, kg-m^2
J_{eq}	equivalent moment of inertia of the dancer, kg-m^2
b_d	rotary bearing friction constant of the idle dancer roll
b	rotary bearing friction constant of the hinge
v_d	tangential velocity of the dancer roll, m/s
v_{d0}	tangential velocity of the dancer roll at steady state, m/s
V_d	variation in tangential velocity of the dancer roll, m/s
v_i	tangential velocity of the i-th roll, m/s
v_{i0}	tangential velocity of the i-th roll at steady state, m/s
V_i	variation in the tangential velocity of the i-th roll, m/s
t_i	tension of the web for the i-th span, N
t_{i0}	tension of the web for the i-th span at steady state, N
T_i	variation in the tension of the web for the i-th span, N
P_0	pressure of the pneumatic cylinder, N/m^2
A_0	area of the piston of the pneumatic cylinder, m^2
F_k	spring force of the pneumatic cylinder, N
ε_i	strain of the web for the i-th span
ρ_u	density of the unstretched web, kg/m^3
A_u	cross-sectional area of the unstretched web, m^2
t	time, s

[5]. Tension disturbances affect the topography as well as functionality of printed layers [9]. For example, the printed fine line whose width was approximately 30 um was disconnected in huge tension variation, as shown in Fig. 1(a) and (b). Thus, the dancer system is employed for unwinding and infeeding to regulate the tension disturbance of a moving substrate, as shown in Fig. 2(b).

Several researchers have studied mathematical models to control the tension. Dancer systems are classified as active and passive depending on the external actuator. Pagilla and his group proposed an active dancer for precise tension control over a wide frequency range of disturbances [10,11]. Dwivedula et al. compared passive and active dancers [12]. The performance of an active dancer is restricted by the dynamics of the actuator for the dancer roll. Normally, the slow response of the actuator degrades the dynamic performance of active dancer systems. A passive dancer comprises a spring, damper, and idle roll. The tension variation of the substrate is regulated by passive movements of the idle roll without an external actuator. A mathematical model of a passive dancer was previously derived by using a torque equation for the hinge and the tension dynamics of the substrate; the resonance frequency of the passive dancer was selected as a design parameter [13]. Fixed-order $H\infty$ control of dancer system was suggested [14]. Comparison of load-cell and dancer based tension control was investigated [15]. Nonlinear tension regulation method was proposed in [16]. Adaptive-PI tension control was developed in [17]. Shelton analyzed the limitations of the passive dancer at measuring the tension [18]. Design guidelines and a gain tuning method have been proposed [19].

A dancer system combines passive and active components and is applied to the R2R printing process to attenuate the tension disturbances of the substrate. For the dancer, the tension disturbance is indirectly controlled by changing the tangential velocity of the adjacent driven roller to keep the dancer roll in an equilibrium position. This approach is effective at operating the dancer in the permitted physical swing range, even if excessive tension disturbances occur. However, there have been no studies on analyzing the dynamics between the position of the dancer roll and the tension variation of the substrate in R2R printing. In this study, the dynamic characteristics of a dancer system were analyzed through numerical simulations to validate the effect of the dancer roll motion on regulating the tension of the substrate. A reduced-order observer was applied to estimate the tension variation and realize precise control over a wide frequency range. Numerical simulations were carried out to analyze the performance of the proposed reduced-order observer.