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Tension monitoring in a belt-driven automated material handling system

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ABSTRACT

The extension of the useful life of manufacturing equipment is one of the keys to sustainable manufacturing. The high uptime requirements of the semiconductor industry result in the need for conservative preventive maintenance schemes, which leads to replacement of key components before the end of their useful life. This paper presents the results of research toward a more intelligent condition based maintenance scheme for belt monitoring in a belt driven automated material handling system. An experimental study of belt dynamics showed that transverse belt vibrations were sensitive to changes in belt length, belt tension, belt misalignment, and excitation location. Based on these findings, a novel, contact based device was designed to consistently excite belt vibrations in the material handling system with greatly reduced variations in belt length and initial condition location. On average, standard deviations of tension estimates using the device were 65% lower than that of a trained technician performing the current standard technique on three different robots. This design was then further adapted to facilitate a non-contact belt excitation and monitoring approach that did not require bringing the material handling system offline in order to obtain sensor readings. Such a procedure greatly eased and accelerated the monitoring process.

1. Introduction

Automated material handling systems (AMHS) are crucial to modern manufacturing. Modern manufacturing requires increased quality and throughput, better inventory control, and a high level of production cell integration. The benefits of using AMHS include reduction of inventory, cycle time, and cost as well as improvement of quality and productivity. These benefits have motivated the use of AMHS by the heath care, printing, automotive, wine distribution, food distribution, and apparel industries [1], as well as postal services [2] and semiconductor manufacturing [3]. The top 20 AMHS suppliers' annual revenue grew from $10.7 billion in 1999 [4] to $15.3 billion in 2008 [5], suggesting a growing need for automated handling.

The semiconductor industry features the quintessential integration of Automated Storage/Retrieval Systems (AS/RS) with automated material transfer. Wafers are buffered in 'stockers' between sequential processing steps, which demands their impeccable reliability. They are a bottleneck for the Work in Progress (WIP), leading to immense cost of a potential stocker failure. This cost of downtime has driven extremely conservative preventive maintenance schedules, which are often wasteful because parts are replaced before the end of their useful life. In fact, spending on plant maintenance in the United States rose from $800 billion in 1991 to $1.2 trillion in 2000. Startlingly, it is suggested that as much as one third to one half of this expenditure is wasted due to poor maintenance management [6].

The work presented in this paper focuses on a unitary belt-driven AS/RS used in the semiconductor manufacturing industry. A belt driven central crane robot operates in an aisle to move storage units to and from storage bins. Belt drives are sensitive to tension, suffering from slipping and skipping teeth if tension is too low, or excessive pulley bearing wear and belt fatigue if the tension is too high [7,8]. Currently, belt tension monitoring is regularly performed by a technician manually strumming the belt and recording the ensuing fundamental frequency of belt vibrations. The tension is estimated from the fundamental frequency of transverse belt vibrations based on the simple one-dimensional wave equation and known belt material properties. Such a manual procedure and restrictive assumptions about the belt result in a high variance in tension estimates, leading to false alarms when belt tension is still appropriate as well as missed detections of situation where belt tensioning is inappropriate.

In this paper, we address the aforementioned issue by exploring and designing sensor arrays and data-driven monitoring procedures for accurate, repeatable and reliable monitoring of tension forces in a belt driven material handling device. Note that the prevalence of belt drives in the semiconductor industry [9,10], automotive industry [10–14], and robotics in general [15–17] suggest significant implications of the work presented in this paper

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on fields other than semiconductor manufacturing. The next section briefly reviews relevant literature on this subject.

2. Research background

Belt drives play a crucial role for power transmission in many applications. Advantages of belts over gears and chains include weight and noise reduction, improved efficiency, shock absorption, damping characteristics, simplicity, cleanliness, and lack of the need for lubricants [7]. Realization of these advantages require adequate pulley radius, path planning, and correct tensioning [7,8]. Under-tensioning causes slip in flat and V-belt drives and tooth skipping in timing belt drives, which is unacceptable for precision placement operations. Over tensioning causes premature belt failure from abrasion or shearing, as well as overloading of pulley bearings [7,8]. Numerous belt tension monitoring techniques have been developed to assure proper tension.

2.1. Stationary belt tension monitoring

Stationary belt tension monitoring occurs when the belt is not moving and thus requires interruption of the normal machine operation. All stationary methodologies rely on the elasticity of the belt to determine tension either by transverse deflection or by initiating transverse vibration.

The simplest methodology for belt tension estimation assumes linear, elastic material properties. Essentially, the force required for a pre-determined, mid-span belt deflection is measured. Since most belts are thin relative to the span, bending is localized around clamps or pulleys and axial deflection dominates the model. Thus, with knowledge of belt material characteristics, the force required for deflection is separated into tension induced by deflection and the initial tension [18]. This methodology suffers from sensitivity to deflection location, lack of elastic linearity in most composite belts, and neglects the flexural stiffness of belts.

Experimental uniaxial tension distribution in a flat belt measured by optical coating and extensometer was reported in [19]. It was noted that optically measured strain was, on average, 15% higher than the extensometer measured strain. However, the introduction of visual tension measurement cannot be underrated, as it formed the basis for use of the laser Doppler vibrometry in deflection measurements.

Next, the one dimensional wave equation is utilized to estimate belt tension from the fundamental frequency of free vibration [10,12]. The model assumes homogenous, isotropic, linear elastic, undamped material condition with pinned boundary conditions [20]. Clearly, composite belts satisfy none of these conditions since composite construction leads to heterogeneity. Furthermore, parallel tension member design leads to anisotropy. In addition, the use of polymeric matrices in belt construction guarantees non-linear elasticity and the viscoelastic nature of polymers creates frequency dependent damping [21]. Lastly, belt drives suffer from pulley misalignment, causing a heterogeneous tension distribution across the width of the belt, which was also found to alter the frequency and modes of vibration in [22]. The drawbacks to this methodology are supported by [13], where the damping effect and geometric complexity were noted although no model was formulated. Despite these shortcomings, tension estimation based on fundamental frequency is used almost universally.

2.2. Dynamic belt tension monitoring

This section provides a brief review of advancements made in dynamic belt tension monitoring (i.e. monitoring while the belt is moving). Both longitudinal and transverse vibrations are present in running belt drives. These two phenomena are coupled due to constant belt length. Also, it has been observed that transverse vibration frequency is dependent on the belt material, geometry, and tension, while longitudinal vibration is largely material and geometry driven, with much less dependence on tension [23,24]. Friction, whether modeled using a Coulomb friction [25–27] or a tri-linear model [27], is responsible for power transmission in V-belt and flat belt drives [28,29], but is largely replaced by geometric considerations in timing belt drives [30,31]. Next, axial stiffness accounts for the majority of belt modeling accuracy, followed by damping, flexural stiffness, and shear deformation respectively [32,33]. This can be understood by noting that flat and timing belts are thin, making contributions from flexural and shear stiffness negligible. Damping has been modeled linearly, in which case there is coupling between transverse natural frequency and oscillation amplitude [30]. Viscoelastic damping has been modeled as well [34,35], in which case viscoelastic stiffness determines the natural frequency and oscillation amplitude is viscoelastic damping parameter dependent [36]. Parametric excitation of vibration is provided by non-constant pulley velocity [37], pulley eccentricity [30], belt inertia [25,26], and belt-pulley tooth meshing [30,31,35].

2.3. Concluding remarks

From the elaboration above one can see that the recently introduced analytical methods for static and dynamic belt tension monitoring are ahead of the manual technique currently used in the semiconductor industry. However, even those advanced methods introduce tractable assumptions in terms of regular belt geometry and homogeneous material properties. However, the belt considered in this study is a serrated membrane made of a viscoelastic material reinforced with steel wires (this is a standard tool utilized in numerous semiconductor facilities). Thus, the standard analytical assumptions of regular geometry and material homogeneity are significantly violated.

Data-driven methods for modeling and monitoring of system performance offer a way to bypass the need to explicitly model the complex belt geometry and material properties, which would require considerable amount of time and would yield intractable models with questionable applicability to system monitoring.

Hence, in this paper we pursue a data-driven paradigm based on observing and characterizing distributions of features extracted from various sensor readings measuring deformation and movements of the belt. The most sensitive feature set was determined through experimental studies performed on a specially designed testing device, referred to as the Test Stand in the remainder of this paper. These experimental results then led the design of two belt excitation and sensing arrays for monitoring of belt tensions. The first monitoring device design was based on the contact-based excitation of the belt vibrations and direct sensing of belt deformations via an array of strain gauges mounted on the belt. This system was improved in the second design, which led to a monitoring device accomplishing belt excitation and belt movement sensing in a fully non-contact manner. Non-contact character of the second design enabled us to obtain snapshots of belt tension conditions in a significantly less intrusive manner. Finally, benefits of the new sensing and monitoring techniques will be demonstrated on data collected from a real production AS/RS.

3. Contact-based monitoring of AMHS belt tension

3.1.1. Contact-Based Monitoring Experimental Study

Estimation of belt tension from the fundamental frequency of manually induced transverse vibrations of the belt is the current industrial standard. Fundamental frequency is a function of the belt length, tension, and linear mass density. Linear mass density