An Assembly Status Identification Method for Wedge Belt Automatic Assembly Based on Dynamic Feature

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Abstract. The assembly of the wedge belt joint relies on the sense and experience of human, which limit the application of automatic assembly technology. In order to implement automatic assembly for higher production quality and efficiency, an assembly status identification method based on dynamic feature is proposed. The contact status of the wedge belt in assembly is analysed and the dynamic model is formulated. The dynamic features for identification are compared and the signal of acceleration is selected. The identification method of assembly status is proposed based on the acceleration signal. An experiment is designed to verify the identification method. The experiment result shows that the amplifier of the acceleration decreases much more sharply as it fits well. The proposed identification method is effective and stable, which could be used for the automatic assembly.

Keywords: Wedge-belt joint; Automatic assembly; Assembly status identification; Acceleration signal.

1. Introduction
The wedge-belt joint is a novel connection and has some advantages comparing with tube nipple connection and bolt connection: making structure compact, making surface smooth and reducing additional mass. Thus, wedge-belt joint is widely used in the connection of thin-wall parts, especially in aerospace equipment and navigation equipment. The structure of a wedge-belt joint is illustrated in Figure 1, which consists of two thin-wall parts and a pair of wedge belts.

![Figure 1. The structure of a wedge belt joint.](image-url)
(1) position and clamp the two thin-wall parts for further connection;
(2) mount the first wedge belt to the groove between two thin-wall parts;
(3) mount the second wedge belt;
(4) impact the second wedge belt to make the joint tight.

To improve the assembly quality and efficiency, the automatic assembly will be applied for the wedge-belt joint. There is a crucial problem for its automation: how to make the machine discriminate whether the joint is tight or not in step (4).

The human could judge it by the sound of impact, which relies on the experience and the hearing of the worker. Inspired by that, we could sample the impact sound and classify the sound signal for discrimination. Some literatures shows it is possible to use impact sound. Wang [1] proposed a novel vibro-acoustic modulation method to detect bolt loosening. Antonio [2] analysed acoustic sound signals to detect faults in induction motors. Mario [3] applied a machine learning method to detect the defective embedded bearings by sound analysis. Lu [4] used sound signal to assist vibration signal to detect bearing state. Alatorre [5] controlled the cutting force in closed loop by the sound signal from the machining process, and it could achieve an accuracy of 0.08 N for the cutting forces. Yun [6] developed a new method to evaluate the state of a diesel engine which is based on the knocking sound signal of a diesel engine. The utilization of the impact sound signal also has some drawback: (1) the sound signal often contains environment disturb; (2) the features for discrimination are hard to find, which could decrease the identification rate.

The impact on a wedge belt is a dynamic process and we could utilize the dynamic features for discrimination. Li [7] established the dynamic model of the two-parallel shaft gear transmission system, which could calculate the effects of speed and damping on the system. Meng [8] proposed the dynamic equations of multi-link multi-DOF flexible manipulator for the study of the vibration responses of damping. Meng [9] proposed a method of stiffness segmentation through the dynamic gear model with six degrees of freedom, which could detect the state of the gear. Ye [10] established a dynamic model with four masses and 19 degrees of freedoms, and the effects on the system from stiffness and damping coefficients between different contacting surfaces are studied. Poursina [11] advanced an analytical formula which used the damping coefficient as a function of system’s parameters in a continuous force model of impact. Fu [12] proposed a dynamic model about the planetary roller screw mechanism, which improved the calculation efficiency of the previous model. To use the dynamic features, the mathematical model is formulated and the selected dynamic feature can be measured by instrument.

To determine whether the joint is tight or not, this paper proposes an assembly status identification based on dynamic features, since it is more stable than the sound discrimination. We will analyse the contact status of the wedge belt and formulate the mathematical model of the wedge belt. Then the dynamic features are compared and selected. The identification method is proposed based on the selected feature. To verify the proposed identification method, an application experiment is designed and done. Finally, the experiment results shows that the identification method is effective and stable.

2. The Identification Method

2.1. The Model of the Contact of a Wedge Belt

The contact status of a wedge-belt joint in assembly is illustrated in Figure 2. The thin-wall parts are positioned for connected and then the wedge belt 1 is fixed to the one of the thin-wall part. When the wedge belt 2 is mounted, there are multiple contact points between wedge belts. There are also multiple contact points between wedge belt 2 and the thin-wall part 1.

For each connect point, its effect in x direction could be modelled as a spring and its effect in y direction could be modelled as a damper. Hence, assume the wedge belt 2 in x direction is rigid, then the abstract physical model of the wedge belt 2 in assembly could be modelled as Figure 3, where $K_1, K_2, \ldots, K_n$ are the rigidity of each contact point, $C_1, C_2, \ldots, C_n$ are the damping of each contact point, $m$ is the mass of the wedge belt, $x$ is the displacement of the wedge belt and the $F_I$ is the impact force.
The number of the connect points $n$ increases significantly as the connection structure is tight according to the contact theory [13]. Let the composite rigidity and composite damping of all contact points be $K$ and $C$, then the mathematical model could be simplified and formulated as Equation (1).

$$m\ddot{x} + C\dot{x} + Kx = F_i$$  \hspace{1cm} (1)

Where $x$, $\dot{x}$ and $\ddot{x}$ are the displacement, velocity and acceleration of the wedge belt respectively. Let $p^2 = \frac{k}{m}$, $q = \frac{C}{2m}$, then the Equation (1) could be written as

$$\ddot{x} + 2q\dot{x} + p^2 x = \frac{F_i}{m}$$  \hspace{1cm} (2)

since the $F_i$ is an impulse force, the Equation (2) could be solved according to literature [14], which is shown as Equation (3):

$$x(t) = e^{-q t} \frac{\bar{F}_i}{mp} \sin pt$$  \hspace{1cm} (3)

where $\bar{F}_i = \int F_i \, dt$ is the momentum of the force. The impulse response function of the contact is shown as Equation (4).

$$h(t) = e^{-q t} \frac{\bar{F}_i}{mp} \sin pt$$  \hspace{1cm} (4)

2.2. The Identification Method of the Contact Status

The rigidity $K$ and damping $C$ of the tight structure are much larger than the loose structure based on the abstract physical model of the wedge belt. According to the Equation (3) and Equation (4), as the $K$ and $C$ become larger, the $p$ and $q$ also become larger, then the displacement $x$ decreases faster. So we can observe the signal of displacement $x$, if it decrease much faster, the wedge belt joint is assembled tightly.
But it is hard for us to measure the displacement signal. The time of impact and the dynamics process is short: the time of the impact is about 100~500 us and the time of the dynamics process is about 100~500 ms, which are determined by the material. But the max response frequency of the common displacement sensor is not larger than 10 kHz and the sensor with higher frequency costs much more.

For that, we decide to use the acceleration signal, which the response function of the acceleration $\ddot{h}(t)$ could be calculated based on Equation (4):

$$\ddot{h}(t) = e^{-\gamma t} \left( \frac{a^2}{p} \sin pt - 2q \cos pt - p \sin pt \right)$$  (5)

Based on the Equation (5), the acceleration amplifier of the wedge belt also decreases much faster when the structure of the joint is tight.

In summary, we could record and observe the acceleration amplifier signal of the wedge belt in $x$ direction. When the acceleration amplifier decreases much faster than the amplifier after first impact, the wedge-belt joint is assembled tightly.

3. Experiment Setup

As illustrated in Figure 4, the experimental apparatus mainly consists of a CMT impact air cylinder, an acceleration sensor, an impact force sensor, a sampling device, a signal amplifier and a computer with sampling program.

![Figure 4. The experimental apparatus.](image)

The application of the CMT impact air cylinder and the force sensor is to maintain the impact force for comparison. The impact force is controlled in 5500 ~ 6000 N. The sampling frequency of the sensors is set as 100 kHz.

The fixture for assembly experiment are illustrated in Figure 5. The wedge belt is fixed to fixture by a pin. When the fixture is impacted by the cylinder, it make the wedge belt move. And the acceleration and impact force of the wedge belt could be reflected by the fixture.

![Figure 5. The fixture for assembly and wedge belts for experiment.](image)

Two pairs of wedge belts are applied for assembly experiment. Each pair is assembled three times and the impact force, acceleration and length $L$ (detailed in Figure 5) will be measured and recorded in each time.
To verify the identification method, the length $L$ and acceleration signal is compared. The assembly craft requires that the variation of the length $L$ could not larger than 0.2mm.

4. Result and Discussion
Following the procedure described in Section 3, we can obtain the acceleration signal and length $L$ of each test, which is illustrated in Table 1.

Table 1. The experiment results.

| No | Pair | Loose signal | Tighten signal | $L$/mm |
|----|------|--------------|----------------|--------|
| 1  | A    | ![Loose signal](image1) | ![Tighten signal](image2) | 4.599  |
| 2  | A    | ![Loose signal](image3) | ![Tighten signal](image4) | 4.634  |
| 3  | A    | ![Loose signal](image5) | ![Tighten signal](image6) | 4.614  |
| 4  | B    | ![Loose signal](image7) | ![Tighten signal](image8) | 6.420  |
| 5  | B    | ![Loose signal](image9) | ![Tighten signal](image10) | 6.388  |
| 6  | B    | ![Loose signal](image11) | ![Tighten signal](image12) | 6.271  |
The acceleration signal might contain some noise as illustrated in Table 1, but the noise could not change the shape of the signal in time domain, which means that the noise does not affect the identification result. We think that the noise is produced by the clearance between the pin and wedge belt. The result in Table 1 shows that the tighten signal could be clearly distinguished with the loose signal, which means that we can identify whether the wedge belt is loose or tight by the acceleration signal. The shapes of signal in time domain show that the acceleration decrease much faster when the structure is tight. The variation of the length $L$ of pair A and B are $\Delta L_A = 0.035mm$ and $\Delta L_B = 0.149mm$ respectively. As $\Delta L_A < 0.2mm$ and $\Delta L_B < 0.2mm$, the proposed identification method can satisfy the requirement of the assembly craft. It means that the proposed method has potential for further application.

5. Conclusion
In this paper, a dynamic feature based identification method is proposed to discriminate the assembly status of the wedge-belt joint for automatic assembly. A mathematical model for wedge belt is formulated and solved. The acceleration response is selected as the dynamic feature for identification. An experiment is designed and done, which the experimental results shows the proposed identification method is effective and could be used for further application. Further development will be undertaken in future, that of the mathematical model of the precise model of the wedge belt in assembly, that of the quantified indication method for identification, and that of the study for engineering application of the automatic assembly.

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References
[1] Wang, F. and G. Song, Monitoring of multi-bolt connection looseness using a novel vibro-acoustic method. Nonlinear Dynamics, 2020. 100(1): p. 243-254.
[2] D. P. Antonio. Methodology for fault detection in induction motors via sound and vibration signals. Mechanical Systems and Signal Processing, 2017. 83: p. 568-589.
[3] Saucedo-Espinosa, M. A., H.J. Escalante and A. Berzones, Detection of defective embedded bearings by sound analysis: a machine learning approach. Journal of Intelligent Manufacturing, 2017. 28(2): p. 489-500.
[4] Lu, S., et al., Sound-aided vibration weak signal enhancement for bearing fault detection by using adaptive stochastic resonance. Journal of Sound and Vibration, 2019. 449: p. 18-29.
[5] Alatorre, D., et al., Closed loop force control of in-situ machining robots using audible sound features. Mechanical Systems and Signal Processing, 2020. 136: p. 106517.
[6] Yun, D. and S. Lee, Objective evaluation of the knocking sound of a diesel engine considering the temporal and frequency masking effect simultaneously. Journal of Sound and Vibration, 2017. 397: p. 282-297.
[7] Li, W., J. Sun and J. Yu, Analysis of dynamic characteristics of a multi-stage gear transmission system. Journal of Vibration and Control, 2019. 25(10): p. 1653-1662.
[8] Meng, D., et al., Dynamic modeling and vibration characteristics analysis of flexible-link and flexible-joint space manipulator. Multibody System Dynamics, 2018. 43(4): p. 321-347.
[9] Meng, Z., G. Shi and F. Wang, Vibration response and fault characteristics analysis of gear based on time-varying mesh stiffness. Mechanism and Machine Theory, 2020. 148: p. 103786.
[10] Ye, S., et al., A theoretical dynamic model to study the vibration response characteristics of an axial piston pump. Mechanical Systems and Signal Processing, 2021. 150: p. 107237.
[11] Poursina, M. and P. Nikravesh, Characterization of the Optimal Damping Coefficient in the Continuous Contact Model. Journal of Computational and Nonlinear Dynamics, 2020. 15(9).
[12] Fu, X., et al., An efficient method for the dynamic analysis of planetary roller screw mechanism. Mechanism and Machine Theory, 2020. 150: p. 103851.
[13] H. Cao. Based on the Ubiquitiform Theory Method to the Contact Stiffness of Mechanical Joint
Surface Studied. Master Degree Essay. Xian University of Science and Technology. 2018.

[14] C. Sisemore and V. Babuska. The Science and Engineering of Mechanical Shock. Springer Nature Switzerland. 2020. p. 58-81.