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Development of a high speed and precision wire clamp with both position and force regulations

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A B S T R A C T

This paper presents the mechanism and robust control of a monolithic wire clamp to achieve fast and precision operations for strong and robust micro device packaging. The wire clamp is piezoelectrically actuated and a two-stage flexure-based amplification was designed to obtain large and parallel jaw displacements. The grasping forces of the wire clamp were evaluated based on finite element analysis (FEA), and the force measurement was presented. The wire clamp was manufactured using wire EDM technique and the position and force transfer functions were obtained based on the frequency response approach. The position/force switching control strategy was employed to regulate the motion position and grasping force, and the position/force switching controller composed of a PID controller for position control and a sliding model controller (SMC) for force control was designed. Experimental tests were carried out to investigate the performance of wire clamp with the position/force switching controller during the grasping and releasing operations. The results show that the wire clamp exhibits good performance and demonstrate that high speed and precision grasping operations can be realized through the developed wire clamp and the control strategy.

1. Introduction

Recently with the rapid development of microelectronic industries, the demand for electronic products with high pin-count IC installations and high assembly density has been increasingly growing [1–3]. As an important cost-effective and flexible interconnecting technology for micro device packaging, thermosonic wire bonding has been widely used for the microelectronic packaging of nearly any type of daily used electronic products [4]. Automatic wire bonders are important equipments for wire bonding, and high performance wire bonders are required to produce smaller pad size and finer pitch of microelectronic products in extreme conditions [5,6].

As an important component of automatic wire bonders, wire clamps perform high-frequency open and close operations during wire bonding process, and thus the characteristics of wire clamps can directly affect the packaging quality and efficiency [7]. During the extreme motion with short strokes and high acceleration [8,9], there will be some undesired disturbances to the wire and wire clamps, affecting the motion of the clamps, which will further have influence on the bonding quality. As a result, it is necessary to develop high performance wire clamps with a novel mechanism and robust controller to provide stable and high speed microelectronic wire bonding.

In the literature, there are some research reported on the wire clamps, most of which mainly focused on the wire clamp actuators and mechanisms, and little attention has been paid to their position/force control issues. The presently used wire clamps usually adopt electromagnetic and piezoelectric actuators as drivers, and they can realize position tracking using position feedback control. However, few of them have a real-time grasping force controller [10,11]. Even if the grasping forces of some clamps were regulated, the grasping force control was mainly carried out in indirect ways, such as through the installation of preload springs or force calibration, making it difficult to achieve real time and precision force control. However, the robust position/force control is of great importance for the wire clamps to achieve robust and precision grasping and releasing operations.

The position/force control has been receiving considerable attention from the researchers. Impedance control strategy can be used to indirectly regulate the force using a single controller through establishing the dynamic relation between the force and position or velocity. However, the environmental conditions of wire clamps for thermosonic wire bonding are not always certain, which makes it difficult to accurately control the force using the indirectly control approach [12,13]. Through hybrid position/force

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control scheme, the grasping and releasing operations can be implemented by controlling the position of the clamp jaws and monitoring the contact forces at the same time, but the control performance largely depends on the division of force and position subspaces, which requires to accurately identify the environmental constrains [14]. To overcome this issue, intelligent control methodologies, such as fuzzy and neural network control, have been proposed to control forces [15,16]. However, the calculation amount becomes larger and the practical implementation process becomes more complicated. Hence, a simple yet efficient approach is desirable to realize the stable and precision force/position control of wire clamps.

Intuitively, a position/force switching control can be used to regulate the grasping jaw position and contact force alternately [17,18]. As for the control scheme, proportional-integral-derivative (PID) controllers have been widely used in industrial applications. However, traditional PID control can not accomplish the wire clamp position/force regulation, because there may be high-frequency dynamic force vibrations when the jaw contacts with the object during the fast grasping and releasing operations. Some advanced control theories including the robust control [19], adaptive control [20], iterative learning control [21] and neural networks control [22], were presented to control precision positioning systems, which show appropriate level of performance. However, their applications are limited in the fast and precision wire clamp control because of the computationally expensive calculations [23]. Sliding mode control has the advantages of fast response and strong robustness for the disturbances, and thus exhibits great potential for the control of high-speed precision wire clamps [24].

This paper presents the mechanism and robust position/force switching control of a novel monolithic piezoelectric actuated wire clamp. Firstly, the mechanism of the wire clamp is introduced. The grasping force is investigated based on finite element analysis (FEA), and the grasping force measurement is presented. The dynamic models of position and force are obtained through frequency response approach, based on which the position/force switching controller, composed of a PID position controller and a sliding model force controller, is designed. The wire clamp is fabricated, and experimental tests are carried out to investigate the performance of the wire clamp and controller.

2. Mechanism and grasping force investigation

2.1. Configuration of the wire clamp

Fig. 1 shows the mechanical structure of the piezoelectric actuated flexure-based wire clamp consisting of a stack piezoelectric ceramic actuator (SPCA), a pair of grasping jaws, a pair of flexible beams, a preload bolt, a base and a flexible motion transmission mechanism designed as a two-stage amplification including a homothetic bridge type mechanism and a parallelogram leverage mechanism. The SPCA is connected with the flexible motion transmission mechanism by the preload bolt at one end of the SPCA, and the preload force to the SPCA can be adjusted by the bolt. Both of the grasping jaws connected with the motion transmission mechanism through two flexible beams, and because of the space limit, a stain gauge is adopted and surface bonded on the left flexible beam to measure the grasping force during the grasping and releasing operations. In order to avoid shear force and bending torque acting on the actuator, the wire clamp is designed symmetrically along the longitudinal axis of the SPCA. Due to the symmetric architecture, the measurement of a single flexible beam is sufficient. A stain gauge is glued on the base end of the flexible beam where is the maximum stress point under the

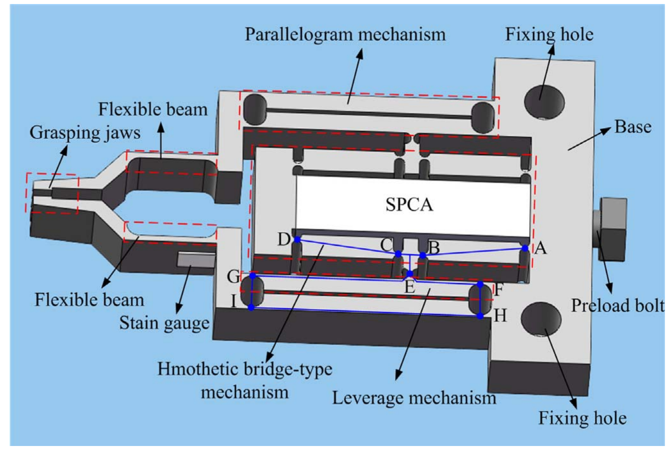

Fig. 1. The mechanism of the wire clamp.

grasping force to generate a high sensitivity and high signal/noise ratio.

Through the two-stage amplification, the motion transmission and displacement amplification from the SPCA to the grasping jaws are realized. As the first-stage amplification the homothetic bridge-type mechanism is composed of a connecting rod mechanism (A-B-C-D) based on double-notch circular flexure hinges, and its working principle is that once actuated with an input displacement, the device produces two vertical output displacements towards the SPCA. In order to obtain a large displacement amplification ratio, a leverage mechanism (E-F-G) integrated within a parallelogram mechanism (F-G-H-I) at each side of the wire clamp is designed as the second-stage amplification connected with the homothetic bridge-type mechanism by two flexure hinges. Through the parallelogram mechanism pure jaw translations can be realized, thus avoiding the sliding between the wire and jaws during the operations, and more stable and firm wire grasping can be ensured due to the fact that the grasping force will act normal to the wire compared with the angular grasping mode.

In order to grasp a wire, a voltage should be applied to the SPCA to make it expand and push the homothetic bridge-type mechanism (A-B-C-D); then the homothetic bridge-type mechanism will pull the leverage mechanisms (E-F-G-H-I), which causes the grasping jaws to close to grasp the manipulated wire. After power is switched off, the SPCA retracts to its initial position, causing the grasping jaws to open and release the manipulated wire.

2.2. Kinematic analysis of the wire clamp

There are various approaches to model a compliant mechanism, such as the pseudo rigid body (PRB) method [25], the compliance matrix method [26], the finite element (FE) method [27] etc. PRB method is utilized to analyze the kinematic characteristics of the wire clamp. Due to the symmetric architecture, only half of the wire clamp is considered and the kinematic model is established as shown in Fig. 2, where i (i=A, B… J) denotes the rotational centers of flexure hinges. From Fig. 2 it is can be seen that A-B-C-D-E-F is equivalent to a six-bar linkage mechanism with one degree of freedom. Based on the geometric and motion relationships the following equations can be get:

$$l_{AB}e^{i\varphi_1} + l_{BC}e^{i\varphi_2} + l_{CD}e^{i\varphi_3} = se^{i\pi/2} \tag{1}$$

$$l_{AB}e^{i\varphi_1} + l_{BE}e^{i(\varphi_2+\alpha)} = l_{AF}e^{i\beta} + l_{EF}e^{i\varphi_4} \tag{2}$$

where s is the distance between the flexure hinges A and D, α is