Modelling of Pretravel for Touch Trigger Probes on Indexable Probe Heads on Coordinate Measuring Machines

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This paper presents a pretravel model for touch trigger probes mounted on indexable probe heads, which can rotate and tilt the probe into a number of orientations for coordinate measurements on coordinate measuring machines (CMMs). Pretravel accounts for the majority of touch trigger probe errors and is caused by bending deflection of the stylus shaft. A trigger force model is derived and used to model bending deflection of the stylus shaft at the trigger instant. Only one model parameter needs to be calculated using the probe calibration data. Experimental data associated with thirteen probe orientations were used to validate the model. It is shown that the model can effectively predict pretravel distances associated with various probe approach directions. The standard deviations of prediction errors are less than 0.71 \(\mu m\), indicating that the proposed model can be used to compensate for pretravels occurring in touch trigger probe applications.

Keywords: Coordinate measuring machine; Indexable probe head; Pretravel; Touch trigger probe

1. Introduction

Touch trigger probes are a key technological innovation in coordinate metrology in modern manufacturing processes and systems. The vast majority of probes used on coordinate measuring machines (CMMs) are touch trigger probes [1–3]. Touch trigger probes have also been used on four- and five-axis machine tools [4–6]. A probe has become one of the basic building blocks for unattended machining in manufacturing cells and systems. Probes can be used to detect errors in part set-up, part fixtureing, improper tool use and tool wear, etc.

However, there are errors associated with touch trigger probe applications. Lobing or pretravel variation is a well-known type of error occurring in touch trigger probe applications [7–9]. Most touch trigger probes employ a kinematic seating mechanism for the probe stylus. A trigger signal is generated when the probe stylus touches the workpiece in the measurement process and the signal initiates a record of an \((x,y,z)\)-coordinate point on the workpiece surface where the probe stylus touches. In fact, the trigger signal is not generated at the touch instant. The probe continues to travel in the probe approach direction and the stylus continues to be deflected until a probing force (on the probe stylus) is large enough to initiate the trigger signal at the trigger instant. Pretravel is the distance travelled by the probe between the touch instant and the trigger instant during the probing process. Pretravel is mainly caused by bending deflection of the stylus shaft and accounts for the majority of touch trigger probe errors [10,11]. Pretravel has a direction-dependent characteristic in that the probing forces and pretravel distances vary in different probe approach directions [11]. Hysteresis and repeatability are other types of probe errors associated with touch trigger probe applications [12].

Errors introduced by touch trigger probes remain largely uncompensated for, although there have been attempts to do so [7]. Methods commonly used to deal with probe lobing include probe calibration (probe datuming) and error mapping. Unfortunately, both these methods, as applied, are not effective in reducing probe pretravel or probe lobing in touch trigger probe applications. There are new probe designs incorporating sensors, such as strain gauges, which reduce pretravel in measurement processes [11]. However, operation reliability, cost, and compatibility with current machines (extra interface and control boxes may be needed) are essential for widespread application of these probes.

There is a need for a model which can predict probe pretravel by taking its causes into account. This motivation has stimulated research into pretravel models for touch trigger probes. Estler et al. [13,14] have developed a multi-parameter pretravel model accounting for the combined effects of rotational displacement, bending displacement, and frictional effects. Shen and Zhang [15,16] have developed pretravel models accounting for bending of the stylus shaft for vertically and horizontally oriented touch trigger probes. This paper presents a general pretravel model for touch trigger probes mounted on indexable probe heads, which can rotate and tilt the probe (and the stylus) into a number of orientations by indexing a number of angular increments (e.g. 7.5° per increment) in two axes (rotation and tilt). There are motorised and
manual indexable probe heads. The probe orientations achieved by such probe heads are referred to as general orientations. In this paper, we use a trigger force model and a cantilever beam assumption (treating the stylus shaft as a cantilever beam) to model bending deflection of the stylus shaft at the trigger instant. Only one model parameter needs to be calculated using the probe calibration data. Probing data for a commonly used 5-way three-dimensional (3D) probe with a 50 mm straight stylus extension used on a direct computer-controlled (DCC) CMM were used to show the prediction effectiveness of the proposed model. Experimental data associated with the thirteen (13) probe orientations were used to validate the model. The standard deviations of prediction errors are less than 0.71 μm, indicating that the proposed model can be used to compensate for pretravels occurring in touch trigger probe applications.

2. Pretravel Model

Probe pretravel results from stylus shaft deflection caused by the probing force between the probe tip and the workpiece in the measurement process. Shen and Zhang [16] used the principles of mechanics and a threshold contact force assumption to derive trigger force models for vertically and horizontally oriented touch trigger probes with straight styli. The trigger force models have been used to derive pretravel models by treating the probe stylus as a cantilever beam. In this paper, we derive the general pretravel model by extending the horizontal pretravel model.

The following is a brief description of contact forces between the tripod and the kinematic seating mechanism for horizontally oriented probes [16]. The free body diagram of the tripod-stylus structure in a horizontally oriented probe with straight styli is shown in Fig. 1. The Cartesian coordinate system defined in Fig. 1 is the probe coordinate system. The spring force, $F_s$, acts in the $-Z$-direction to hold the tripod in its rest position until the tripod is tilted causing the trigger signal to be generated in the measurement processes. The weight of the tripod-stylus structure, $W$, acts downward, and $\phi_w$ defines the angle between the direction of $W$ and the tripod leg $C$ (from $W$ to leg $C$, from $+X$ to $+Y$ is defined as positive), $R$ is the tripod leg length, $l_w$ defines the location of the centre of gravity of the tripod-stylius structure, and $l$ is the stylus length. There are six contact forces ($F_{A1}$, $F_{A2}$, $F_{B1}$, $F_{C1}$, $F_{C2}$, and $F_{C3}$) at the six contact locations between the tripod and the kinematic seating arrangement. Each tripod leg ($A$, $B$, $C$) is supported by two contact forces. The directions of the six contact forces can be obtained by analysing the orientations of the tripod legs and the supporting cylinders. We use a kinematic support angle, $\alpha$, to describe the contact force direction. Friction is assumed to be negligible. The probing force, $F_p$, is the force between the probe tip (a stylus ball) and the workpiece. Before the probe touches the workpiece, $F_p$ equals zero. When the probe tip touches the workpiece, before the trigger signal is generated, $F_p$ has a magnitude greater than zero. The direction of $F_p$ is opposite to the probe approach direction and can be described by $\theta$ (polar angle) and $\phi$ (azimuthal angle) as shown in Fig. 1. The six contact forces can be derived by solving the six equilibrium equations (three force equilibrium equations and three momentum equilibrium equations) expressed as follows:

\[
F_{A1} = \frac{F_s}{6 \sin \alpha} + \frac{F_p}{6 \sin \alpha R} \frac{l}{6 \sin \alpha R} (\cos \phi - \sqrt{3} \sin \phi) - \frac{\cos \theta}{6 \sin \alpha} + \frac{\sin \theta}{6 \cos \alpha} (\sin \phi + \sqrt{3} \cos \phi) \\
+ W \left[ \frac{l}{6 \sin \alpha R} (\cos \phi_w - \sqrt{3} \sin \phi_w) + \frac{1}{6 \cos \alpha} (\sin \phi_w + \sqrt{3} \cos \phi_w) \right]
\]

\[
F_{A2} = \frac{F_s}{6 \sin \alpha} + \frac{F_p}{6 \sin \alpha R} \frac{l}{6 \sin \alpha R} (\cos \phi + \sqrt{3} \sin \phi) - \frac{\cos \theta}{6 \sin \alpha} + \frac{\sin \theta}{6 \cos \alpha} (\sin \phi + \sqrt{3} \cos \phi) \\
+ W \left[ \frac{l}{6 \sin \alpha R} (\cos \phi_w - \sqrt{3} \sin \phi_w) - \frac{1}{6 \cos \alpha} (\sin \phi_w + \sqrt{3} \cos \phi_w) \right]
\]

\[
F_{B1} = \frac{F_s}{6 \sin \alpha} + \frac{F_p}{6 \sin \alpha R} \frac{l}{6 \sin \alpha R} (\cos \phi + \sqrt{3} \sin \phi) - \frac{\cos \theta}{6 \sin \alpha} + \frac{\sin \theta}{6 \cos \alpha} (\sin \phi - \sqrt{3} \cos \phi) \\
+ W \left[ \frac{l}{6 \sin \alpha R} (\cos \phi_w + \sqrt{3} \sin \phi_w) + \frac{1}{6 \cos \alpha} (\sin \phi_w - \sqrt{3} \cos \phi_w) \right]
\]

\[
F_{B2} = \frac{F_s}{6 \sin \alpha} + \frac{F_p}{6 \sin \alpha R} \frac{l}{6 \sin \alpha R} (\cos \phi + \sqrt{3} \sin \phi) - \frac{\cos \theta}{6 \cos \alpha} - \frac{\sin \theta}{6 \cos \alpha} (\sin \phi - \sqrt{3} \cos \phi)
\]