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Paper

AUTOMATIC CONTROL OF CUTTING SPEED FOR CURVILINEAR CUTTING

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ABSTRACT

The cutting paths of memory cards are curvilinear not straight; the cutting speeds with abrasive suspension jet (ASJ) for curvilinear cutting have to be changed along the path. The speed variation may cause the x-y table motor vibration that results in the cutting edge quality badly. The cutting accuracy of ASJ for curvilinear cutting is depended strongly on the smooth cutting speed. The paper explores the way for automatic control of cutting speed for curvilinear cutting to insure the cutting with high precision. It analyzes the cutting speed variation along the cutting path and then describes the relationship between the speed and acceleration. Next, it describes the x-y table motor characteristic to clarify why a consistent desired cutting speed cannot be reached. At last, it explores our way how to reach a smooth cutting speed to insure the curvilinear cutting with high precision to meet the requirement of semiconductor manufacturing.

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1. INTRODUCTION

The concept of cutting speed (v) of abrasive suspension jet (ASJ) singulation can be defined as the rate of nozzle movement on the microelectronic chip irrespective of direction; it is equal to distance traveled divided by travel time. So, the cutting speed is here a scale quantity which refers to “how fast the nozzle is moving on the chip”. A fast-moving nozzle has a high speed while a slow-moving nozzle has a low speed.

The cutting path means the route along which the nozzle travels. The cutting paths of microelectronic chips with ASJ singulations are determined by the shapes of the microelectronic chips, and are curvilinear not straight, Figure1.

It would be desirable to perform a continuous cutting path with a constant high speed throughout the entire path. Everyday experience motion, defined as the act or process of changing position or place, along a curved path reminds us it is often necessary to slow down for corners, and the speed has to be changed along the curvilinear path. Same as vehicle motion, moving nozzle cannot travel with changing speeds erratically at the corners. In physics, whenever the speed, direction, or both is changed, a change in rotational motion will cause a “rotational force” called a torque or a moment. All motors have some torque/force limitations. Generally force is proportional to the speed change this implies that we must live within a limitation based on motor characteristics. Otherwise, the change may cause the motor vibration that result in the cutting edge quality badly.

The paper explores the way for automatic control of cutting speed for curvilinear cutting to insure the cutting with high precision. It analyzes the cutting speed variation along the cutting path and then describes the relationship between the speed and acceleration. Next, it describes the x-y table motor characteristic to clarify why a consistent desired cutting speed cannot be reached. At last, it explores our way how to reach a smooth cutting speed to insure the curvilinear cutting with high precision to meet the requirement of semiconductor manufacturing.

2 NOZZLE MOTION ALONG A CURVED PATH

Nozzle motion along a curved path is a curved motion; the nozzle velocity, both a direction and a speed, will necessarily be changing as the nozzle moves. The change is called acceleration and must be tied to a force. Newton's laws of motion explain this. Therefore, whenever a nozzle travels in a curved path with/without a change in speed, there must be unbalanced force acting upon it since its direction is changing.

2.1 Speed Variation

Ferris driver has to slow down to pass the corners and speed up to reach the desired speed again though he tries to maintain his car with a constant high speed when going around the curved path. Obviously, the driver changes the car speed according to the curvature of the path, the car motion could be described with a sequence of circular motions of different radii; the speed is in proportion to the radius of curvature, Figure 2. Clearly, the circular segment with the smallest radius represents the maximum curvature; curvature and radius of curvature are inverse to each other, the speed is in proportion to the radius of curvature.

Figure 3 shows the nozzle motion along the curvilinear path of the microelectronic chip, the speed is represented by the radius of motion circle. Same as car motion, moving nozzle cannot change its speeds over a very short time erratically, and has to change the speed smoothly from the straight line section to the corner and from the corner to the straight line section. The speed is not in proportion to the radius of curvature of path exactly.

2.2 Acceleration

Both the speed and direction of the velocity are changing along the curved path in nozzle motion, Figure 3. The change is named acceleration, which includes two components, Figure 4.

- **Radial acceleration (A_r):** must be

$$A_r = {v^2}/{r} \tag{1}$$

in the direction of r, where r is the radius of curvature of the path and v is the speed of the nozzle. The **radial acceleration** contributes only to the change in direction of the nozzle since it is perpendicular to the path and therefore can not affect the speed of the nozzle along the path.

- **Tangential acceleration (A_t):** is the derivative of the velocity at the given point:

$$A_t = {\Delta v}/{\Delta t} \tag{2}$$

that contributes the change of speed of the nozzle in the direction of travel. The direction of **tangential acceleration** could be decided with a simple rule of thumb: a nozzle which is slowing down will have a **tangential acceleration** directed in the direction opposite of its motion. Applying this *rule of thumb* would lead us to conclude that a moving nozzle can have a backward directed **tangential acceleration** if the nozzle is slowing down when traveling from a straight line section to a corner, and have a forward directed acceleration if the nozzle is speeding up when traveling from a corner to a straight line section. Figure 4 illustrates these acceleration components on the curved path when a nozzle is moving toward x direction.

2.3 Force

Newton's laws of motion claimed that the acceleration must be tied to a force accord. Whenever a nozzle travels along a curved path with the change in speed and direction, there must be unbalanced force acting upon it.

The **radial acceleration** is caused by a **centripetal force** which is composed of the mass and **radial acceleration** and pulls the moving nozzle towards the center of the curved path. Without the force, the nozzle would move inertial in a straight line according to Newton's first law of motion.

The magnitude of the **tangential acceleration** is not equal to zero because the speed is non-zero and changing during the nozzle motion. There must be forces that act on the nozzle to cause the speed changing in addition to the **centripetal force**. These forces include the weight and others forces due to the environment the nozzle is in such as friction and inertia.

3 X-Y TABLE MOTOR

The nozzle motion is controlled by an x-y table motor in water jet singulation system, and there is an interaction between the nozzle and the x-y table motor. Newton's third law, "For every action, there is an equal and opposite reaction.", states that in every interaction, there is a pair of forces acting on the two interacting objects. The magnitude of the forces on the nozzle equals the force on the x-y table motor; the direction of the force on the nozzle is opposite to the direction of the force on the motor. Forces always come in pairs - equal and opposite action-reaction force pairs.

The weight of a nozzle is very lower, and a high operating speed may be possible. However, all motors have some force/torque (defined by linear force multiplied by a radius) limitations. When the nozzle operating speed is very high or the velocity of the nozzle is changed suddenly, the force/torque limitation of the mechanical system may be approached, structural vibrations, or *ringing*, can be induced. This oscillation will lessen the effective torque and may result in loss of synchronization between the motor and controller, and results in the bad cutting quality.

4. AUTOMATIC CONTROL OF CUTTING SPEED

Generally force is proportional to acceleration, which implies that we must live within an acceleration limitation based on motor characteristics. This requires bounding both **tangential acceleration** and **radial acceleration** if there is a constraint on the amount of force/torque available.

4.1 Trapezoidal Motion Profile

In order to achieve smooth high speed motion without over-taxing the motor, the allowable acceleration and deceleration times must be increased, and the motor has to be directed to change velocity judiciously to achieve optimum results. Figure 5 shows the principle to limit the accelerations and decelerations required. Graphing velocity versus time results in a trapezoidal plot. When accelerating/decelerating, the velocity changes in a linear manner until it reaches the requested velocity.

The trapezoidal profile changes velocity in a linear fashion until the target velocity is reached. Though it is adequate for most applications, it may cause some system disturbances at the “corners” that translate in small vibrations which extend the settling time. The microelectronic chip cutting sensitive to this phenomenon, we modify the velocity profile with an S shape during the acceleration and deceleration periods, which minimizes the vibrations caused in a mechanical system by a moving mass.

4.2 Automatic Control of Cutting Speed

Same as the traffic road, we place a series ‘markers’ along the curvilinear path, which ‘markers’ indicate the speed limitation. For example at the beginning of a radius there is a marker which can be thought of as a speed limit sign on a road indicating that the corner best be handled at a particular speed and no faster. These speed limit signs represent speed limits along the path based on the geometry of the path and the acceleration settings of the motors.

During the execution of the path, the controller dynamically **looks ahead down the road**, much as a driver might, to see these speed limit signs. As a requirement to reduce speed is foreseen, the controller judges when it must start decelerating so as to have achieved the **reduced speed** by the beginning of the radial feature that requires it. This prevents the controller from beginning a radial feature at excessive speed. In this manner the **radial accelerations** are respected and when given the opportunity (such as a straight away departure from a radial feature) the **tangential acceleration** speeds up the motion to accomplish as much speed as possible before another acceleration limiting feature. Deceleration and acceleration is accomplished with a trapezoidal velocity profile. The following gives one example.

Supposed the Cut Path includes two Arcs and one Line; the radii of Arc AB and CD are R_{AB} and R_{CD} respectively, the length of Line BC is S Figure 6. Based one motor characteristics, the maximum speed of nozzle is $V_{\max}$ and the acceleration limitation is A.

Nozzle motion follows from point A to point D. When moving at points B and C, the speeds of nozzle are $V_{AB} = \sqrt{A \times R_{AB}}$ and $V_{CD} = \sqrt{A \times R_{CD}}$ respectively based on the Equation 1. When traveling from point B to point C, the nozzle speeds up with a **tangential acceleration**, A, to reach the desired speed $V_{\max}$ at point m_i, moves from point m_i to point m_j with a constant speed $V_{\max}$, and slows down with a **tangential acceleration** $, -A$, to reach the speed V_{CD} so to pass Arc CD safety.

Suppose the length of Line Bm is S_m. According to the relationship among the speed, acceleration, and distance, the speeds of Line Bm and Line mC will be:

$$V_{Bm} = \sqrt{V_{AB}^2 + 2 \times A \times S_m} \qquad (B, m)$$

$$V_{mC} = \sqrt{V_{CD}^2 + 2 \times A \times (S - S_m)} \qquad (m, C)$$

At the point m, the nozzle gets the maximum speed:

$$V_m = \sqrt{\frac{V_{AB}^2 + V_{CD}^2}{2} + A \times S}$$

- If $V_m <= V_{\max}$, the nozzle speeds up when moving from point B to point m, and slows down from point m to point C. The nozzle does not reach its desired speed along the straight line path; the length of speeding up section is:

$$S_m = \frac{V_{AB}^2 + V_{CD}^2}{4 \times A} + \frac{S}{2}$$

- If $V_m > V_{\max}$, the nozzle speeds up from point B to reach the desired speed $V_{\max}$ at point m_i, moves from point m_i to point m_j with a constant speed $V_{\max}$, and slows down from point m_j to reach the speed V_{CD} at point C. The lengths of speeding up section (S_{Bmi}) and of slowing down section (S_{mjC}) will be respectively:

$$S_{Bmi} = \frac{V_{\max}^2 - V_{AB}^2}{2 \times A}$$

$$S_{mjC} = \frac{V_{\max}^2 - V_{CD}^2}{2 \times A}$$

5. CONCLUSION

Despite be desirable to perform a continuous cutting path with a constant high speed, the nozzle motion has to undergo changes in speed throughout the entire curvilinear path. We present a way for automatic control of cutting speed for curvilinear cutting to reach the cutting with high precision. The method applies looks ahead down road principle, much as a driver might, to adjust the cutting speed along the path. Within bounding both acceleration and speed that are based on the constraint of the force/torque of the motor, the controller adjusts the cutting speed according to the feature of the path dynamically and smoothly. With the way, ASJ singulation insures the curvilinear cutting with high precision to meet the requirement of semiconductor manufacturing.

6. FIGURES

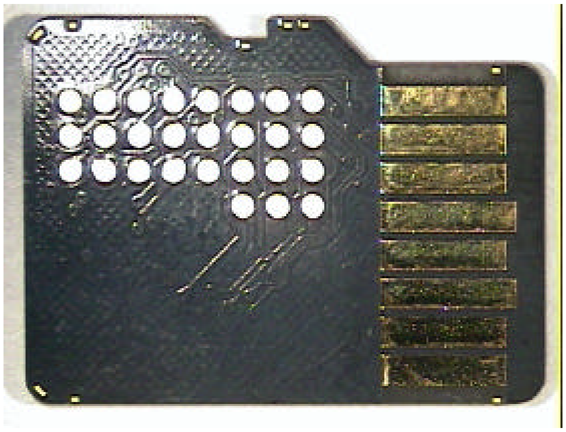

Figure 1 Memory Card Singulated with ASJ Singulation

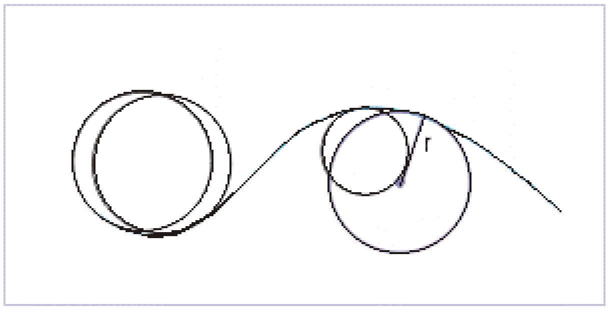

Figure 2 Motion along a curved path with a constant speed. The speed is in proportion to the radius of curvature.

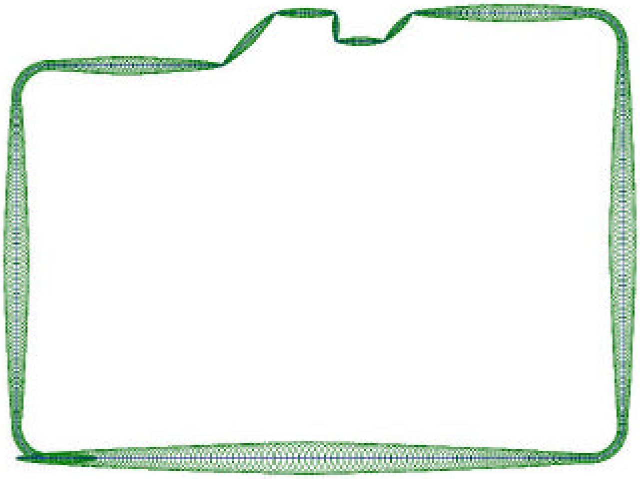

Figure 3 Nozzle motion along a curvilinear path. The speed is represented by the radius of motion circle, and not in proportion to the radius of curvature exactly.

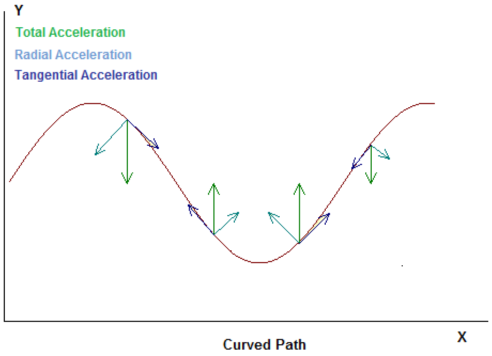

Figure 4 The Curved Path display illustrates these acceleration components. The magnitude of the radial component of the total acceleration, shown in green, is $^{v^2}\!/_{r}$. The magnitude of the tangential component of the total acceleration, shown in blue is the rate of change of the speed, $^{\Delta v}\!/_{\Delta t}$.

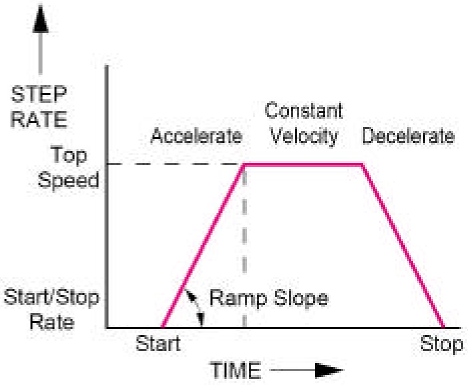

Figure 5 Trapezoidal motion profiles are required to obtain higher speeds without skipping steps or stalling.

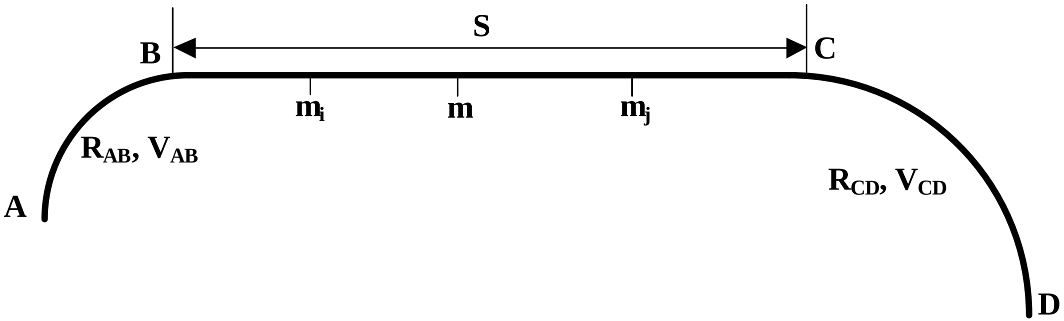

Figure 6 One example cut path