MODELING AND CONTROL OF AN AIR JET BASED VIBRATORY BOWL FEEDER ORIENTING SYSTEM

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ABSTRACT: Vibratory bowl feeders are widely used in industry for feeding and reorienting small parts in high volume production. Standard vibratory bowl feeder tooling consists of various mechanical barriers inserted in the bowl path which are prone to jamming and limit the feeder to only one type of part. Programmable feeders have been developed to improve the flexibility of these devices, however feed rates are often low.

This research describes a novel air jet based computer controlled orientation system that can handle a wide range of parts at high feed rates with no jamming. The system consists of air jet tooling controlled by a computer algorithm. The control algorithm accepts the part’s weight, geometry, and its orientation. It then compares the present with the desired orientation and delivers the appropriate pulse of air to produce the desired orientation. The modeling of the air jet is discussed in this paper as well as some preliminary performance results for this novel feeder.

INTRODUCTION

Part feeders are devices that orient parts for production operations. They can be divided into two major groups: vibratory and non-vibratory. A typical vibratory bowl feeder (VBF) is comprised of a shallow cylindrical bowl supported by several leaf springs attached to a cylindrical base containing an electromagnet. Inside the bowl is an inclined helical track. The cycling of the electromagnet causes the bowl to vibrate and the parts to move along the track either by sliding or hopping.

The conveying velocity of a part moving along the track depends on the amplitude of the track vibration $a_0$, the track inclination angle $\theta$, the angle between the track and its line of vibration $\psi$, the effective coefficient of friction between the part and the track, the total mass of parts in the bowl $[1,2]$, the vibration frequency of the bowl $f_b$, the natural frequency of the bowl $f_n [1,2,3]$, the stiffness of the leaf springs $k [4]$, the shape of the electromagnetic and vibration waves $[5,6]$, geometric characteristics of the part, the orientation of the part with respect to the track $[7]$, and the number, sequence and type of orienting devices.

The orienting devices can be classified as either active or passive. Passive devices reject parts with non-desired orientations by guiding them off the track and back into the bowl. A possible disadvantage for the use of passive devices is that they reduce feed rate. Active devices manipulate
the part into the desired orientation instead of returning the part back to the bottom of the bowl. This reduces potential damage to parts and improves feed rate.

**BOWL TOOLING RESEARCH**

One problem with conventional VBF tooling is that it often causes part jamming which disrupts feeder output. Attempts at making this tooling programmable [8] still encounter the same problem of jamming. The Programmable Silhouette Recognizer (PSR) [9] was an early attempt to use sensors and an air jet tool as a passive orienting device. The problems the PSR system faced were low throughput due to the use of a passive tool and the system’s inability to deal with stacked, overlapping or contiguous parts and only relatively simple geometries were distinguishable.

Further development of the PSR system solved the problems of contiguous and overlapping parts. The part resolution was improved and the speed of the recognition and decision making portion of the system was increased [10], however feed rates remained low.

Cronshaw et al [11] developed a flexible assembly module using a vibratory bowl feeder, pusher, belts and a camera. This assembly system represented an early attempt to design active tooling coupled with a vision system.

In this research a set of active orienting devices were developed that could be made programmable for feeding different parts using active air jet tooling to eliminate jams and improve bowl throughput [12].

**AIR JET BASED TOOLING EQUIVALENCE EXAMPLE**

Figure 1 shows a set of air jet based active tools which can be used to replace a sequence of mechanical tools. As rectangular parts encounter the wiper blade in Figure 1-a, the stacked or overlapping parts are rejected. The air jet in Figure 1-b at the bottom performs the same function. Its operation does not depend on sensing inputs, though its performance can be verified by using a sensor array embedded in the track.

The narrow track discriminates between the length and width of a part. An air jet placed in the track wall and close to the track surface performs the same function. This however requires sensor information to select the correct parts for rejection. Finally, a roll up (an active tool) reorients parts to their final orientation. The same function is performed by an air jet placed in the track of the bowl.

**MATHEMATICAL MODEL OF PART MOTION**

For a part on the track in orientation \( a \) [Figure 2], an active device would reorient the part to orientation \( b \). The orienting device must exert a force on the parts passing it. The device could be used as a passive device if the reorientation was unsuccessful. In this mode the parts would be returned to the bottom of the bowl.

When the part is reoriented into orientation \( b \) its center of gravity has traveled an angular distance of \( 0^\circ \) with respect to the bowl coordinate system, while traveling an optimum distance \( s \) in X direction, \( 0 \) in Y direction, and rotating \( \theta = 90^\circ \) CCW around the z-axis of the part coordinate system.
According to the part geometry shown in figure 3 the path $s$ is equal to

$$s = \frac{\sqrt{l^2 + w^2} - w}{2}$$

(1)

The origin of the part coordinate system can be represented in the bowl coordinate system by a vector and its final position/orientation can be obtained from the transformation matrices.

The pulse of air from the air jet orients and repositions the part a distance of about $(\sqrt{l^2 + w^2} - l)/2$ away from the bowl wall. The centrifugal force exerted by the VBF then moves the part back into contact with the wall.

Knowing the part geometry the optimal part trajectory can be calculated. For example when length $l = 1$ cm and a width $w = 0.5$ cm the trajectory $s$ is 0.309 cm.
If the air jet exerts too large of a force on the part, then there is an additional radial component in the center of gravity path equation. If this component places the center of gravity beyond the inner edge of the bowl track, the part would be returned back to the bowl. Also, too large of a force exerted by the air jet may cause over-rotation of a part that results an incorrect orientation.

Figure 3: Simplified snapshot of part position/orientation
From figure 3, if the point A is to stay in contact with the bowl wall and move along the x-axis, the following condition should be satisfied

\[ v_1 = v_2 \cos(\alpha + \theta) \]  

(2)

Where,

\[ \alpha = \arctan\left(\frac{w}{l}\right) \]  

(3)

and \( \theta \) is the angle of rotation about the center of gravity.

![Free body diagram for a rectangular part](image)

Observing the free body diagram in figure 4 we can sum the forces and the moments with respect to the center of gravity as

\[ F_a + F_w - \mu mg = ma \]  

(4)

\[ F_a l_1 - F_w l_3 - \mu mg l_2 = I\dot{\omega} \]  

(5)

where \( F_a \) is the force of the air jet, \( F_w = F_{wy} \) the reactive force exerted by the bowl wall on the part, \( m \) the mass of the part, \( \mu \) coefficient of friction between the part and the bowl track,

\[ l_1 = \frac{l}{2} \]  

(6)

the torque arm for the force of the air jet,

\[ l_2 = \frac{1}{lw} \int_{\frac{w}{2}}^{\frac{l}{2}} \int_{\frac{w}{2}}^{\frac{l}{2}} \sqrt{x^2 + y^2} \, dx \, dy \]  

(7)

the equivalent torque arm for the friction torque,
the torque arm for the force exerted on the part by the bowl wall, and

\[ I = \frac{m}{12} (l^2 + w^2) \]

the moment of inertia for the part. Using equations (4) and (5), condition (3) and geometric conditions and applying differential calculus a computer model of the part motion is obtained.

This model neglects the curvature of the bowl wall and the resulting friction force between the part and the wall.

MODEL JUSTIFICATION AND VERIFICATION

Parts travel along the track of a VBF by sliding or hopping. Comparing experimentally the two modes of part motion, we confirmed that by hopping parts move 2 to 3 times faster than in the sliding mode. Modeling the part motion in the hopping mode is difficult due to the erratic part behavior caused by elastic forces acting between the part and the bowl. To solve this difficulty, the VBF is operated at high speed until the part reaches a sensor. Then, the VBF is momentarily turned off, the part is reoriented, and the VBF turned back on.

While rotating, the air jet exerts a constant force on the part. The kinetic energy developed by the air jet is dissipated by friction as the part rotates and translates.

\[ KE_{\text{air-jet}} = KE_{\text{translation}} + KE_{\text{rotation}} = W_{\text{translation-friction}} + W_{\text{rotation-friction}} \]

where:

\[ KE_{\text{air-jet}} = m_a \frac{v_a^2}{2} \]

\[ m_a \] is the mass of the air hitting the part and \( v_a \) is the air velocity. The conservation of momentum can be expressed as

\[ \int_{0}^{\Delta t} F_a \, dt = m_a v_a \]

The forces at various distances from the jet were experimentally measured and found to remain constant in range of 0.2 to 5 cm. Then

\[ \int_{0}^{\Delta t} F_a \, dt = F_a \Delta t = m_a v_a \]

Work done against the friction due to the parts translation is

\[ W_{\text{translation-friction}} = \mu N s = \mu mgs \]

where \( \mu \) is the dynamic coefficient of friction between the part and the bowl track, \( N \) the normal force, \( m \) the mass of the part and \( s \) the distance the part moves. The work against the friction due to the rotation about the center of gravity of the part is

\[ W_{\text{rotation-friction}} = \theta T = \theta \mu P \int_{A} \sqrt{x^2 + y^2} \, dA = \theta \mu \frac{mg}{lw} \int_{A} \sqrt{x^2 + y^2} \, dx \, dy = \theta \mu mgl^2 \]
where $\theta$ is the angle of rotation about the center of gravity, $T$ is the frictional torque, $P$ is the pressure on the area of the part exerted by the parts weight. For $\theta = \pi / 2$, equations (10), (13), (14), and (15) can be solved for $\Delta t$

$$\Delta t = \frac{2\mu mg}{F_a v_a} \left(s + \frac{\pi}{2} l_2\right)$$

(16)

Figure 5: A part in various stages of reorientation obtained by high-speed camera
The model was verified experimentally using the parameters listed in table 1.

<table>
<thead>
<tr>
<th>Process Characteristics</th>
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<tbody>
<tr>
<td>Part length: 3.8 cm</td>
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<tr>
<td>Part width: 2.2 cm</td>
</tr>
<tr>
<td>Part height: 1.2 cm</td>
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<tr>
<td>Part mass: 8.8 grams</td>
</tr>
<tr>
<td>Coefficient of friction: wood on Plexiglas: 0.4</td>
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<tr>
<td>Air velocity: 12 m/s</td>
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<tr>
<td>Force of air: 0.044 N</td>
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<tr>
<td>Ideal path length: 1.1 cm</td>
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</table>

Figure 5 shows experimental results obtained with the part described in table 1 and the air pulse duration of 130 ms. The separation of the part from the bowl wall can be seen in figure 5-c. The arrow on the part indicates the direction in which the part is traveling along the track prior the action of the air jet.

CONCLUSIONS

Active air jet tooling has distinct advantages for part orientation in VBFs. In this research a mathematical model of a part behavior in a vibratory bowl feeder equipped with an air jet tooling was developed. The model was validated experimentally for a specific part. This model will give the designer the knowledge required to develop a new generation of VBFs.

REFERENCES


