Full Length Research Paper

Investigation of flow and vacuum lifting force on a non-contact end effector for robotic handling of non-rigid material

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This study identifies the need for a new range of end effectors suitable for non-rigid products and introduces a novel non-contact gripping device. The end effector operates on the principle of generating a high-speed fluid flow between the end effector and product surface thereby creating a vacuum which levitates the product. The lifting forces and conditions are discussed by using optimization methodology and finite element analysis. The experimental results are presented using the end effectors that have been operated to lift non-rigid food materials such as jelly blocks.

Key words: Vacuum lifting force, end effector, robotic handling.

INTRODUCTION

All modern manufactured and processed goods require handling and packaging at some stage in their production and distribution. The handling and packaging of discrete food products, both old and new rely heavily on the role of the human operator. The human provides a high degree of dexterity and flexibility which can be readily applied to a wide variety of food products ranging from fish fillets, jelly blocks, meat and poultry portions, through to sliced ham and other sliced processed meats. Each of these products features variations in texture, color, shape and size. The food products are also often delicate, easily marked or bruised, compliant, adhesive and slippery. Conventional handling and gripping technology which features two or more jaws is not directly applicable. All forms of contact end effectors can potentially cause product bruising and deformation. The air permeability, elasticity, surface adhesiveness and smoothness, shapes and weight of food products as mechanical properties are their most important characteristics from the point of view of handling and invariably have to be considered when selecting end effectors to handle food products (Pham et al., 1986). The end part of the robot or programmable machine arm is referred to as an end effector. Thus, the end effector is the device mounted at the distal end of a robot arm, enabling it to pick up an object and hold, manipulate, transfer, place and release it accurately in a discrete position (Madwed, 1985; Schneider, 1992). Thus, the gripper is the all-important mechanical interface between the robot and its environment without which, in many circumstances, the robot cannot function effectively, irrespective of the degree of sophistication it may otherwise possess. All currently available methods for gripping a workpiece have fallen under one of two general categories, clamping and attracting methods by Tella et al. (1982). The first category, clamping methods is comprised of jaw-type devices which exert pressing forces on at least two opposing elements of a workpiece. The workpiece is held in place by the resulting frictional forces. The second category attracting methods is comprised of vacuum, magnetic, adhesive and all other methods characterized by attractive holding forces. There are two major advantages of clamping end effectors. First, these end effectors are less dependent than attracting methods on workpiece surface conditions and irregularities. Secondly, their gripping force is only limited...
by their clamping force. The major disadvantage of clamping methods is that they require access to more than one surface of the work piece for gripping to occur.

The clamping end effectors are intended for handling rigid, usually three-dimensional objects. Despite the clamping end effectors being successfully used in manufacturing, it is difficult to use them for handling non-rigid materials such as jelly blocks and sliced meats (Erzincanli and Sharp, 1995). Vacuum end effectors on the other hand require only single surface access to the work piece for successful gripping. The gripping force of vacuum methods is limited by the accessible surface area of the work piece holding side. Suction end effectors can also remove essential fluids and other particles from the product which can result in contaminated pipelines. Ideally, there needs to be a non-contact handling device which can be simply controlled in much the same way as a suction end effector and which can introduce a temporary level of rigidity into the product in order to facilitate high speed handling and manipulation (Simonton, 1991; Heilala et al., 1992). The aim of this research was to develop a non-contact end effector that could handle non-rigid, relatively flat and thin food products with slippery or sticky surfaces, particularly jelly blocks and sliced meat, meeting the rigorous hygienic standards of the food industry and to carry wool non-contact for textile industry. Sliced meat and jelly blocks are quite good examples of delicate food products from the handling point of view as they are very flexible, covered with either slippery or sticky substances, relatively flat and thin. The thickness dimension of such products is much smaller than their surface area dimensions (Erzincanli et al., 1994; Erzincanli, 1995). In this way, an efficient, effective and automated design strategy is proposed to design a non-contact effector. In this strategy, ‘finite element analysis’, ‘approximate model’ and a ‘numerical optimization algorithm’ are integrated to create an automated design tool. Shape design of non-contact effector is formulated in the form of an optimization problem that can be solved easily by a conventional numerical optimization algorithm.

Finite element analysis results are replaced with their approximations before the optimization problem is solved. Solution of the optimization problem leads to the optimum design.

METHODS AND EXPERIMENTAL SETUP

A shape design optimization problem can generally be formulated as a constrained minimization problem as follows (Kayabasi and Erzincanli, 2007):

\[
y_0(\mathbf{x})
\]

\[
y_j(\mathbf{x}) \leq 0 \quad (j = 1, \ldots, n_c)
\]

\[
x_{il} \leq x_i \leq x_{ui} \quad (i = 1, \ldots, N)
\]

Where \( y_0(\mathbf{x}) \) is the objective function, \( y_j(\mathbf{x}) \) are the constraint functions and \( \mathbf{x} = [x_1, x_2, \ldots, x_N] \) is the vector of design variables. \( x_{il} \) and \( x_{ui} \) describe physical upper and lower bounds on design variables. \( n_c \) and \( N \) are the number of constraints and number of design variables, respectively. The constraint and objective functions may correspond to weight, constraints and number of design variables, respectively. The bounds on design variables.

Solution of equations for shape optimization problems can be efficiently done by replacing objective and constraint functions with their response surface (RS) approximations. Optimization with approximations is often referred to as approximate optimization in the literature. The approximate optimization method implemented in ANSYS and used in this paper is shown in Figure 1. ANSYS generates and utilizes polynomial RS approximation for objective or constraint function as follow:

\[
y(\mathbf{x}) = a_0 + \sum_{n=1}^{m} a_n x_n + \sum_{j=1}^{N} b_n x_j^2 + \sum_{n=1}^{N} \sum_{m=n+1}^{N} c_{mn} x_n x_m
\]

Where \( a, b, c \) are coefficients to be determined.

In design optimization process, ANSYS first creates \( N + 2 \) design sets to construct a linear approximation. Here, set indicates values of all parameters for a specific design. ANSYS will either generate design sets randomly or use the existing ones in the optimization database. Shape optimization analysis is carried out at available design sets. Analysis results are then used to create linear approximations of objective and constraints. Higher order approximations such as quadratic and quadratic with cross terms RS approximations are created using least square method when there are enough design sets in the database. The optimum design is predicted by solving Equations 1 to 3 with a numerical optimization algorithm based on penalty functions. The predicted optimum is verified by exact analysis (ANSYS). If the predicted objective and constraints are identical with the results from ANSYS, or the estimated optimum design is satisfactory enough, the optimization loop is stopped. Otherwise, the newly calculated results are added to the existing design sets and new approximations are created followed by the solution of the optimization problem.

Parametric and geometric modeling

A schematic diagram of the radial outflow configuration is shown in Figure 2 where compressed air from a source enters through a pipe at the centre of the upper disk and after striking the lower disk flows radially outwards between the two disks which are circular. The system is called a radial flow nozzle, and consists of two narrowly spaced circular disks placed parallel to each other and perpendicular to a central inlet pipe. The radial outflow of air between the parallel disks causes either an attracting or a repelling force to exist between the disks. In general, in order to create an attracting force, the clearance gap of a nozzle must be very small as compared with the diameter of the central tube and the radial distance through which the fluid flows. With increasing mass flow, the Reynolds number at the inlet may exceed a critical value so that turbulent flow will exist for some distance downstream of the inlet corner. This type of flow causes the attracting force between the two disks. When the velocity, which decreases with increasing
radius has fallen sufficiently for the local Reynolds number to become sub-critical, a reverse transition from turbulent to laminar flow results. If the mass flow is increased further still, the flow in the channel becomes fully turbulent and eventually the inertia terms

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**Figure 1.** Approximate design optimization process with ANSYS.

**Figure 2.** Schematic representation of the working principles of the nozzle.
predominate over the viscous terms in determining the pressure distribution. As the radius increases, the pressure raises in the radial direction (Erzincanli and Sharp, 1995; Moller, 1963); therefore, the attracting forces decreases.

A non-contact end effector for robotic handling of non-rigid material has been designed. Design of a non-contact end effector is of interest to lift non rigid material such as meat, wool etc. and to provide hygiene for food while handling. The goal and the requirements are expressed in the form of an optimization problem as follows:

Find:

\[ X = (d_1, D_1, d_2, D_2, \alpha_1, \alpha_2) \]  

To minimize (displacement between a non-contact end effector surface and non rigid material surface)

\[ \text{(6)} \]

Subjected to:

\[ 2 \text{ mm} \leq d_1 \leq 5 \text{ mm}, \ 3 \text{ mm} \leq D_1 \leq 6 \text{ mm} \]

\[ 7 \text{ mm} \leq d_2 \leq 13 \text{ mm}, \ 8 \text{ mm} \leq D_2 \leq 14 \text{ mm} \]

\[ 30^\circ \leq \alpha_1 \leq 45^\circ, \ 30^\circ \leq \alpha_2 \leq 45^\circ \]  

\[ \text{(7)} \]

Where \( d_1 \), \( D_1 \), \( d_2 \), \( D_2 \) are the diameters and \( \alpha_1 \), \( \alpha_2 \) are the angles of the nozzles as shown in Figure 3. Initial values of design parameters were taken as \( d_1 = 2 \text{ mm} \), \( D_1 = 3 \text{ mm} \), \( d_2 = 7 \text{ mm} \), \( D_2 = 8 \text{ mm} \), \( \alpha_1 = 40^\circ \) and \( \alpha_2 = 40^\circ \).

A nozzle geometry that will yield low gap between non rigid material surface and nozzle surface is investigated. Nozzle is modeled parametrically using ANSYS parametric design language (APDL). The parameters used in parametric model are referred to as design parameters and they are shown in Figure 3. Best nozzle shape (dimensions) is to be found by adjusting these parameters. More design parameters gives the better nozzle shape (that is better performance). However, the number of analysis (that is computational cost) needed in finding the best nozzle design will be linearly or quadratically proportional with the number of design parameters selected.

**Finite element modeling**

The first step with finite element method in numeric solution is to build finite element model equivalent to geometric model. FLUID142 elements are applied. The conservation equations for viscous fluid flow and energy are solved in the fluid region, while only the energy equation is solved in the non-fluid region. The complete model consisted of 3,840 elements. The second step of finite element method is to apply loading and boundary condition. Inlet and outlet pressure boundary conditions are set to 6.13769e+6 dynes/cm\(^2\) and 0, respectively. The VY velocity component is set to 500 m/s\(^2\) along the axis of symmetry and the VX and VY velocity components are set to 500 m/s\(^2\) along the outer surface.

**Experimental setup**

After finding optimum shape, results are verified by experimental setup. The experimental rig consists of several pieces of basic and auxiliary equipment. This equipment is individually discussed. A schematic representation of the equipment that forms the experimental rig is illustrated in Figure 4. An over-view picture and a close-view picture of the experimental rig with a four nozzle head configuration are illustrated in Figures 5 and 6. The air supply tank and the auxiliary air flow control equipments are not illustrated in Figures 5 and 6 due to the fact that they were positioned at a separate location in the laboratory. The experimental rig was designed and assembled as flexible as possible in order to carry out different experiments. The end effectors with different nozzle
head configurations can easily be replaced with different ones using the screwed rods and nuts. The compressed air supply tube from the air tank can be connected to a replacement end effector system with a flexible connection, reducing time to change over.
RESULTS AND DISCUSSION

Optimization history graphics for clearances gap values and design parameters using approximate optimization method are demonstrated in Figures 7 to 9. Figure 7 shows the change of clearances gap between nozzle surface and non-rigid material surface with iterations. Figures 8 and 9 demonstrate the change of the design parameters of \( d_1, D_1, d_2, D_2, \alpha_1 \) and \( \alpha_2 \) with iterations.

Optimum nozzle geometry found after 50 optimization
iterations. To reduce the computational cost, optimization process was limited with 50 iterations. More iteration may provide a better design. The results obtained from simulations are outlined in this study. From Figure 10, it can be concluded that the clearance gap increases with increasing volumetric air flow rate by using optimization methodology and finite element model. After optimization results, four nozzles were configured and used to lift various materials during experimentation. The surface area of the standard specimen was divided equally into four sections. Nozzle heads were positioned over the centre of each divided section. Thus, the forces were equally distributed across the specimen surface. The four divisions of the material surface and the positions of the nozzle heads are illustrated in Figure 11. In this figure a cross section through two nozzles and the nozzle holder
Figure 10. Air flow rate versus clearance gap (P: 100 kPa).

Figure 11. The positioning of four nozzles across a specimen surface.
is also illustrated. The distance between nozzle heads, from edge to edge is 11 mm. The total surface area of four nozzles covers 36.9% of the total area over the specimen top surface. In order to supply air to this configuration, the air distributor for four nozzles was used. The jelly with standard ingredients was molded with standard dimensions (70 × 70 mm) and four different thicknesses to obtain weights of 35, 70, 105 and 140 g. The results of the experimentation for the weight of 70 g are illustrated in Figure 12.

From Figure 12, it can be concluded that the clearance gap increases with increasing volumetric air flow rate with experimental and finite element model. The experimentation was carried out under gauge pressure of 100 kPa. Figure 13 shows a jelly block during the lifting process. In the picture, the clearance gap between the
jelly block and the nozzle could not be shown due to inadequate focusing.

**Conclusion**

A design consideration for the non-contact end effector was outlined in detail regarding experimental results. An operational sequence and a conceptual application of the non-contact end effector in a practical handling environment were introduced. At the end of experimental results, it shows that nozzle can be designed and studied in computer environment before it is not manufactured. This will save time for the design and prevent loss product. Developed non-contact end effectors according to numerical analysis results are quite successful as well as applying them to handle regularly-shaped rigid and non-rigid materials with relatively smooth surfaces. The radial flow through nozzle causes vacuum. The vacuum force of end effectors is capable to lift materials with porous structures and surfaces covered by viscous substances.

**REFERENCES**


