Numerical characterisation of the performance of flow rate on a non-contact vortex gripper

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Abstract. On manufacturing industries like semiconductor wafers, Manufacturing of medicine or Food processing industries require repeated handling of clean products such as wafers, Food products, etc. which are needs to be frequently handled and transported. This handling can be further ameliorated by Vortex Grippers. Vortex levitation can achieve Non-Contact handling by blowing air through a tangential nozzle into a vortex cup, thus swirling air flow forms which generates negative pressure. The suction force generated by the vortex is more than enough to keep the workpiece without contact. In the present study, a non-contact handling device called vortex gripper is modified by changing some design parameters. However, when a conical shaped vortex cup is used, a 60% increase in gripper lifting force is achieved with the same air consumption as reported early.

1. Introduction
The Production plants are becoming automated day by day, so repeated type of handling and manipulation is desirable which is mainly achieved by employing robots. The majority of the robotic grippers available are of contact type, but due to their unpredictable and unstable behaviour may cause damage to the object/workpiece. Such type of damages are very sensitive to certain objects like silicon material wafers, LCD or LED Screen panels, bakery products, manufacturing of biscuit, etc. The earliest study on the vortex gripper was proposed by Xin li, Kenji kawashima and Toshiharu kagawa in 2008. They demonstrated the vortex gripper mechanism of negative pressure generation and force development [1]. Mainly there are two kinds of pneumatic non-contact handling methods, and are Bernoulli levitation and vortex levitation. According to Vortex gripper, the suction force is developed by the constant supply of compressed air through the tangential nozzle attached with the vortex chamber which develops a swirling flow inside the cylindrical design of the cup creates a vacuum at the middle portion. The lifting force produced is due to the pressure difference in the upper surface of the workpiece and lower surface of the gripper. However, the pressure difference depends on the clearance between the device and the object, stated by Xin li et.al [1] Also, the dynamic characteristics and the dynamic modelling of the gripper are reported [2,3]. In addition, the main advantages of vortex levitation is that it requires low supply of air than the Bernoulli levitation, these characteristics are studied [2]. However, Stress generation and breakage, on handling and transportation of silicon material wafers clearly denotes the stress developed in the wafer region and also the crack size and location of breakage developed [4]. As reported in many previous studies for the high speed inspection procedure for LCD or LED glass
screen panels, non-contact method is desirable [5]. Furthermore, for the reduction of food contamination as well as damages to the food products, non-contact type of grippers are desirable. Consequently, a rectangular shaped non-contact gripper for the handling of bakery products was developed by Rawal et.al [6] and Bernoulli gripper for handling of sliced fruits and vegetables was proposed by Davis et.al [7]. Furthermore, the best numerical method for predicting the flow characteristics of the vortex levitation is RNG K-Σ (Re-Normalisation group) [8]. Recently, the tangential nozzle are improved by the implementation of double nozzle and the pressure distribution is improved. Performance of the gripper is assessed by the maximum force, suspension – Region & stiffness. However, as the supply flow rate increases the relationship with force and clearance has an inclination towards the left side of the curve which decreases the suspension region [9]. Among these studies the vortex gripper is characterised by its gap height (Clearance) thus the levitation is stably suspended underneath as in Bernoulli effect gripper the suspension occurs an squeeze film flow which the workpiece performs a vibrational characteristics due to the damping force exerted into the workpiece which oscillates and finally makes it stable. Also, the outer diameter of Bernoulli gripper influence the suction force and the stiffness [10]. Based on a recent study the vortex chamber is slightly improved by the implementation of a diversion body, which improved the overall suction force of the gripper and the stability. Thus 25% larger suction force and the stability improves to 2.5 times greater than the already existing one [11].

The vortex gripper are continuously researched because of its high practical applications. This paper improves an early reported non-contact gripper. The simulation of the K-Σ model is used for the numerical purpose. The above said gripper is modelled and analysis is carried out to validate the model with the accepted gripper. The design is modified by changing the design parameters such as nozzle angle, nozzle shape, size of the nozzle and number of attached nozzles. The new design can generate higher lifting force than the early reported design with the same air supply which is discussed later.

2. Mechanism of vortex gripper

Figure 1 represents the schematic diagram of a newly developed vortex gripper. The table-1 shows different size of the gripper. The vortex gripper consists of a circular vortex chamber (Cup) and a cylindrical tangential nozzle. When high pressure air is blown through the tangential nozzle the air will be circulated cyclonically. By this action the center of the vortex cup will have less pressure. A vacuum is generated. The vacuum generated will levitate the object at bottom surface, but due to the flow of air the workpiece will not touch the gripper surface. The arrows inside the bottom view indicates the air flow direction.

![Figure 1. Schematic sketch of Vortex gripper (New model).](image)

Table 1. Dimensions of vortex gripper (mm).

| D1  | D2  | D3  | D4  | Dn | H1  | H2  | H3  | H   |
|-----|-----|-----|-----|----|-----|-----|-----|-----|
| 9   | 18.5| 23  | 40  | 2.5| 1.5 | 10.5 | 3.5 | 1.25 | 0.2 to 1.5 |
3. Numerical method

The newly developed model is numerically analysed to bring out the characteristics of the gripper. Ansys Fluent & CFX are the main numerical softwares used for the study. First an analysis is carried out for a vortex cup filled with one nozzle. The Navier-stoke equations are the governing equations for these numerical study.

Continuity Equation
\[ \frac{\partial \rho}{\partial t} + \rho \frac{\partial u_i}{\partial x_i} = 0 \]  

Momentum equation
\[ \rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j \]  

Where
\[ \tau_{ij} = -\mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \frac{2}{3} \delta_{ij} \mu \frac{\partial u_k}{\partial x_k} \]  

I: Local change with time  
II: Momentum convection  
III: Surface force  
IV: Molecular-dependent momentum exchange (diffusion)  
V: Mass force

3.1. Different Boundary Condition

The main boundary condition is the mass flow rate in the inlet and atmospheric pressure at the outlet. The cylindrical shaped geometries are the wall and the interiors. There is no heat transfer through the wall. The finite volume method were used for the Solution procedure with initial solution with first order discretization, latter it is changed into higher order discretization for improved accuracy of the final solution. The skewness is kept below 0.98. The boundary conditions used in the procedure was listed in the table 2. The RNG K-\(\Sigma\) method is used for the solution of viscous model.

| CONDITIONS          | SETTINGS                                      |
|---------------------|-----------------------------------------------|
| Fluid               | Ideal gas                                     |
| Viscous             | Turbulent                                     |
| Inlet boundary      | Mass flow rate (1.87x10^{-4} kg/s)            |
| Outlet boundary     | Pressure outlet (Atmospheric pressure)         |
| Grid cell           | 1000835                                       |

4. Results and discussions

The Xin li et.al model is created and analysed to validate the technique used. The design dimensions are obtained from Xin li et.al [2]. The space (Clearance) between the gripper and work piece are modelled for analysis. The analysis is conducted for the clearance ranging from 0.2 to 0.85mm, using the ANSYS FLUENT software. The results are validated with the results of Xin li et.al [2]. Further, the technique is validated using the results of recently developed model using Xin li et.al [3]. This model consists of the tangential nozzle attached parallel with opposite faces of inlet nozzle. Figure. 2 shows the fluid domain model with 0.3mm clearance and the validation of the gripper is done for different clearance (h) from 0.15 to 1.5 mm. The comparison of the results with different clearance is shown in figure. 3. The results obtained are in good agreement with the results of Xin li et.al [3]. The maximum force occurs when the clearance is 0.3mm and the static pressure developed is about 680Pa.
4.1 Optimisation

The optimisation of the vortex gripper is conducted by changing the design parameters such as the nozzle angle, nozzle shapes, number of nozzles and vortex cup design. Overall performance of the vortex gripper depends on the above parameters.

4.1.1 Optimisation of nozzle angles

The aim of optimisation of nozzle angle is to find the best angle for better pressure distribution and better stability of the work piece. The angles are varied from $5^\circ$ to $65^\circ$ with an interval of $5^\circ$ each. The figure. 4 shows the static pressure vs nozzle angle. From the figure it is understood that at the interval of $35^\circ$ to $40^\circ$ the static pressure is improved and also stable. These calculations were done for a clearance of 0.3mm. Figure. 3 shows that the maximum force obtained in the gripper is between 0.3 to 0.4mm clearances. However the selection of maximum force changes according with different flow rate of air and reduces the range for maximum force developed.

From the graph it is observed that at about $35^\circ$ – $40^\circ$ nozzle angle the static pressure developed was about 520Pa which is more than the value reported by Xin li et.al [2] and at this angle the workpiece is stable. When the angle is increased towards $40^\circ$ – $60^\circ$ the lifting force is slightly decreasing and also it was noted that there is an inclination of the work piece which may be due to the change of center of negative pressure slightly away from the central axis of the workpiece.

4.1.2 Optimisation of nozzle shape

The optimisation of nozzle shape is by changing the nozzle design by introducing three different types of nozzles namely Convergent, Divergent and combination of both convergent and divergent nozzles. The boundary conditions and the dimensions used were the same as proposed in the Xin li et.al [2]. A vortex gripper with convergent nozzle is developed with inlet diameter of 3mm and outer diameter of 1.5mm. Figure. 5 shows the model and Figure. 6 shows the pressure distribution, in this case the value obtained for the negative pressure is 635Pa, which is 1.5 times more than the Xin li design. And the velocity developed by the nozzle is also higher.
For the divergent nozzle with inlet diameter of 0.75mm and outlet diameter of 1.5mm, the pressure developed is only 150Pa as compared to Xin li design which is about 450Pa. The convergent-divergent nozzle design, similar to that used in the rockets, reported by Biju kuttan et.al [12] is developed and analysed numerically.

4.1.3. Optimisation of Number of Nozzles
Model having two nozzle is already discussed and validated. Now vortex gripper with triple nozzle is developed with same diameter which are placed equally around the vortex cup having an angle of 120° separation each. The results were further analysed, the pressure distribution was not increased rather it decreased, the maximum negative pressure developed is of only 500Pa and the positive pressure increased rapidly. This may be due to the formation of turbulence from all the nozzle in spite of vortex formation. On increasing the number of nozzles from three to four nozzles the pressure needed for the levitation of the workpiece is increased but a high turbulent positive pressure is developing at the vortex cup which is highly unstable for the handing of the workpiece. In the four nozzle design the negative pressure developed is 600Pa and the positive pressure inside the vortex griper is 1200Pa. So it is evident that two nozzle is the optimum number of nozzle for vortex gripper.

4.1.4. New Design
From many designs developed, the one which gave best result is selected, which has high stability and lifting force than the Xin li’s gripper. The model design consists of Cup having divergent shape. The inlet and other boundary conditions used are of same as that of the previous model. Figure. 1 consists of the schematic sketch of the design with the clearance of 0.3mm. The results of the analysis shows that the pressure distribution is 60% greater than the Xin li’s gripper. The pressure developed inside the newly developed vortex gripper and the pressure generated is about 723Pa. In this case the gripper has a higher stability for the handling of the workpiece.

The design is further improved for higher lifting force by changing the number of nozzles to two. The results obtained are far better than the Xin Li’s design and the stability of the design is enhanced. Figure. 7 provides the static pressure of the gripper with clearance of 0.3mm.

The pressure distribution curve has a high negative pressure of 1310Pa. The pressure distribution of the newly designed vortex gripper has about 2 times of the negative pressure than Xin Li’s design for two nozzle gripper.
5. Conclusion

The non-contact gripper named vortex gripper can be worked with the help of swirling air flow to cause an upward lifting force and thus it can pick up a desired weight and hold the workpiece which is placed under the gripper without any contact. A vortex gripper is modelled and analysed using ANSYS CFX and Fluent software. The model is validated with pressure distribution of different position along the radius, with the results of Xin li et.al [2] & [3]. A detailed study of different models by changing the parameters such as nozzle shape, nozzle angle, Size of nozzle and number of attached nozzles. The effect of changing nozzle angle was analysed with different nozzle angle from 5° to 65°. It was observed that, at about 35° - 40° nozzle angle the static pressure developed was about 520Pa for which the work piece is stable. The shape of the nozzle is varied using divergent, convergent & convergent-divergent nozzle and it is analysed. In divergent nozzle the static pressure decrease due to increase in nozzle diameter near the cup. In convergent nozzle static pressure was developed 1.5 times more than the existing tangential nozzle with the same amount of mass flow rate. In Convergent-divergent nozzle the static pressure observed was 5 times more than the existing tangential nozzle and the velocity augmented by the nozzle design structure. For three nozzle, the static pressure developed is 1.5 times higher than Xin li’s designs, but the positive pressure of the vortex cup is higher. Further addition of nozzle showed a gradual decrease of static pressure because of high positive pressure inside the vortex chamber. From the above result it was found that the nozzle used need not to be increased beyond two nozzles.

The design with divergent vortex cup shows an improved result than Xin li gripper. The pressure distribution shows a 60% increase for both single and double nozzle design.

6. References

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