Aerodynamically Augmented Air-Hockey Pucks

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AERODYNAMICALLY AUGMENTED AIR HOCKEY PUCKS –
LATERAL AND ROTATIONAL MOTION

A Thesis Presented

by

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ABSTRACT

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Air hockey is an interesting fast-paced arcade game which involves levitating a puck at a very small height from above the table allowing it to traverse seamlessly on a cushion of air and participants on either side of the table striking the puck with a handheld paddle. Over a period of time, the game becomes predictable and less challenging for a player with significant experience. Primary goal of this research is to make the game more exciting and we do this by naturally generating lateral and rotational aerodynamic forces on the puck by adding patterns and features on the bottom surface of the puck. This creates an asymmetry in the flow and generates pressure gradients along the pattern walls and a net unbalanced force is exerted on the puck throughout the game as long as air keeps flowing through the table. In this work, we provide a comprehensive study of numerical and experimental results for design-based optimizations that produce lateral and rotational motion with insights obtained from prior work.
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1. INTRODUCTION

![Figure 1](image)

**Figure 1**: (A) Schematic diagram of a standard air hockey puck. (B) represents the direction of impact on the puck by the paddle and resulting trajectory of the puck.

Air hockey is a sport played by many, both professionally and casually. This sport was founded in the late 1960’s and popularized in the 1970’s. The game is a table-top arcade version of ice hockey that uses the principles of lubrication theory to levitate a thin plastic puck over a bed of high-pressure air jets emitted from a regular array of holes in the porous air hockey tabletop as shown in Figure 1. By levitating the puck over a lubricating layer of air, direct contact between the puck and the table is avoided and the puck is allowed to move across the table with very little friction or resistance. This makes the game fast moving, exciting to play and explains its continued popularity even today. The game itself involves two individuals on either side of the table striking the puck with a handheld paddle with the goal of hitting the puck into their opponent’s goal while simultaneously defending their own goal. The puck naturally follows a straight line along the direction of impact by the paddle and upon striking the side wall of the table the path of the puck is governed by the rule of reflections where the incidence and reflection angles are the same. Unlike billiards, where “English” applied to the pool balls can affect their motion, air hockey pucks tend to travel in straight and predictable ways. Over time
this means that the game can become less challenging and more predictable for an experienced player. The primary goal of this research is to use our knowledge of fluid dynamics in general and lubrication theory specifically to make the game of air hockey more exciting. We will do this by producing lateral and rotational aerodynamic forces on the puck through the incorporation of specifically designed patterns on the tail or bottom surface of the puck as shown in Figure 1 to produce “English” on the air hockey puck and create a level of uncertainty in the puck movement that can make the game more interesting.

Figure 2: Schematic diagram of a standard puck and flow through the porous table is visualized.

Understanding the lubrication effect produced by the cushion of air under a standard puck can provide us insights on how fluid structure interaction can be altered to achieve our goals. We will start with a theoretical lubrication analysis of the flow under the puck. For the sake of ease in calculations, the puck is assumed to be rimless and flat on both its tail and head surfaces as shown in Figure 2. We will account for the height difference between the rim and the center of the puck in the full numerical simulations we present later in this proposal. Note that scaling analysis is performed in cylindrical coordinates rather than cartesian coordinates is to simplify Navier Stokes equation.
Air at a pressure $P$, density $\rho$ and dynamic viscosity $\mu$ flows from under the table with a velocity $V$ in z-direction through the porous surface and levitates a puck of mass $M$ and radius $R$ by creating a cushion of air of thickness $h$ under the puck as shown in Figure 2. Forces exerted by the incoming air onto a standard puck is presented in $r$ and $z$-direction alone since flow is symmetrical about $\theta$- direction, and are governed by the steady state Navier-Stokes equations (M.White, 2006)

$$
\rho \left( \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g}. \tag{1}
$$

Under the lubrication approximation, all the convective acceleration terms in equation 1 can be eliminated in the limit that $h/R << 1$ and $Re (h/R)^2 << 1$, here $Re = \rho UL/\mu$ is the Reynold’s number. Pressure $p$ (at $r=R$) is equal to atmospheric pressure $P_o$, and velocity components $u_r$ and $u_z$ (at $z=h$) are both zero since we assume no slip boundary condition at the walls. Similarly, velocity components $u_r = 0$ and $u_z = V$ (at $z=0$) since inlet air is flowing in $z$-direction alone. Pressure gradient along $z$-direction is determined to be constant since the film thickness is extremely small, so $\frac{\partial p}{\partial z} = 0$ and variations in pressure gradient along $r$-direction is solely considered for force calculations. From the above declarations, the Navier-Stokes equations in the $r$-direction reduce to

$$
0 = -\frac{\partial p}{\partial r} + \mu \left( \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial (ru_r)}{\partial r} \right) + \frac{\partial^2 u_r}{\partial z^2} \right). \tag{2}
$$

From conservation of mass (the continuity equations) the form of the velocity in the $r$-direction can be inferred to be $u_r = rf(z)$ where $f(z)$ is an unknown function of $z$ only. Substituting into equation 2 and solving, the pressure distribution under the puck becomes
\[ p = P_0 + \frac{3V\mu}{h^3}(R^2 - r^2) \]  

(3)

and velocity components of air flow under the puck in both \( r \) and \( z \)-direction are found to be

\[ u_r = \frac{3V}{h^3}(zh - z^2)r \]  

(4)

and

\[ u_z = V - \frac{6V}{h^3}\left(\frac{z^3}{3} - \frac{z^2h}{2}\right). \]  

(5)

By integrating the pressure across the bottom of the puck, the pressure force \( F \) exerted on the puck by the incoming air flow is calculated to be

\[ F_z = \frac{3\pi V\mu R^4}{2h^3}. \]  

(6)

From equation 6, force can be correlated to velocity of incoming air \( V \), radius of the puck \( R \) and the film thickness \( h \). This tells us that by keeping velocity and radius of the puck constant, the normal force has a very strong, 3\(^{\text{rd}}\) order, dependence on the levitation height. By varying the film thickness through the introduction of different patterns on the bottom surface, we can impact the distribution of the pressure and shear forces acting on the puck. Since the tail surface of the puck is flat on a regular puck, pressure force in the theoretical model we just described is exerted vertically, normal to this tail surface such that it provides the necessary amount of lift to keep the puck levitating on a cushion of air. If the bottom surface, however, was not flat, but contained topography that was sloped, the pressure would still act normal to the surface, but now that force would provide both lift and thrust to accelerate the puck to one side or to rotate the
puck in place. Note that shear force exerted by air on a standard puck is balanced out and provides no thrust in the radial direction.

Research works in the past have proven the effect of having patterned porous substrates on producing lateral and rotational forces on a levitating object (Baier et al., 2013; Quéré, 2013; Soto et al., 2016, 2017; Weirauch, 2007). As discovered by Leidenfrost (Quéré, 2013), liquids placed on very hot substrate levitates on a cushion of their own vapor as liquid evaporates due to the radiative and convective heating in the gap between the droplet and the hot surface producing enough mass flow of evaporating gas that a lubrication flow is introduced that can support the weight of the drop until the drop completely evaporates. Lagubeau et al. showed that by introducing a hot ratchet, drops self-propel as dissipated vapor propagates from the trailing edge to the leading edge of the drop by flowing along the teeth of the ratchet carrying the entire puck along as shown in Figure 3. The propelling force \( F_p \) exerted by the vapor is scaled to be (Lagubeau et al., 2011)

\[
F_p \sim \left( \frac{R}{a} \right)^{3/2},
\]

where \( a = (\kappa \eta \Delta T/L \rho \rho_o g H)^{1/2} \), \( R \) is drop radius, \( \kappa \) is thermal conductivity of the vapor, \( \Delta T \) is the temperature difference between the solid and the liquid, \( L \) is the latent heat of evaporation, \( \rho \) is the vapor density and \( H \) is the Leidenfrost body height. Lagubeau et al. concluded that a
propelling force $F_p$ of order 10 µN is exerted on a drop of radius 4mm, moving the drop at a terminal velocity of 10 cm/s. Baier et al. was successfully able to correlate shear stress $\tau$ exerted by the vapor to height of the teeth $H$ and droplet radius $R$ as

$$\tau \sim \left( \frac{H}{R} \right)^3,$$  

(8)

telling us that shear stress increases when height of the teeth is increased and radius of the droplet decreased.

![Herringbone pattern](image)

**Figure 4**: (A) Top view of the setup illustrating the herringbone structure with an angle $2\alpha$ and each channel of width $w = 1$ mm separated by walls of thickness $\lambda = 0.3$ mm. (B) Side view of the device showing herringbone channels with a height $h = 0.18$ mm on top of which a glass plate with length $a$, width $b$ and thickness $c$ is placed (Soto et al., 2017).

Using liquid droplets on hot ratchets tends to evaporate over time and needs to be adjusted before every trial making detailed experimental investigations difficult. Instead, Soto et al. introduced a smooth flat glass plate onto a porous substrate with evenly distributed jets and a herringbone structure over the substrate and under the glass plate (Soto et al., 2017) as shown in Figure 4. The authors showed that the glass plate was capable of being propelled along the herringbone pattern at a terminal velocity of 10 cm/s with a maximum lateral force of order 60
µN induced on the plate with length $a = 30$ mm, width $b = 12$ mm and thickness $c = 1$ mm. Soto et al. showed that this maximum propelling force was established when the herringbone half-angle $\alpha = 45^\circ$ and this behavior was reported valid regardless of the glass plate dimensions. Propelling force approached to zero as the herringbone half-angle approached to either $0^\circ$ or $90^\circ$. Based on experimental and theoretical results from the herringbone device, Soto et al. was also able to show that a rotational force can be generated on the glass plate by introducing a pattern with four quadrants aligned at $90^\circ$ to each other as shown in Figure 5 and experimentally deduced the terminal angular velocity of the plate to be of order 8 rads/s.

In this thesis, we will investigate how a series of patterns applied to the tail surface of our puck instead of the air hockey table induces a self-propelling force and a torque responsible for the lateral and rotational motion. This method of introducing patterns to the levitating subject has been proven to be effective in producing additional lift force (Weirauch, 2007) on the puck due to asymmetrically placed dimples on its tail surface as shown in Figure 6. Contactless movements of objects have drawn a lot of attention due to their isolated nature. A lot of unwanted effects can be minimized such as frictional losses, chemical reactions, thermal exchanges, shock, and damage etc. Even though the lateral forces

![Rotational motion](image1.png)

**Figure 5:** Illustrates the direction of rotation due to pattern orientation.

![Dimples](image2.png)

**Figure 6:** Schematic diagram illustrating the dimpled structure on the tail surface.
produced on the subjects used by Soto et al. are as low as 1% of its body weight, these forces are large enough to propel the subjects due to frictionless situations.
2. METHODS

From the information obtained through experiments and numerical simulations described in the previous section, a series of patterns and features were introduced onto a standard air hockey puck with a goal of maximizing the lateral and rotational forces. These designs for lateral and rotational motion of the puck were validated and optimized through detailed numerical simulations using Ansys Fluent and experiments. This computational fluid dynamics (CFD) package from Ansys Fluent allows us to model the flow under the puck in great detail and extract velocity fields and pressure profiles making it possible to calculate levitation force along with lateral/rotational force for a series of pucks with complex 3D surface topographies. Although analytical solutions are possible for some of these cases, the lack of azimuthal symmetry in the final geometries makes closed form solutions impossible.

2.1. Preliminary Model Geometry

Patterns were incorporated onto the bottom surface of the puck using Solidworks. By applying the patterns to the pucks, it enables a player to interchange pucks with their corresponding effects into the game at any moment unlike introducing patterns onto the table which is highly resource draining. The base model of our air hockey puck weighs 15 grams and has a diameter of $D = 64$ mm with an annular rim measuring $w_r = 5$ mm wide. The center region of the base model has a thickness of $t = 5$ mm and the rim has a thickness of $t_r = 6.25$ mm resulting in a step height of $\Delta t = 0.625$ mm as the air passes from the central core of the puck and under the rim before escaping out the edge of the puck.
2.1.1. Lateral Motion

The initial design tested incorporated grooves inclined at 5° from the horizontal into the bottom surface of the puck as shown in Figures 7 and 8B. The grooves are 2 mm wide and are partitioned with walls of 1 mm thickness at regular intervals as shown in Figure 7. The grooves terminate at the rim. By not cutting through the rim, the design maintains lubrication and the

**Figure 7:** (A) Top view of grooves engraved into the tail surface of the base model. (B) Side view illustrating the angle of inclination of these grooves.

The initial design tested incorporated grooves inclined at 5° from the horizontal into the bottom surface of the puck as shown in Figures 7 and 8B. The grooves are 2 mm wide and are partitioned with walls of 1 mm thickness at regular intervals as shown in Figure 7. The grooves terminate at the rim. By not cutting through the rim, the design maintains lubrication and the

**Figure 8:** (A) Base model used for other designs. (B) Single slotted grooves. (C) Double slotted grooves partitioned along the diameter splitting the grooves in half. (D) Quadruple slotted grooves partitioned similar to the double slotted model. All the patterns are engraved onto the tail surface of the puck.
force necessary to levitate the puck by forcing the airflow down the rim wall and through the narrow gap between the rim and the air hockey table. As shown in Equation 6, the levitation force is heavily dependent on the size of the gap between the puck and the table. If the rim were to be removed the puck would not levitate. Additionally, through detailed pressure profiles obtained from our CFD simulations, these walls were determined to be a source for lateral force generation as pressure acts normal to these walls and help in propelling the puck along the direction of the grooves without any external sources other than the incoming air flow from the table. Similarly, other models were designed by introducing repeated patterns of grooves as shown in Figure 8. This required an increase in the groove angle from 5° for a single groove to 7° for a double groove and to 9° for a quadruple groove as shown in Figure 8C and 8D. Pressure and velocity profiles of these models are obtained by providing boundary conditions and solving through multiple iterations.

2.1.2. Rotational Motion

The primary purpose of this model is to provide levitation for gliding across the table and rotation to induce “English” onto the puck when struck by a player. Depending on the orientation of the blades, the puck rotates in a clockwise or an anti-clockwise manner and creates a level of uncertainty in the game. In this model, the central region comprises a standard air-hockey puck with similar dimensions as mentioned in Section 2.1.1. Turbine blades of thickness \( t_b = 1.75 \text{ mm} \) protrudes all the way from circumference of the puck to the walls of the enclosure as shown in Figure 9. These blades are modeled within the thickness of the enclosure \( t_c = 5.25 \text{ mm} \) and does not pass the bottom surface of the enclosure as shown in Figure 9B. Note that the bottom surface of the enclosure and the blades does not come in contact with the surface when placed on top of
The blade was extruded up to an angle of $\theta_b = 18^\circ$ and maintains a constant thickness throughout. This model contains 18 blades in total and all the blades follow a similar geometry lying within the enclosure. The enclosure was provided around the blades to increase structural integrity and also guide the incoming airflow through the blades efficiently to provide maximum torque. The outer and inner radius of the enclosure is given by $R_{out} = 50$ mm and $R_{in} = 48$ mm, respectively as shown in Figure 9C. Streamline visuals of air flow and the amount of rotational

**Figure 9:** (A) Represents the parts involved in this model. (B) Illustrates the top surface and bottom surface of the puck and thickness of the enclosure and the central region. (C) Top view of the model showing outer and inner radius of the enclosure. (D) Illustrates the blade extrusion angle.
force exerted on the blades are studied extensively through iterative simulations using Ansys fluent package.

2.2. Modified Model Geometry

2.2.1. Variations in Outlet Holes Featured Lateral Models

Upon numerical and experimental analysis from preliminary studies, the puck with single slotted grooves outperformed the models with double and quad slotted grooves and was chosen as the preliminary model for investigating aerodynamic performance of the pucks on incorporating outlet features. The outlet hole was placed at the bottom of the groove wall towards the deeper end as shown in Figure A since pressure accumulates at the end of these grooves when air starts flowing into the puck.

The outlet hole feature is converging in nature to compress air flowing out through the outlet which in turn produces more lateral

Figure 10: Illustrates the outlet hole feature and its location on the single slotted groove puck.

Figure 11: Illustrates the outlet hole feature dimensions.
thrust due to momentum conservation compared to an outlet without the converging feature. Base of the outlet hole is 2 mm wide and 2.5 mm tall as shown in Figure B. Further, a draft angle of 10 degrees was utilized to provide for the converging nature of the outlet hole as shown in Figure B. This angle was arbitrarily chosen to provide for minimum gap requirement on the converging side of the outlet hole in order to 3D print without enclosing the smaller end.

![Figure 12: Illustrates the variations in number of outlet holes for each model.](image)

Unlike rotational models, there are no geometric parameter variations for lateral models. Rather, the number of outlet holes incorporated was varied starting from a single outlet placed at the end of the central groove and increasing the number of outlets by adding them on either side
of the central groove all the way till the last groove on either side as shown in Figure C. The above six models are used to study the effects of increasing outlet holes on lateral and lift forces.

2.2.2. Variations of Geometric Parameter in Rotational Models

Numerical investigation was performed on the preliminary model by varying geometric parameters and studying their effects on aerodynamic performance. The preliminary model used for rotational motion essentially consists of two main components, the central region and the turbine blades located along the circumference of the central region. The central region plays an important role in providing the majority of lift force while the turbine blades are responsible for torque generation. The two distinct parameters used for investigating the aerodynamic performance are outer radius of central region and blade extrusion angle. Geometric parameters that are kept constant throughout this investigation are outer (50 mm) and inner radius (48 mm) of enclosure, blade thickness (1.75 mm), lip thickness (5 mm) of the central region, enclosure thickness (5.25 mm) and central region thickness (6.25 mm).

![Figure 13: Illustrates increments of blade extrusion angle from top view.](image)
The preliminary model utilizes an 18° blade extrusion angle and 32 mm as outer radius for the central region. The first parameter of consideration is the blade extrusion angle $\theta_b$. Increments of 4 degrees were made above and below the blade extrusion angle used in the preliminary model as shown in Figure A while keeping the outer radius of the central region constant. This blade extrusion angle has a direct effect on blade length and as a result affects the torque generation. As blade extrusion angle decreases from 26° to 10°, the blade length reduces proportionally. Note that normal vector of the blade is affected by the variation in blade extrusion angle as shown in Figure B and plays a significant role in determining the lift and drag forces acting on the blade due to incoming airflow.

**Figure 14:** Illustrates blade length highlighted in red lines and its normal vector shown along the front view of each puck.

**Figure 15:** Represents the number of blades in each model corresponding to 26°, 22°, 18°, 14° and 10° blade extrusion angle.
The preliminary model consists of 18 blades in total corresponding to an 18° blade extrusion angle. The number of blades were determined solely by maintaining zero gap between each blade with minimum overlap when viewed from the top. This was primarily done to maximize interaction between the blades and the incoming airflow. As the blade extrusion angle varies, the total number of blades were also varied in accordance with the criteria discussed above as shown in Figure C.

The second parameter of interest is the outer radius $R_c$ of the central region. Preliminary model consists of a central region with an outer radius of 32 mm. This central region comprises a lip that is 5 mm thick and remains constant while the outer radius and blade extrusion angles are varied. For this investigation, the outer radii of the central regions are 25 mm, 32 mm and 38 mm as shown in Figure D.

![Figure 16: Depicts the variation in central region when viewed from the top.](image)

The blade extrusion angle used for all three models shown in Figure D is 18°. For each geometric variation in the central region, there exists 5 different variations in blade extrusion angle as discussed above, resulting in a total of 15 different combinations. By studying these models using Ansys fluent, we can determine the optimum design for generating maximum torque while maintaining required amount of lift force. Note that there are numerous possible
variations in geometric parameters apart from the two main parameters considered for this study and left for future investigations.

2.3. Numerical Simulation Setup

![Diagram](image)

**Figure 17:** Schematic diagram of particle tracking to determine jet velocity.

A standard 110 V 60 Hz UL motor powered air hockey table was used for experimental purposes to test the 3D printed models serving towards lateral motion. The “active” surface area or the porous surface area is 1.83 m long and 1 m wide with 1.5 mm diameter outlets spaced at equal intervals of 10 mm along its length and its width. Velocity of air flowing out through individual outlets is crucial data for modeling one of the boundary conditions and was measured through particle tracking. Here, silver coated glass particles of order 25 microns in size were dispersed around the orifice of a single outlet. A cylindrical lens was placed in between the laser and the table to fan out a single beam to a plane of light, which was aligned in line with the outlet containing reflective particles. These particles are then carried along when air flows through the outlet. The reflections of the laser light off the particles were captured on a high-speed camera (Phantom V4.2) at 2000 frames per second revealing the flow pattern of the jets of air produced.
by the air hockey table as shown in Figure 10. The motion of the particles was tracked frame by frame using image tracker to determine the particle velocity exiting the air hockey table. Since these particles are extremely small, the particles will move affinely with the air and as a result, the velocity of these particles can be taken to be the velocity of air flowing out. This allows us to accurately determine the velocity of air flow through each outlet by taking all the losses into consideration due to manufacturing defects. The average air velocity exiting the air hockey table was determined to be 1.7 m/s. Images of the puck before and after levitation were captured and displacement of the puck was obtained through image tracking. This puck displacement is given by air film thickness between the puck and the table for the base model and was measured to be 0.5 mm.

The table used for experimenting 3D printed pucks serving towards rotational motion was a high-end Air hockey table specifically designed for arcade centers and tournaments. This table utilizes motor fan rated at 110 V and 60 Hz but spins at a much higher RPM compared to the table used for testing lateral motion models, generating close to 400 cubic feet per minute of air. The table consists of 3741 outlet holes with a diameter of 1.5 mm spaced at 25 mm from each other. With this data, we are able to find the average velocity of air flowing through each outlet and was determined to be 7.15 m/s without accounting for any losses and is used was the inlet velocity for rotational motion-based simulations while retaining the gap between the puck and the table as 0.5 mm for all cases.
2.4. Numerical Simulation Methods

2.4.1. Lateral Motion Simulation Methods

![Diagram of subject modeled within the environment illustrating inlet ports, subject positioning, and outlet parameters.](image)

Figure 18: (A) Diagram of subject modeled within the environment illustrating inlet ports, subject positioning, and outlet parameters. (B) Image of mesh refinement at high density

In order to perform numerical simulations, the geometry of the air hockey puck and table were modelled rigorously within a 3D environment that emulated a real-time air hockey puck and a table as shown in Figure 11. In order to optimize efficiency and minimize computation time, mesh refinement was localized to areas with complex structures: within corners of the grooves, in between puck and the table, and at the inlet ports as shown in Figure 11. Tetrahedral elements with an average and minimum element sizes of 7.5 mm and 0.5 mm were used, as they do a better job of covering nooks and corners of our geometry with lowest element skewness. This allows us to efficiently mesh our geometry while limiting total number of nodes to 220,680. Pressure based steady state simulation were performed for over 600 iterations to achieve a converged solution with errors of order $10^{-6}$ and a computational time of 60-70 mins per simulation. The air flow was modeled using the Sst k-omega turbulence model with the default parameters for air. Walls of the environment and the subject were set to be stationary, with a no slip boundary condition on the subject walls and a zero-shear boundary condition on the
environment walls to reduce computation time. Since the gap between the subject and inlet is so small, air has very less room to move around and backflow issues are likely to arise at the inlet, hence a zero-backflow condition was provided to eliminate these reverse flows.

2.4.2. Rotational Motion Simulation Methods

Unlike the environment modeled for lateral motion pucks, this model utilizes a cylindrical chamber where inlet velocity is set to 7.15 m/s as shown in Figure 12 flowing through 1.5 mm outlet holes spaced at 25 mm from each other along x and y direction. Outlet holes are oriented under the puck in such a way that torque and lift force generated are lowest among all possibilities. Subject walls were set to no slip boundary condition while the chamber walls were set to 0 shear boundary condition since viscous effects do not matter along these walls. Tetrahedral elements with an average and minimum element sizes of 7.5 mm and 0.5 mm were used, as they perform a great job of covering nooks and corners of our geometry with the lowest element skewness. This allows us to efficiently mesh our geometry while limiting total number
of nodes to 3147710 and reduce computing time as much as possible. Pressure based steady state simulation were performed for over 600 iterations to achieve a converged solution with errors of order $10^{-6}$ and a computational time of 150-200 mins per simulation. The air flow was modeled using the Sst k-omega turbulence model with default parameters of air. Torque exerted and flow through the puck were visualized in detail using CFX post processing.
3. RESULTS AND OBSERVATIONS

3.1. Preliminary Numerical Results

3.1.1. Lateral Motion Simulations

Numerical simulation was performed on a series of different geometries with grooved bottom surfaces. The grooves were designed with a saw tooth pattern that spanned the bottom surface of the puck from one end of the rim to the other. Patterns of zero (flat), one, two and four saw teeth shaped grooves were modeled as shown in Figure 13.

![Figure 20](image)

**Figure 20:** Contour plots of velocity magnitude along yz-plane for all four models illustrating flow fields of the incoming jet streams.

Air flows at a speed \( V = 1.7 \) m/s through every single inlet hole located under the puck, and these jets are positioned in such a way that the stream in the middle is aligned with the center of the puck. Comparative study reveals that this alignment results in producing the lowest lateral and lift forces and naturally becomes the choice of alignment for all other numerical simulations.
involved in optimizing geometric parameters. Contour plot of velocity along the diameter of the puck containing maximum number of inlet jets were plotted in 2D for all four models as shown in Figure 13. Note how all three jets split symmetrically on either side after impinging onto the bottom surface of the puck for the base model. These streams further diffuse into adjacent jet streams and exits with a mass flow rate of \(1.63 \times 10^{-5}\) kg/s on either side under the base model of the puck as shown in Figure 13. This is exactly half the total mass flow coming in through all the jets under the puck, proving that the flow is symmetric along y-axis for the base model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass flow rate to left (kg/s)</th>
<th>Mass flow rate to right (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single slotted grooves</td>
<td>1.60E-05</td>
<td>1.66E-05</td>
</tr>
<tr>
<td>Double slotted grooves</td>
<td>1.65E-05</td>
<td>1.63E-05</td>
</tr>
<tr>
<td>Quad slotted grooves</td>
<td>1.63E-05</td>
<td>1.63E-05</td>
</tr>
</tbody>
</table>

Table 1: Mass flow rates of air exiting on both left and right side the puck for the models with pattern.

Table 1 clearly proves that incorporating grooves and saw tooth type patterns affect the flow symmetry. Unlike the base model, these designs exhibit a difference in mass flow rates through the outlet on both left and right side of the pucks except for the design with quad slotted grooves. Asymmetry in flow is particularly highest for the model with single slotted grooves since all three jets interact and diffuse along a single groove without obstructions caused by including slots. Note how this asymmetry deteriorates as the number slots are increased as shown in Table 1. Contour plots of static pressure under the pucks for all four models helps us correlate crucial data of pressure forces responsible for lift (y-axis) and lateral forces (z-axis) exerted on vertical/groove walls to further optimize the design based on geometric parameters.
Average static pressure under the base model puck is 0.244 pascals with a maximum static pressure of 3.01 pascals acting at the three points on the bottom surface of the puck right above the inlet jets as shown in Figure 14. Pressure force exerted on the base model is of the order $7.8 \times 10^{-4}$ N in magnitude acting along the normal to the bottom surface which is in $y$-direction alone since it has a flat surface. Maximum static pressure points are located on the groove right above the jet stream located closest to the groove wall as shown in Figure 14. Note how static pressure is higher at the corner of each groove where the vertical and groove wall meet. This tells us that components of normal pressure force along $y$ and $z$-axis acting on the groove walls are ideally responsible for lift and lateral drag forces, respectively. Maximum static pressure and lift force drop as slots are added to the grooves, while lateral forces due to pressure and shear on vertical and groove walls increase as slots are added to the grooves.

**Figure 21:** Contour plots of static pressure illustrating points of maximum pressure along the grooves.
As shown in Table 2 proving the relation between pressure and gap under the puck as shown in equation 3. As illustrated, lift force is significantly low for double and quad slotted grooves compared to single slotted grooves and base model pucks. Lateral forces along x-axis are assumed to be 0 since numerical results reveals that total force exerted on the puck walls along x-axis is of the order $10^{-9}$ N for all three models and this can be associated to numerical errors. An increasing trend is observed for lateral forces due to pressure on both groove and vertical walls as slots are added to the grooves. Note that lateral forces exerted on vertical and groove walls along z-direction are almost equal in magnitude but slightly lower on vertical walls. Table 2 also illustrates that lateral forces exerted on groove walls due to shear for single slotted and double slotted grooves is much lower compared to lateral force exerted on quad slotted grooves due to shear. This is due to increased number of inclined groove walls in quad slotted grooves resulting in a larger area available for shear. Total lateral forces exerted due to both pressure and shear are much lower since the lateral forces exerted on vertical and groove walls are opposite to each other and cancel out.

<table>
<thead>
<tr>
<th>Model</th>
<th>Max static pressure (Pa)</th>
<th>Lift force (N) due to pressure</th>
<th>Lateral force (N) on groove walls due to pressure</th>
<th>Lateral force (N) on vertical walls due to pressure</th>
<th>Lateral force (N) on groove walls due to shear</th>
<th>Total lateral force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single slotted grooves</td>
<td>2.76</td>
<td>0.00069</td>
<td>3.60E-05</td>
<td>-3.49E-05</td>
<td>1.73E-07</td>
<td>1.25E-06</td>
</tr>
<tr>
<td>Double slotted grooves</td>
<td>2.61</td>
<td>0.00049</td>
<td>4.48E-05</td>
<td>-4.47E-05</td>
<td>8.59E-07</td>
<td>9.73E-07</td>
</tr>
<tr>
<td>Quad slotted grooves</td>
<td>2.58</td>
<td>0.00042</td>
<td>12.39E-05</td>
<td>-1.23E-4</td>
<td>1.54E-06</td>
<td>2.88E-06</td>
</tr>
</tbody>
</table>

**Table 2**: Illustrates numerical results of static pressure, lift, and lateral forces exerted on the puck for all three models respectively. Note -ve sign indicates negative z-direction.
3.1.2. Rotational Motion Simulation

The central region of the rotational model extends further than the blades and the enclosure by 0.5 mm on the bottom surface as shown in Figure 15 and plays the role of a regular air hockey puck, to levitate once air flows through the table. Air escapes from under the lip of the central region and is forced to flow through the enclosure by the outlet holes located right below these blades generating necessary amount rotational force to spin the puck as shown in Figure 15.

Figure 22: Illustrates streamlines of air flow under the puck and into the blades.

Figure 23: Schematic diagram of velocity contour along yz-plane.
Air flows at a speed of 7.15 m/s through every outlet and contour plot of velocity magnitude along the section containing maximum number of outlet holes is plotted in 2D as shown in Figure 16. Note that the stream of air flowing in through the outlet holes located under the central region of the puck splits symmetrically after impinging under the puck and escapes through the gap between the table and the lip of the puck to further diffuse into the stream of air flowing through the outlets located under the blades. Contour plots of static pressure plotted at the same location as the velocity contour reveals more insights on pressure forces responsible for lifting and rotating the puck.

**Figure 24:** Schematic diagram of static pressure plotted along yz-plane.

Figure 17 discloses two points of maximum static pressure acting under the central region of the puck and is primarily responsible for all the lift force necessary to levitate the puck on a cushion of air. A maximum static pressure of 34.24 pascals is exerted underneath the puck producing $9.6\times10^{-4}$ Newtons of lift force along positive y direction as shown in Figure 17. A torque of $6.09\times10^{-6}$ N-m is exerted onto the blades of the puck about y-axis and is more than sufficient to rotate the puck on a cushion of air since no friction is involved between the puck and the table after levitation. Real time analysis of 3D printed pucks on an Air hockey table helps us correlate simulation and experimental results.
3.2. Numerical Results of Aerodynamically Modified Pucks

3.2.1. Lateral Motion

Numerical simulations of all six models were performed to study the loss of lift force and increase in lateral force due to progressive addition of outlet holes. The orange plot in Figure D represents improvement in lateral force while the blue plot represents loss in lift force. Note that the lift and lateral force data corresponding to zero outlet holes is essentially the puck model with no outlet holes. The plot clearly shows the increasing trend for lateral force and a decreasing trend for lift force as expected. Notice the abrupt improvement in lateral force for the puck with one outlet hole compared to the puck with no outlet holes and a sudden drop in lift force for the puck with 7 outlet holes compared to the puck with 5 outlet holes. Models with 7 or more outlet holes were disregarded since the value for loss of lift is not sufficiently accounted by the improvement in lateral force.

Figure 25: Represents a plot of lift and lateral force as a function of number of outlets holes.
The model with the best aerodynamic performance was chosen by introducing a factor which involves the ratio of magnitude of lift loss to the improvement in lateral force. This factor is evaluated for all the models with outlet holes in comparison to the model with no outlet holes as shown in Table A and allows us to choose the best performing model. The model corresponding to the lowest lift loss to lateral force gain ratio indicates that lift loss is minimal while lateral force improvement is significant which is ideally the best performing model. The model with 1 outlet hole was chosen as the optimized design for 3D printing and further testing on a real time air hockey table.

<table>
<thead>
<tr>
<th>Model</th>
<th>Lift force (N)</th>
<th>% Lift loss</th>
<th>Lateral force (N)</th>
<th>% Lateral force gain</th>
<th>Lift loss/Lateral gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 outlet holes</td>
<td>0.000690</td>
<td>-</td>
<td>1.25E-06</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1 outlet hole</td>
<td>0.000688</td>
<td>0.2692</td>
<td>1.71518E-06</td>
<td>3.72E+01</td>
<td>3.99E+00</td>
</tr>
<tr>
<td>3 outlet holes</td>
<td>0.000684</td>
<td>0.8616</td>
<td>1.87111E-06</td>
<td>4.97E+01</td>
<td>9.57E+00</td>
</tr>
<tr>
<td>5 outlet holes</td>
<td>0.000682</td>
<td>1.1847</td>
<td>2.11798E-06</td>
<td>6.94E+01</td>
<td>9.42E+00</td>
</tr>
<tr>
<td>7 outlet holes</td>
<td>0.000675</td>
<td>2.2078</td>
<td>2.40385E-06</td>
<td>9.23E+01</td>
<td>1.32E+01</td>
</tr>
<tr>
<td>9 outlet holes</td>
<td>0.000674</td>
<td>2.3155</td>
<td>2.63773E-06</td>
<td>1.11E+02</td>
<td>1.15E+01</td>
</tr>
<tr>
<td>17 outlet holes</td>
<td>0.000667</td>
<td>3.2310</td>
<td>3.91112E-06</td>
<td>2.13E+02</td>
<td>8.38E+00</td>
</tr>
</tbody>
</table>

Table 3: Describes numerical results of lift and lateral force of all 7 models. Loss of lift and lateral force gain percentage are calculated with respect to the model with no outlet holes.
3.2.2. Rotational Motion

Numerical simulations were performed on all 15 models and torque induced by these designs are plotted against the number of blades. Red squares indicate correlation of torque vs number of blades for models with 38 mm as central region radius, green circles represent models with 32 mm as central region radius and blue triangles represent models with 25 mm as central region radius. Figure E clearly shows that models with 38 mm outer radius exhibit an overall higher torque compared to models with 32 mm and 25 mm outer radii. All 3 plots follow a similar increasing trend in torque as number of blades increases. This can be associated to blade extrusion angle $\theta_b$, as $\theta_b$ reduces, component of force aiding in inducing torque increases while the component of force aiding towards lift force decreases. Torque generated was found to span between $3 \times 10^{-6}$ N-m to $12 \times 10^{-6}$ N-m which is large enough to rotate the puck in this frictionless situation.

Figure 26: Represents torque as a function of number of blades for three different central region radii.
All 5 models with 38 mm as the central region radius exhibit higher lift forces compared to the models with 25 mm and 32 mm central region radii. This is due to larger surface area at the central region responsible for producing majority of the lift force required to lift the puck. Simultaneously, a minor drop in lift force is observed in the trend as number of blades are increased since the component of force responsible for lift at the blades decreases while component of force responsible for torque is increased as discussed above. Based on the above two plots, it is clear that the models with 38 mm as the central region radius exhibit superior aerodynamic performance. In order to pick the optimized design among these 5 models, we can further classify the models with 38 mm central region radius by studying the loss of lift force to gain in torque ratio for each model compared to the base model. The base model chosen for comparison here will be the puck with 14 blades, loss of lift force and improvement in torque of other models with higher number of blades will be compared to the chosen base model.

Figure 27: Represents lift force as a function of number of blades for three different central region radii.
Table A distinctly elaborates loss of lift and improvement in torque as the number of blades are increased. Notice that improvement in torque percentage is significant as blades are increased compared to loss of lift force percentage. Torque to weight ratio of each model helps us identify the optimized design and is calculated by obtaining the weights of each model through Solidworks measurement tool. The optimized design was chosen by comparing this ratio and the model yielding the highest torque to weight ratio was considered for 3D printing and testing on a real time air hockey table. According to the data provided in table A, model with 30 blades corresponds to the highest torque to weight ratio and was chosen as the optimized design due to its superior performance. Further, this model was used to 3D print and test on a real time Air hockey table for experimental trials.

<table>
<thead>
<tr>
<th>Model</th>
<th>Lift force (N)</th>
<th>% Lift loss</th>
<th>Torque (N-m)</th>
<th>% Torque gain</th>
<th>Torque/Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Blades</td>
<td>0.00841</td>
<td>-</td>
<td>4.77E-6</td>
<td>-</td>
<td>1.36E-4</td>
</tr>
<tr>
<td>16 Blades</td>
<td>0.00834</td>
<td>.775</td>
<td>6.21E-6</td>
<td>30.3</td>
<td>1.77E-4</td>
</tr>
<tr>
<td>18 Blades</td>
<td>0.00829</td>
<td>1.42</td>
<td>6.43E-6</td>
<td>34.8</td>
<td>1.82E-4</td>
</tr>
<tr>
<td>24 Blades</td>
<td>0.00814</td>
<td>3.17</td>
<td>8.05E-6</td>
<td>68.9</td>
<td>2.25E-4</td>
</tr>
<tr>
<td>30 Blades</td>
<td>0.00797</td>
<td>5.17</td>
<td>1.17E-5</td>
<td>145</td>
<td>3.21E-4</td>
</tr>
</tbody>
</table>

Table 4: Describes numerical results of lift and torque of all 5 models with 38 mm as central region radius. Loss of lift and torque gain are calculated with respect to the model with 14 blades.
3.3. Preliminary Experimental Results

3.3.1. Lateral Motion

The net unbalanced force in z-direction as shown in Table 2 was primarily expected to be responsible for inducing motion to the puck along the direction of groove orientation. Although the lateral forces are very small, this is sufficient to propel a floating object over a smooth surface. All three puck models are 3D printed using ABS (Acrylonitrile Butadiene Styrene) plastic of density 1052 kg/m$^3$ and tested on a real time air hockey table. Puck motion was captured by placing a camera above the puck and studied using image tracker to obtain motion parameters and validate numerical results from CFD.

Experimental trials successfully showed that the puck with single slotted grooves propelled laterally as expected along the orientation of grooves while double slotted and quad slotted groove models remained stationary. This can be associated insufficient lift force required for these two models to levitate over imperfections on the surface of the table. Acceleration of puck with single slotted grooves was estimated to be 0.00421 m/s$^2$ and is calculated by determining the average acceleration of the puck aligned along both positive and negative z-axis to minimize errors. Using this acceleration and know mass of the puck, a total lateral force of $5 \times 10^{-5}$ N was estimated to be exerted on the puck.

3.3.2. Rotational Motion

Trails were conducted on a tournament grade Air hockey table by 3D printing the optimized model using ABS (Acrylonitrile Butadiene Styrene) plastic similar to the lateral models and their motion was captured using a camera placed right above the table. Image tracker was used to study the motion of the puck frame by frame and analyze angular acceleration. To
minimize errors in the readings recorded by the image tracker, the puck was spun in the opposite
direction first and allowed to decelerate and spin in the intended direction afterwards. An
average angular acceleration of 12.9 rads/sec² was obtained by collecting data over 5 different
runs. Moment of inertia of the rotating puck about y-axis was determined to be 2.27×10⁻⁵ kg·m²
using Solidworks and the torque exerted on the puck was derived to be 2.9×10⁻⁴ N·m.

3.4. Experimental Results of Aerodynamically Modified Pucks

3.4.1. Lateral Motion

Through numerical analysis, the puck model with 1 outlet hole placed at the central
groove was chosen for experimental trials. The puck failed to propel along the lateral direction
even though the puck levitated at a small height. The levitation height or the gap between the
puck and the table was observed to be lower than usual and as a result did not slide across the
table in a smooth manner.

3.4.2. Rotational Motion

The puck with 16 blades and a central region radius of 38 mm was chosen as the
optimized model and 3D printed using ABS plastic. The trials were carried out on an industrial
grade air hockey table similar to the one used for our preliminary rotational model. A similar
approach on spinning the puck against the direction of induced torque to allow the puck to
deaccelerate and accelerate was used in order to reduce experimental errors. On obtaining
average results over 5 different trials, the angular acceleration of the puck was determined to be
18.27 rads/sec². Moment of inertia of the puck about y-axis was determined to be 3.6×10⁻⁵ kg·m²
and the torque induced onto the puck was derived to be 6.57×10⁻⁴.
4. CONCLUSION

The overall goal of this thesis was to develop models of pucks producing lateral and rotational motion when placed on the table without any external applications other than the air flow from within the table itself. Utilizing the information provided by literature, a series of patterns and features were introduced on a standard air hockey puck to aid in generating a pressure gradient as a result producing the desired force.

A systematic approach was followed to further develop the preliminary models for both lateral and rotational motion by adding features and varying geometric parameters to maximize lateral force and torque exerted. Design based optimizations were performed by 3D modeling using Solidworks and obtaining numerical results of pressure-density profiles using Ansys fluent package. Numerical solutions were then cross verified by 3D printing optimized designs and testing them on a real time Air hockey table. Empirical data was recorded by image tracking the motion of these pucks frame by frame. Both models proved to fulfill their purpose of design and were successfully able to perform on a real time Air hockey table as intended. The lateral models with outlet feature did not meet our expectations since the position of incoming air jets do not align with the groove containing the outlet hole most of the time. The jet alignment with patterns under the puck never impacted aerodynamic performance for the preliminary models and this opens up discussion to a wide range of solutions and a possible answer for future research work.
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