OPTIMUM DESIGN OF THE AIR-TURBINE FOR THE HIGH-SPEED DENTAL AIR-TURBINE HANDPIECE USING DESIGN OF EXPERIMENT

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Abstract- High-pressure air enters the air-turbine of the dental handpiece and strikes the blades to drive the impeller. The air-turbine has impeller and the air tube is connected to the air-turbine housing. The flowfield of the air-turbine were investigated for the optimum air-turbine design using ANSYS CFX. The objective of the research was to find an optimum design variables for the air-turbine to increase the torque. Design of Experiments (DOE) was used for the optimization design of the air-turbine. The airflow inside the air turbine was analyzed by changing the impeller blade number and angle and the gap as the design variables. The computational results showed influential design variables for the optimization to improve the performance of the air-turbine. The optimum values of the design were observed using Analysis of Variance (ANOVA). The optimum design variables were when the blade angle and number and the gap were 90 degree, 7 and 0.13 mm, respectively. The dental handpiece with the optimum air-turbine was manufactured for the performance analysis. The performance results of the existing advanced handpieces were compared by the high quality accuracy, reliability and flexibility. The designed dental air-turbine handpiece was compatible with advanced handpieces.

Index terms- Air-turbine, ANSYS CFX, Concave type blade, optimization, Torque

I. INTRODUCTION

The high-speed dental air-turbine handpieces were developed to remove dental caries and for cavity preparation. The dental handpieces are largely divided into three parts: head, neck and body. The air-turbine is located at the head while the air tube which is inside the body is connected to the head to supply the compressed-air. Improving the air-turbine performances increases the dental handpiece performance [1, 2].

The impeller blades influences the high rotational speed with enough torque to drive a dental drill. The impeller blades rotate at high speed, and the bur is applied to the teeth [3]. The torque at the impeller has high influence on the vibration of the handpiece and the capability of cutting the tooth. The cutting capability is improved when the torque value is high and the torque is important to determine the performance of the air-turbine [4]. The design parameters which influence the performance of the dental handpieces were studied in numerical simulations and experimentally [5, 6].

The objective of research was to find the optimum the air-turbine to increase the torque. The flowfield inside the air-turbine was analyzed numerically using ANSYS CFX software [7]. Design of Experiments (DOE) of Minitab was used to generate the design variables and to analyze the optimization processes [8]. The influences of the design variables on the air-turbine design were analyzed by Analysis of Variance (ANOVA). The performances of the advanced dental air-turbine handpieces and the dental air-turbine handpiece with the optimum air-turbine were compared.

II. COMPUTATIONAL ANALYSIS

THE COMPUTATIONAL DOMAIN AND TOOLS

The flowfield of the air-turbine with the concave type impeller blade was investigated. The dimensions of the air-turbine impeller blade, housing, air inlet and air outlet are given in Table 1. The impeller is the main part of the air-turbine and is rotated by the compressed-air supplied through the air tube. Figure 1 show the cross-section view of the head of the dental handpiece. The compressed-air passes through the gap between the impeller blade and shroud of the turbine cartridge and exhausts through the air outlet. The inner and outer radii of the blades were 3.716 mm and 5.675 mm, respectively. The angle of the impeller blades was 90° and the gap (or tip clearance) between the housing and the impeller blade was 0.15 mm. The height of the impeller blade was 4.325 mm.

The flowfield of computational domain was turbulent flow of an air. The domain was computed by the k-ε turbulent model of ANSYS CFX. Computational Fluid Dynamics (CFD) simulation software helps to predict fluid flows and to design new air-turbine for manufacturing [9]. CFD solves Reynolds-averaged Navier-Stokes equations using turbulence models to compute the averaged turbulent stresses. k-ε turbulence model was used for the computation [10]. Standard two-equation turbulence models often fail to predict the onset and the amount of flow separation under adverse pressure-gradient conditions.

III. THE SOLVER AND BOUNDARY CONDITIONS AND THE GRID VALIDATIONS STUDY

The computational results were obtained using parallel computers running a Linux operating system. The computational domain was divided into multiple domains to compute using CFX. The air-inlet and air-outlet domains were fixed. The solid turbine blade part of the computational domain was rotated with specified angular velocity about the given axis to simulate the running impeller. Table 2 presents the solver conditions of the computational domain for CFX. The working fluid was an air under atmospheric pressure condition and the reference temperature of the air was 25°C. The wall boundary condition was used for the housing wall and the impeller blades. All walls of the domain were treated as viscous adiabatic surfaces with a no-slip velocity condition. The boundary conditions were applied for the computational domain as given in Table 3. The inlet gage pressure condition of 300,000Pa was applied at the air inlet. The outlet condition was applied at the air outlet while the relative pressure was zero atmospheric pressure.

The grid of the computational domain was generated by hex grid and the hex dominant meshing is applicable to small domains. The element size was 0.00025m for this domain to create well shaped hexes. The grid validation study was performed to ensure that the computed quantities would properly converge. The numbers of the grid elements were between 0.7 million – 2.4 million. The grid validations for the computations using CFX indicated that the proper numbers of grid elements were about 1.9 million and 2.2 million.

Table 1. Dimensions of the impeller and housing for the computation

<table>
<thead>
<tr>
<th>Dimensions of impeller</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius, mm</td>
<td>3.5</td>
</tr>
<tr>
<td>Blade Angle degree</td>
<td>90</td>
</tr>
<tr>
<td>Outer radius, mm</td>
<td>5.65</td>
</tr>
<tr>
<td>Gap, mm</td>
<td>0.15</td>
</tr>
<tr>
<td>Height, mm</td>
<td>4.325</td>
</tr>
<tr>
<td>Blade number</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2. Solver conditions for the computation

<table>
<thead>
<tr>
<th>Analysis type</th>
<th>Steady</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air properties</td>
<td>Incompressible</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>k-Epsilon</td>
</tr>
<tr>
<td>Domain type (impeller)</td>
<td>Immersed solid</td>
</tr>
<tr>
<td>Rotating speed, RPM</td>
<td>300,000</td>
</tr>
</tbody>
</table>

Table 3. The boundary conditions for the computational domain

<table>
<thead>
<tr>
<th>Boundary Conditions</th>
<th>Locations</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>Air inlet</td>
<td>3000000 Pa</td>
</tr>
<tr>
<td>Outlet</td>
<td>Air Outlet</td>
<td>0 Pa</td>
</tr>
<tr>
<td>Wall</td>
<td>Housing wall</td>
<td>No-slip, adiabatic</td>
</tr>
</tbody>
</table>

IV. THE OPTIMIZATION METHOD

The Minitab DOE software can assign design variables, produce a set of experimental conditions, analyze results, translate design variable effects into graphs, and predict optimal results that the quality objectives are met. The DOE has the four phases such as planning, characterization (screening), optimization and verification. The DOE provides information about the interaction of design variables and shows how interconnected design variables respond over a wide range of values, without requiring the testing of all possible values directly. DOE is structured, organized method for determining the relationships among the design variables affecting the performance. The optimization methods in Minitab are general full factorial designs, Response Surface Method, mixture designs and Taguchi designs. The planning helps to avoid problems during the execution of the experimental plan.

The DOE begins with determining the objectives of an experiment and selecting the process design variables for the study and makes a detailed experimental plan before doing the experiment. The screening reduces the number of variables by identifying the key variables that affect product quality and suggests the optimal settings for the design variables. The optimization determines the best settings and defines the nature of the curvature. The verification performs the predicted processing conditions to confirm the optimization results.
V. RESULTS AND DISCUSSION

ANALYZING THE FLOWFIELD OF THE AIR-TURBINE

The air-turbine is rotated by the compressed-air supplied through the air tube. The compressed-air passes through the gap between the impeller blade and housing and exhausts out. The flowfield of the air-turbine with the concave type impeller blade was investigated. The dimensions of the air-turbine impeller blade are given in Table 1. The angle of the impeller blades was 90° and the gap between the housing and the impeller blade was 0.15 mm. The height of the impeller blade was 4.325 mm.

Figure 2. The impeller torque value at the blade cycle

Figure 3. The pressure and velocity distributions at the air-turbine

Figure 2 shows the torque values of the blade cycle. The maximum torque value at the impeller blades was 0.002474 Nm. The rotational speed of the impeller was 300,000 RPM and the number of the impeller blades were eight. The periodic cycles achieved after about 270 degree at the intervals of 45 degree. The most of the airflow from the air inlet bumped against the impeller blade, and the loss incurred which resulted in the minimum torque value. The pressure was applied in the opposite direction of the rotation and thus it resulted in the low torque. Figure 3 shows the velocity and pressure distributions of the computational domain of the air-turbine. The compressed-air from the air inlet pushed the front part of the front surface of the impeller blade and passes through the gap between the impeller blade and shroud of the turbine cartridge and exhausts through the air outlet. Most part of the compressed-air from the air inlet pushed the impeller blade while the other part of the air passes through the gap and pushes the front surface of the next blade.

VI. INFLUENCES OF GAP, THE IMPELLER BLADE NUMBER AND BLADE ANGLE ON THE PERFORMANCE OF THE AIR-TURBINE

The air turbine is the main part of the dental handpiece. The computational domain of the air-turbine was analyzed to determine the effect of the design variables. An existing air-turbine was selected as the original air-turbine. Some related dimensions of the air-turbine were changed, while rests of them were fixed during the computation.

The influences of the impeller blade number and blade angle on the torque was investigated with different impeller blade numbers and angles. The impeller blades were seven and nine, and other dimensions were the same. Most part of the airflow from the air inlet pushed the front surface of the impeller blade. The airflow affected the front and rear surfaces of the blades when the impeller had eight blades. The airflow from the air inlet was divided into two branches due to the position of the blade at the air inlet entrance. Table 4 shows the torque value with different blade number and angle. The relatively highest torque value was 0.002319 Nm when the impeller has eight blades.

The pressure distributions at the impeller blades were different depending on impeller blade angles. The air tube was connected to the housing so that the airflow hits at the center of the impeller blade. The relatively highest torque value of 0.002647 Nm was obtained when the compressed air hits the impeller blade. Figure 4 shows the pressure distributions at the blade with the velocity distributions when the gap was 0.15mm. All airflow from the air-inlet hits the front surface of the blade and the vortex was formed at bucket of the blade. The gap was slightly increased while the other dimensions were the same.

Table 4.

<table>
<thead>
<tr>
<th>Blade piece</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque, Nm</td>
<td>0.002127</td>
<td>0.002607</td>
<td>0.002474</td>
</tr>
<tr>
<td>Blade angle, degree</td>
<td>80</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Torque, Nm</td>
<td>0.00238</td>
<td>0.002413</td>
<td>Low torque</td>
</tr>
</tbody>
</table>

Figure 4. The pressure and velocity distributions at the air-turbine when the gap was 0.15mm
VII. THE OPTIMIZATION DESIGN OF THE AIR-TURBINE USING DOE

The gap, blade angle and blade number were selected as influential design variables from the computational studies as shown in Figure 5. The results of the design variables were evaluated by the torque. The variables influence the air-turbine performance substantially. DOE helped to investigate the effect of the variables on air-turbine and was used to specify the variables. The data was generated using general full factorial design that generates a design in which the design variables have three levels. The level of the variables were selected to limit the range of possible values due to the manufacturing. The levels of the design variables are presented in Table 5. The values of the design variables were assigned. The object function to evaluate the performance of the generated data was the torque.

D-optimality of the design minimizes the variance in the regression coefficients of the fitted design model and is used to determine an optimal design. The factorial design was used to predict the value of the torque for the combinations of the design variables as fitted values. Figure 6 presents the optimum value of the design variables for the optimum configurations. The composite desirability is 0.9610 and indicates how well the settings optimize the set of responses overall. The maximum torque was 0.00266 Nm when the blade angle and number, the gap were, 90 degree, 7 and 0.13mm, respectively. The results were analyzed using ANOVA, and the blade angle and number were a more significant design variable (p<0.05).

Table 5. The values of the design variables

<table>
<thead>
<tr>
<th>Levels</th>
<th>Level Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade number,</td>
<td>3</td>
</tr>
<tr>
<td>Blade angle, degree</td>
<td>3</td>
</tr>
<tr>
<td>Gap, mm</td>
<td>3</td>
</tr>
</tbody>
</table>

VIII. VALIDATIONS OF THE OPTIMUM RESULTS

The optimum and original air-turbine were computed under the same initial conditions to verify the optimized results of previous section. Table 6 presents the original and optimum design variables of the air-turbine. The blade number and angle were more significant variable while the gap was less significant variable.

Table 6. The results of the original and optimum air-turbine

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Blade number</th>
<th>Blade angle, degree</th>
<th>Gap, mm</th>
<th>Torque, Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>8</td>
<td>90</td>
<td>0.15</td>
<td>0.002473</td>
</tr>
<tr>
<td>Optimum</td>
<td>7</td>
<td>90</td>
<td>0.13</td>
<td>0.00266</td>
</tr>
</tbody>
</table>

Table 7. The results of the investigations

<table>
<thead>
<tr>
<th>Noise, dB</th>
<th>Bur eccentricity, mm</th>
<th>Rotational speed, rpm</th>
<th>Withdrawal force, N</th>
<th>Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSK</td>
<td>74.9</td>
<td>1/100</td>
<td>about 340.000</td>
<td>25.2</td>
</tr>
<tr>
<td>KaVo</td>
<td>72.7</td>
<td>1/100</td>
<td>about 340.000</td>
<td>26.8</td>
</tr>
<tr>
<td>The new handpiece</td>
<td>72.3</td>
<td>0.003</td>
<td>268.320</td>
<td>22.4</td>
</tr>
</tbody>
</table>

The prototype of the dental handpiece with the optimum air-turbine was manufactured for the performance analysis. The performance of the existing advanced handpieces were compared for the high quality accuracy, reliability and flexibility. The dental handpiece with the optimum air-turbine was compatible with advanced dental handpieces. The existing high-speed dental air-turbine handpieces have different structures by manufacturer with the shape and size of the head and with length of the body and coupling. The performance of NSK and KaVo type dental handpiece were analyzed by noise, bur eccentricity, rotational speed, withdrawal force and corrosion. Table 7 presents the investigated results of the existing dental handpieces and the dental handpiece with the optimum air-turbine and the results show almost similar performance.

CONCLUSIONS

The computational domain of the air-turbine of the dental handpiece was studied by solving Reynolds averaged Navier-Stokes equation along with a standard k-ε turbulence model of ANSYS CFX.
software. DOE method and Minitab software were used for the data generation and optimization. The computational domain was investigated to understand the flowfield of the air-turbine. The blade angle and number and the gap were analyzed to find the design variables which influence the torque. The blade angle and number and the gap were selected as the design variables for the optimization. The computational results were evaluated by the torque at the impeller. The levels of the design variables depend on the manufacturing conditions. The maximum torque was 0.00266 Nm when the blade number and angle, and the gap were 7, 90 degree and 0.13 mm, respectively. The blade number and angle were significant variables (p<0.05). The results of the optimum air-turbine were compared with the advanced existing handpieces. The results of the dental handpiece with the optimum air-turbine had the similar performance as the existing dental handpieces.

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REFERENCES


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