Design, Manufacturing and Analysis of Integrated Motor and Fan Assembly

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***Abstract*— the paper deals with optimization of the overall efficiency of a high mass-flow rate axial Fan meant for cooling purpose of electronic devices by shifting the motor assembly towards the rim (making it a rim driven Fan) and reducing the size of the hub. The design procedure aims to improve the blade geometry for reducing the losses due to swirls and vortex thus increasing the overall efficiency of the Fan. The design procedure follows an inverse method where in the air foil sections are derived from the mean-line profiles. The CFD Analysis reveals that the vortex and swirls were reduced to a certain extent as compared to the normal axial Fan with motor mounted in the hub.**

Keywords—axial Fan, cooling, optimization, swirls, vortex , *Rim motor, BLDC motor*

I. PROBLEM DEFINATION

A fan can be thought of as a low-pressure air pump that utilizes power from a motor to output a volumetric flow of air at a given pressure. An axial flow fan moves fluid parallel to the axis of rotation. Axial fans can have wide operating characteristics depending on the blade width, chord length, shape, number of blades and tip speed. Axial fans are generally used when a higher air flow rate is required in the system. So, depending on the application for which the fan has to be used for, the designer has to develop their own design technology so as to attain maximum efficiency. The analysis needs to be done by modifying various design variables, so the efficiency of the fan depends on design parameters.

There are two methods for designing a fan direct and indirect method.

Direct method assumes the profile generation through systematic geometrical technique and series of geometries that results in determining the most efficient aerodynamic performance. It involves air foil shapes with analytical polynomials and it shows that continuous curvature and slope are necessary to improve blade design, other direct method describes of the parametric fourth order which results in continuous slope of curvature with smooth Mach number and pressure distributions. Also, a mixture of analytical polynomials and mapping the air foil surfaces from a desirable curve distribution will provide an improved blade surface. But we have used the inverse design methodology where the air foil sections are being developed using the mean line profile and specifying various inlet and outlet angles for different sections. Mean line profile is one dimensional. During the designing process a set of different inlet and outlet angles were obtained and so the combination of these different angles has been used for iterations and blade profiles have been created. After the analysis of these various iterations the best of the iteration has been chosen for the development of the model.

For driving the Fan BLDC motor was selected and designed for the use. A Motor construction selected was such as to encompass the fan so as to make maximum use of area for air flow and reduce any obstruction for air flow.

II. DESIGN METHADOLOGY

A. List of Symbols

q_v Volume Flow Rate (m^3/sec)

D outer diameter of the Fan (m)

p_{sf} Static Pressure of the Fan (Pa)

p_t Total Pressure of the Fan (Pa)

p_{df} Dynamic Pressure of the Fan (Pa)

Φ Flow Coefficient

ψ Pressure Coefficient

δ_{op} Diameter Number

σ_s Speed Number

n rotor speed (rpm)

ω rotational speed (rad/sec)

v_a Axial velocity (m/sec)

R Radius of Fan (m)

w Tangential Flow velocity (m/s)

c Absolute Flow velocity (m/s)

γ Blade Profile Angle (deg)

c_u Radial Velocity(m/s)

z number of blades

D_h Diameter of Hub

B. Evaluation of Dimensionless parametes using Cordier Diagram.

The main purpose of evaluating the dimensionless parameters are that is gives a starting point of the design. In 1953 Otto Cordier linked the optimum operating conditions ie. the volume flow rate (q_v) and the operating pressure p_{sf} with optimum values of diameter(D) and the rotational speed (n) for the maximum possible efficiency for one stage machines with the aid of Speed number (σ_s) and the diameter number (δ_{op}).

The dimensionless parameters are useful in comparing performance of geometrically similar Fan design with different operating parameters, the equation of the Flow coefficient (Φ) and the Pressure coefficient (ψ) is given as

$$\Phi = \frac{q_v}{\left(\pi\frac{D^2}{4}\right)\left(\frac{\pi n D}{60}\right)} = \frac{v_a}{\omega R} \qquad (1)$$

$$\psi_f = \frac{p_f}{\frac{1}{2}\rho(\omega R)^2} \qquad (2)$$

The Cordier Diagram is given as Diameter number (δ_{op}) on X axis and Speed number(σ_s) on Y-axis. These both terms are expressed in the form of Flow Coefficient and Pressure Coefficient as

$$\delta_{op} = \frac{\psi_f^{\ 0.25}}{\Phi^{0.5}} \qquad (3)$$

$$\sigma_s = \frac{\Phi^{0.25}}{\psi_f^{\ 0.75}} \qquad (4)$$

Few operating conditions were considered for the evaluation based on the maximum efficiency line on Cordier Diagram.

The values consist of assuming the value of q_v (volumetric flowrate) to be in the range of 46 CFM – 108 CFM, the diameter is a major constraint imposed on the design considering the magnets available for the construction of rim driven motor, D = 76mm.

q_v	n	ΔPs	σ_s	δ_{op}
46	2000 3000 3500	46	0.7749 1.2869 1.5599	1.345
75	2000 3000 3500	46	0.8757 1.4537 1.7627	1.0539

After plotting the same in Cordier Diagram it is clear that the point with q_v = 46 CFM, n = 3500 rpm and ΔPs = 46 Pa locates a point in the diagram in close proximate with the Maximum Efficiency Curve.

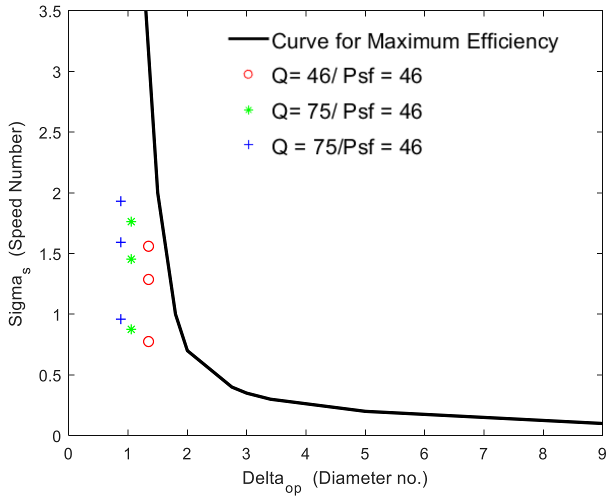


Figure 1:Cordier Diagram,Note:This Diagram has been Plotted in MATLAB by referring the original Cordier Diagram as given in the references

The fan configuration parameters which will give the maximum efficiency are selected as q_v = 46 CFM at n = 2000 rpm which will handle a static pressure difference of 46 Pa. According to the Fan application which is supposed to be used as an exhaust Fan which is open to atmosphere at both the ends, requires very less static pressure to overcome for generating the required flow. The power required to drive this fan is very less, most of the power being consumed by the fan to generate the flow rate and some part to overcome the pressure and losses in the form of air foil drag.

C. Selecting the Fan assembly configuration.

The Fan configuration plays an important role in improving the efficiency of the overall unit, there are major two configurations we have taken into consideration which are RO (Rotor only) configuration and RS (Rotor Straightener/Stator)

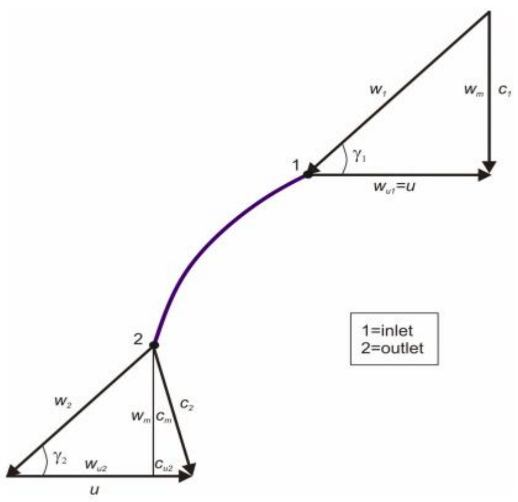
RO (Rotor only): This configuration consist of only Fan rotor and casing assembly, swirl velocities nearer to hub section cannot be recovered in this type of design, hence only suitable for higher hub-to-tip ratio, the maximum achievable efficiency is up to 75%, though due to simplicity of design this configuration is used a lot.

RS (Rotor Straightener/Stator): This configuration incorporates a stator blading which is static (does not rotates) to converts the swirl energy into static pressure. This increases the efficiency considerably and the maximum efficiency achievable is about 87%. This configuration becomes less compact due to incorporation of the stator blading, hence increases the weight of the assembly.

The Rotor only configuration was preferred for the design due its simplicity and compact nature.

D. *Mean Line calculations*

As mentioned in the introduction part there are 2 methods to proceed with the design i.e. direct method and indirect method, we proceed with the indirect method in which we calculate the inlet and the outlet Blade angle and develop a preliminary blade profile as a mean line assuming a suitable distribution, which may be parabolic or cubic. These calculation proceeds with developing a velocity triangle for a individual blade section and assuming a appropriate velocity and pressure distribution.



The static Pressure difference by Euler's Formulae is given as :

$$\Delta P_t = \frac{1}{2}\rho\{(w_1{}^2 - w_2{}^2) + (c_2{}^2 - c_1{}^2)\} \quad (5)$$

By solving this equation further, we can evaluate the value of γ_1 and γ_2 at different Blade sections.

The inlet blade angle γ_1 is calculated as

$$tan\gamma_1 = \frac{w_m}{w_{u1}} = \frac{w_m}{u} \quad (6)$$

$$tan\gamma_2 = \frac{w_m}{w_{u2}} \quad (7)$$

The Formulae are modified as

$$tan\gamma_1 = \frac{q_v}{\pi(r_t{}^2 - r_h{}^2)}\frac{1}{2\pi rn} \quad (8)$$

the outlet angle γ_2 is given as

$$\frac{1}{tan\gamma_2} = \frac{2\pi n}{rw_m}\left[r^2 - f(r)r_h{}^2\right] \quad (9)$$

Where f(r) is defined as a pressure distribution function

The design considers 3 components of velocity in the Axial Fan, those are the axial velocity, the tangential velocity/ swirl velocity and the Radial velocity, the required velocity is the axial velocity and the radial and swirl velocities are to be minimized by the blade design, the radial velocity distribution should be such that there will be a radial equilibrium that is the centrifugal force produced by the mass of the fluid should be balanced by the pressure force created by radial velocity distribution towards the centre. This is given by a equation.

$$\frac{1}{\rho}\frac{dp}{dr} = \frac{c_u{}^2}{r} \quad (10)$$

The stagnation Pressure is 0 for the value of $c_u r$ = K(constant) this can be confirmed after evaluating equation (10) In this case the flow is a non-vortex flow if $c_u r$ = g(r) which is a function of section radius then the flow is classified as a arbitrary vortex flow or the forced vortex flow. The design considers all the kind of flows in the form of iterations.

E. *Parameterization of Pressure distribution*

The Pressure distribution is given as the ratio of the

$$\frac{\Delta P_{t,r}}{\Delta P_{h,r}} = f(r) = x\left(\frac{r_{tip}}{r_{hub}}\right)^x (r - r_h)^y + 1 \quad (11)$$

The following distribution is considered for the flow, the references from where it is taken considers a very high hub to tip ratios, but in our case the ratio is too low to increase the flow, therefore the equation needs to be modified to incorporate with our type of flow.
We consider different values of 'x' and 'y' for our iterations.

The chord length distribution was assumed to be linear with decreasing chord length towards the hub.
The number of blades was assumed to be 8 which were to be the maximum for the configuration.

The number of sections were kept minimum to 4 section for maintaining the smoothness in the blade geometry. The blade geometry was created in SOLIDWORKS (3D Modelling Software) and the CFD Analysis was carried out in ANSYS.

III. ANALYSIS OF THE FAN IN ANSYS FLUNT

The Analysis is carried out in ANSYS FLUENT which is a commercial CFD code.

There were three iteration carried out for the model and the best of the iteration is chosen for the purpose of manufacturing.

Steps followed in the simulations

1. Pre processing - the solid model is imported into the design model and rotating and stationary domain are created . ANSYS meshing was used to create the mathematical mesh for the analysis and subsequently named sections are also assigned.
2. Boundary conditions - at the inlet and outlet were pressure inlet and pressure outlet with Pressure as atmospheric Pressure, since the Fan is open to atmosphere from both the end.
3. Post processing- In post processing stage the results are loaded and post processed for viewing and comparing with the traditional fan.

1. Iteration 1
   Conditions:
   Volume Flow rate (q_v) = 46 CFM
   D = 100mm
   n = 2500 rpm
   z = 8
   D_h = 10mm

Table 1:Inlet angle and Outlet angle for Blade Section at different locations

Design Variable	x = 1		x = 2		x = 3	
Section	γ_1	γ_2	γ_1	γ_2	γ_1	γ_2
1	85.6342	90	85.63	90	85.63	90
2	71.17	72.12	71.17	73.73	71.17	90
3	58.7977	59.23	58.79	59.97	58.79	74.1
4	48.9655	49.20	48.96	49.60	48.9	57.1

The design type considered for iteration is the arbitrary vortex flow i.e x = 2 and y = 1.35
This results in a Blade geometry as follows

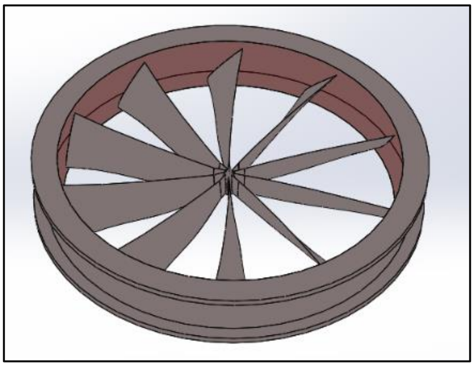


Figure 2:3D Model of Iteration 9

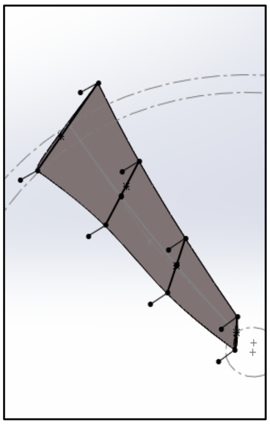


Figure 3: Blade element with 4 section

The ANSYS results are as follows
Axial Velocity = 5.23 m/s

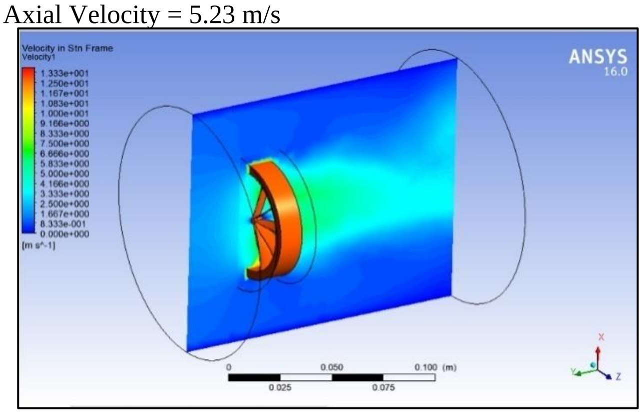


Figure4:Velocity Contour of Axial component of the velocity

This is the average Axial velocity generated through the fan
The Torque required to drive the Fan is coming to be

T = 0.000196767 [N m]

This is due to the Aerodynamic Drag generated by the air foil section

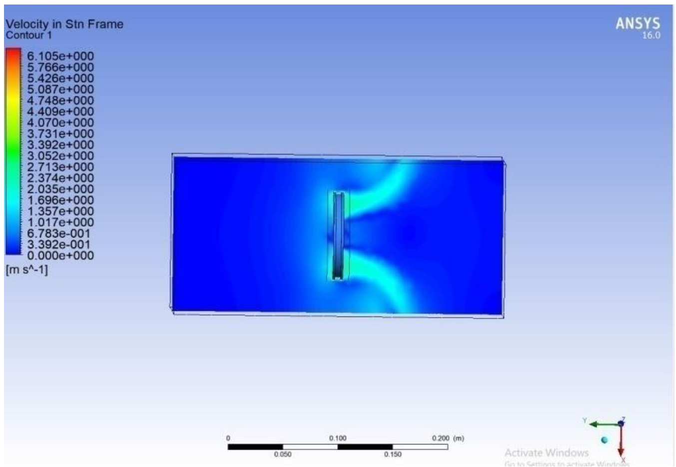


Figure 5:Velocity contour of the Fan

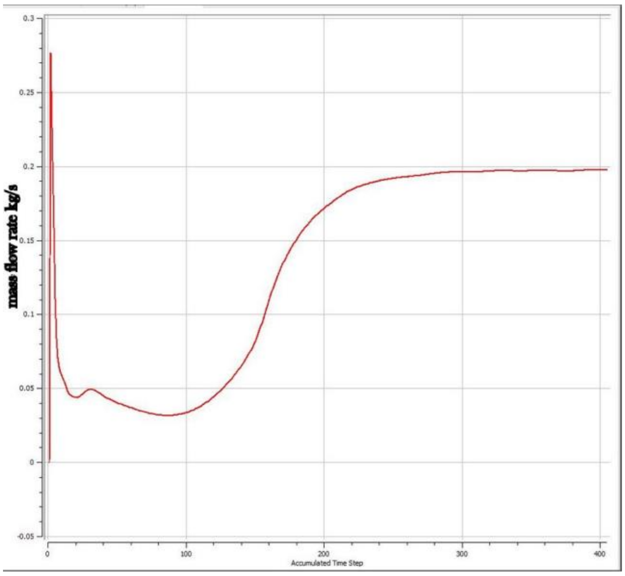


Figure 2Figure 6:plot of mass Flow rate

IV. BLDC MOTOR DESIGN APPROACH:

A. Selecting a drive mechanism:

The fan which is to be driven in the design is essentially a small-hub fan. This prohibits the use of shaft-motors (motors having a rotating shaft as the work producing component) as the mounting for the fan. The fan needs a driving mechanism which will not obstruct the flow of air (which is the primary objective) and which will be compact, will have small axial-length and which can be controlled easily. The driving mechanism was hence selected to be a BLDC motor. Any other motor – Brushed DC, AC etc would be impractical to be implemented in the design because these possess various mechanical as well as speed-control constraints.

B. Design Procedure for BLDC motor drive:

1) Deciding the INPUT PARAMETERS:

The BLDC motor being an electronically commutated motor, the design process needs to be carefully defined. The main inputs from the fan would be the continuous torque that is to be achieved, whereas the circumferential magnets would give the peak torque pertaining to the rotor inertia. The RPM of the fan also needs to be known for the desired mass flow of Air. Hence, the main inputs for the motor would be:

- The Continuous Torque
- The angular speed
- Operating Voltage
- Allowable Current Density

2) Selecting the magnet-strength and number of turns configuration:

The BLDC motor essentially has a set of permanent magnets and a set of stator coils (copper windings) which are mounted on silicon steel teeth. Now, the strengths of magnets and number of turns per

Coil, both depend on the ‘application’. The applications which demand very high torque and very low to moderate speed, need high power Neodymium Magnets which have a Remnance flux density of 12000 to 13000 Gauss. Such high strength magnets facilitate the use of comparatively low number of turns per coil, and also reduce the space needed for the rotor body. However, the mountings for magnets need to be stronger and this inevitably increases the overall dimensions, stator and rotor yoke widths and hence the weight drastically. Also, high power magnets would easily saturate the conducting core which would lead to a decrease in the flux- fluctuation allowance of the core.

Another configuration incorporates very low power magnets and comparatively higher number of turns. This allows the use of vey compact stator (reduced stator dimensions and hence the weight). Also, the lighter grade magnets will just produce the necessary torque for sustaining the load and hence the motor will not be overdesigned. Hence, we select a low-power magnet and higher number of turns configuration.

3) Magnet Material (Grade) and Type selection:

The magnet grade as shown earlier, greatly influences the motor dimensions. The high power magnets prove to be un-necessary for such a light load application. Hence flexible magnets made of polymer infused with iron particles and then magnetized are used. These materials have somewhat same characteristics of Ferrite Magnets. It is light weight and hence are perfect for the intended application.

4) Stator Material Selection:

Out of many metal options available for the stator, silicon steel is deliberately chosen which is the most widely used option for electrical applications. The reason being simple: Silicon steel has diffused Silicon in the steel which reduces the eddy current losses. Grain Oriented Silicon Steel is further chosen to improve the performance.

5) Actual Motor Design:

The BLDC motor can now be designed by considering the magnetic characteristics of the above mentioned materials for the Stator and Magnets. The design proceeds as:

1. **Stator design:**
   - Calculation of Stator Yoke Width
   - Calculation of Teeth thickness
   - Calculation of Stator Inside and Outside Radius
   - Calculation of Slot Area
   - Calculation of Shoe length
2. **Winding Design:**
   - Deciding the number of rotor and stator poles
   - Deciding the winding type
   - Calculation of various winding parameters
   - Deciding the wire diameter by the max current density allowed
   - Deciding the number of turns per coil

Formulae for stator Design are:

1. $\Phi t = \Phi total / Nst$
2. $Wsy = (\pi * Rro * Bg) / (Nm * Kst * Bsy)$
3. Shoe Length = $R_{so} - R_{si} - W_{sy}$
4. $As = (\pi / Ns) * [(Rso – Wsy)2 – (Rro + lg + dsht)2] – [Wtb * (Rso – wsy – lg – dsht)]$ (slot area)
5. $T = 4 * N_m * Bg * L_{st} * R_{ro} * N * I_{line}$ (torque)

   (Following are the direct results of Matlab code)
   Iteration 2:

Enter the Number of Magnet Poles (Nm): 32
Enter the Number of Stator Poles (Ns): 27
Enter the Remnance Magnetic Flux Density (Br) in Tesla: 0.03

- Flux concentration factor vs Number of turns:

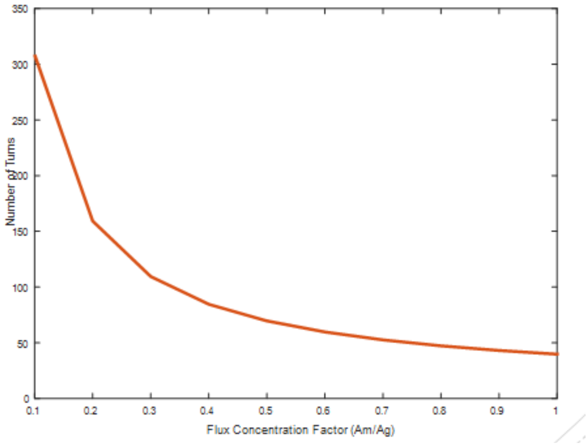


Figure 6: graph of flux concentration Factor Vs number of turns

Enter the Material Saturation Flux Density in Tesla: 0.8
Enter the Flux concentration factor (c): 0.8
Enter the Motor Axial Length in mm (LST): 5
Enter the ratio of Rotor Radius to Stator radius needed: 0.8
Enter the Desired RPM: 2500
Enter the Continuous Torque needed in N-mm: 0.004

Magnet Characteristics:

Permeance Coefficient = 5.0000
Air-gap Flux Density (Wb/sqm) = 0.018681
Total Flux (Wb) = 0.000023

Motor Geometry:

Tooth Width in mm = 0.2173 approximate to 1.5 mm
Stator Yoke Width in mm = 0.0917 approximate to 1.2 mm
Stator's Outer Radius in mm = 48.9968 approximate to 49 mm
Stator's Inner Radius in mm = 39.6975 approximate to 39.7 mm

- Remnance flux density vs Tooth width/ Stator Yoke Width:

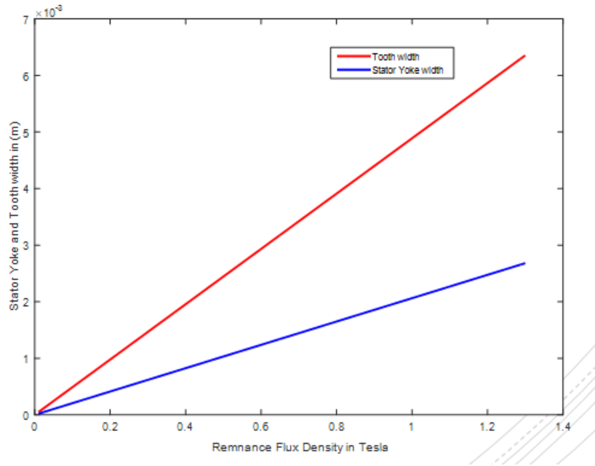


Figure 7: Graph of Remanance flux density vs tooth width/stator yoke width

The above graphs are plotted to see the performance characteristics of motor in various iteration and the selected ones are as mentioned below;

Mechanical Charachteristics:

Inertia Torque in N-mm = 0.000004700
Continuous Torque in N-mm = 0.0080
Continuous Power in Watts = 1.0472

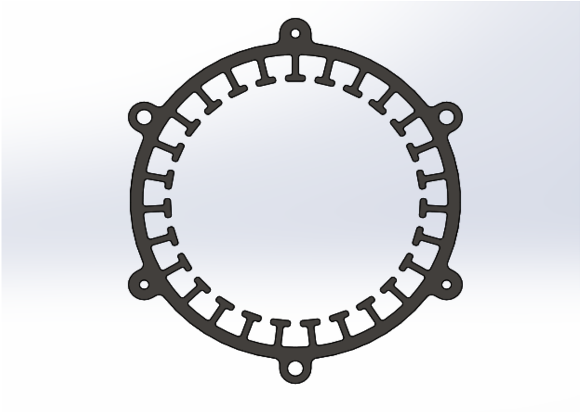


Figure 8: Stator Geometry

Winding Charachteristics:

Number of turns per coil = 45.5757 approximated to 46 turns

V. FINAL ASSEMBLY

The final assembly is as follows
Stator is made up of CRNO steel laminates (10 plates 0.5 mm each) riveted together and winding done with 28 gauge copper enamel wire. This stator is placed in a 3D printed casing.
The Fan is pivoted in the centre using a pin. This assembly is fixed in a frame work.

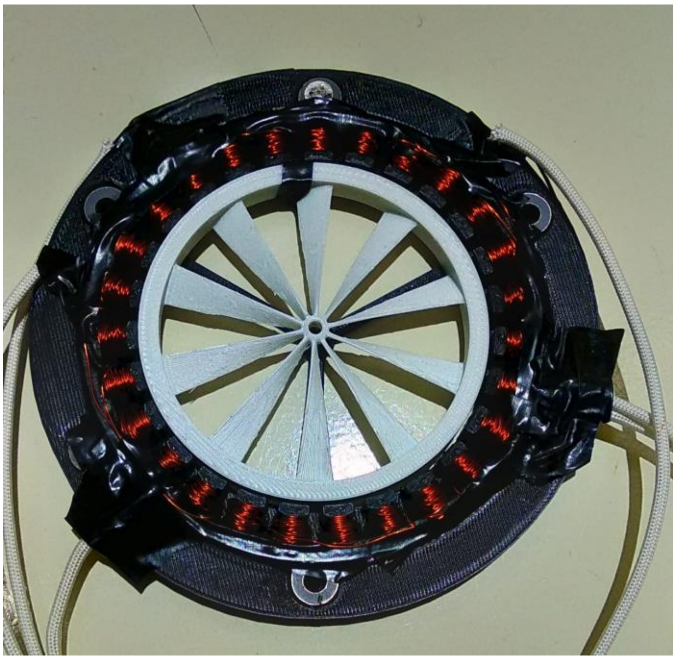


Figure 9: Final test setup

VI. RESULTS

From the above CFD analysis we found out that the that the above design is successfully producing higher velocity than conventional axial fans. The CFD analysis also reveals that the vortex and swirls have been reduced.
The fan efficiency is higher in this case.

VII. CONCLUSION and DISSCUSION

As per our results we can conclude that due to the removal of the motor mounting in the centre a much better vortex free and swirl free flow is achieved. This makes it suitable for a variety of applications in case of cooling. Due to flow properties, air is much more effective in heat absorption.
This makes it ideal for applications like electronic cooling fans, HVAC Ducting. Also its very small thickness gives a distinct advantage in terms of space and might prove to a highly advantageous.

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