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Mitigation of Destructive Effects of Tip Vortex in Ducted Axial Non-Twisted Fans by Utilization of Different Arrangement of Fanlets

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Abstract- On the circumstances that ducted axial fans are used abundantly in propulsion, air conditioning, power generating and other systems, studying their performances to find ways to optimize them is of immense importance. To minimize destructive effects of tip vortices on fan performance, in this study, effects of using different configurations of fanlets have been investigated. Therefore, using Blade Element (B.E.) theory, a basic blade was designed to generate 2, 4, and 6-blade models. Then each model was separately investigated in three different configurations of: up-let, down-let and fresh i.e. without fanlet, resulting in 9 final models. K-e turbulent modeling was used to evaluate performance of the models. Besides, Horizontal Element Separation (H.E.S.) was used as a post processing means to gain data of aerodynamic forces acting on the elements of blade to plot distribution profiles along the span. Convergence of C.F.D. outcome with results of blade element method for a two-blade fresh model proved C.F.D. method usage validity. Concluding results obviously demonstrate that performance of an axial aerial fan could be enhanced by maximum 3.6 percent using fanlets. Studying and analyzing distribution profiles reveals why and how fanlet affects performance of axial fans.

Keywords- *Axial Fan, Fanlet, H.E.S. method, K-epsilon Method*

I. INTRODUCTION

Tip vortices have indisputable negative effects on function of axial aerial fans. Periodic force produced by tip vortices intensifies vibration and noise of the blade. This consequently leads to a considerable drop in blade efficiency. Besides, tip vortices decrease thrust, increase torque, and affect induced angle of the blade elements. Due to similarities which exist between fan tip and wingtip vortices, common endeavors have been made in order to reduce their repercussion. Different strategies such as changing airfoil, using special covers and changing chord distribution have been presented to reduce tip vortex effects so far [1]. One of the most popular schemes to achieve this is application of a small vertical secondary wing on tip of the main wing which is usually called winglet. Although so far many studies have been carried out to find ways of optimizing performance of winglets on aircraft wings, little attention has been paid to the effects of winglets on axial turbo machines. This lack of research on the mentioned field is due to complexity of winglet function in axial turbo machines. It must be reminded that winglets used in aerial fans and propellers are respectively known as fanlets and propellers.

Main focus of researches about fanlet utilization on turbo machines is on horizontal axis wind turbines. Van Holten [2] in Delft University is considered to be the first person who investigated the use of fanlets. Result of his researches illustrated that power coefficient of an axial aerial turbine can be enhanced up to 0.45 using fanlets. Van Basel [3] presented Momentum theory and accordingly studies were carried out on the effects of fanlets on the wake. Later tastings [4] clearly refuted this theory’s accuracy. Eventually, researches conducted by Imamura [5] and Johansen [6,7] based on the C.F.D. tests showed that power coefficient of a wind turbine is predicted to be upgraded to 1.74 percent using fanlets.

Compared to wind turbines, fewer researches have been conducted on utilization of fanlets on axial fans. In this field, P. Anderson [8] in 1997 showed that using small wings improves the performance of marine propellers. Later J. P. Sullivan [9,10] in Purdue University through his investigations demonstrated that applying small wings improves the performance of propellers working in low viscosity fluids as well. Although there have been no significant attempts to investigate implication of the idea on Ducted axial flow fans.

Several attempts have been made to investigate effects of tip vortex in axial ducted fans. Inoue and Koroumarow [11] measured effects of tip clearance on fan tip leakage, before and after the rotating disk. Furukawa [12] studied break down of tip leakage in a low speed axial fan. However, there have been few attempts to orchestrate preventive measures to overcome destructive effects of tip vortex [13].

Beside proposing a preventive measure for effects of tip vortex, this study also accounts one additional unseen aspect of ducted fans. Nowadays, especially in small-sized fans, which by nature require slight twisting, there is a growing interest to produce non-twisted axial fans to reduce costs of fans in applications such as electrical fans [14]. Utilization of non-twisted blades most probably means effective changes in distribution of aerodynamic forces and strength of tip vortex. This study for the first time investigates the effects of winglet application on non-twisted ducted aerial fans. Formatter will need to create these components, incorporating the applicable criteria that follow.

II. C.F.D. METHOD

Since it was stated as a reliable method by former investigators [15], the two equations K-e: R.N.G. turbulence model was utilized through ANSYS Fluent commercial software package to gain performance information of the models. Since objective of this study was not to investigate proper usage of C.F.D. methods to analyze axial fans, conditions of numerical tests were based on previous efforts of authors [16] and other researchers [17, 18]. The tests were carried under unsteady conditions but to provide a perspicuous comparison between models results of final points of first periods of each model were compared.

In the present Standard k–ϵ turbulence model has been utilized with logarithmic surface function. The equations of mass and momentum protection used by the program can be written for the compressible and incompressible steady flows as follows in the Cartesian tensor rotation:

Continuity equation:

$$\frac{\partial}{\partial x_j}(\rho . u_j) = 0 \qquad (10)$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho . u_j . u_i - \tau_{ij}) = \frac{\partial p}{\partial x_j} + S_i \qquad (11)$$

In these two equations we have:

x_i Cartesian coordinate (j=1, 2, 3)

u_i Absolute velocity components in the direction of x_i .

p Piezometric pressure = $p_s - \rho_0 . g . x_m$ here, p_s is static pressure, ρ_0 is the reference dencity, g is the gravity acceleration andx_m is the coordinate defined by ρ_0

τ_{ij} Stress tensor components

Here, the stress tensor is as follows:

$$\tau_{ij} = \mu . s_{ij} - \frac{2}{3}\mu . \frac{\partial u_k}{\partial x_k} . \delta_{ij} \qquad (12)$$

Here, μ is the viscosity of the fluid, δ_{ij} (Kronecker delta) and s_{ij} is the change of shape modification tensor and written as follows:

$$s_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial x_i} \qquad (13)$$

If the Kronecker delta δ_{ij} is

$$i \neq j \Rightarrow 0, i = j \Rightarrow 1$$

Effective viscosity is:

$$\mu_{eff} = \mu + \mu_t \qquad (14)$$

Here, turbulent viscosity is obtained from

$$\mu_t = \rho . f_\mu . C_\mu . \frac{k^2}{\varepsilon} \qquad (15)$$

Turbulent kinetic energy (k):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}\left(\rho u_j k - \frac{\mu_{eff}}{\sigma_k} . \frac{\partial k}{\partial x_j}\right) = \mu_t s_{ij}\frac{\partial u_i}{\partial x_j} - \frac{2}{3}\left(\mu_t \frac{\partial u_i}{\partial x_i} + \rho k\right)\frac{\partial u_i}{\partial x_i} - \rho\varepsilon \qquad (16)$$

Dissipation rate of turbulent kinetic energy (ϵ):

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}\left(\rho . u_j . \varepsilon - \frac{\mu_{eff}}{\sigma_\varepsilon} . \frac{\partial \varepsilon}{\partial x_j}\right) = C_1 f_1 \frac{\varepsilon}{k}\left[\mu_t s_{ij}\frac{\partial u_i}{\partial x_j} - \frac{2}{3}\left(\mu_t \frac{\partial u_i}{\partial x_i} + \rho k\right)\frac{\partial u_i}{\partial x_j}\delta_{ij}\right] - C_2 f_2 \rho \frac{\varepsilon^2}{k} - C_3 \rho\varepsilon \frac{\partial u_i}{\partial x_i} \qquad (17)$$

In the above equations, the subscripts i,j,k and the empirical constants for the turbulence model $C_\mu, \sigma_k, \sigma_\varepsilon, C_{1\varepsilon}, C_{2\varepsilon}$ are equal to 1, 2, 3 and 0.09, 1.0, 1.3, 1.44, 1.92, respectively.

III. H.E.S. METHOD

C.F.D. codes themselves are not able to demonstrate distribution profiles along axial fan blades. In order to obtain such data, precise post processing methods are needed. Up to now main propose of illustration of aerodynamic distribution profiles was to demonstrate pressure-related parameters. However, recently by introduction of Horizontal Elements Separation (H.E.S.) method by same authors [19, 20], it was possible to illustrate actual thrust and torque distribution profiles along the blade. Expressing functional parameters and involving shear stresses on blade, thrust and torque distribution profiles are more comprehensive means to study an axial fan. By representing classic concepts of a finite wing regarding to drop of lift and drag profiles in wing tips, these profiles also bring a unique ability to conduct a perceptible investigation about effect of tip vortices on blade span.

In fact, H.E.S. method is a pre and post processing method, which enables the user to process output of a state of the art C.F.D. test by well-known blade element theory concepts. In this method, blade span is divided into a certain number of horizontal elements (same as blade element theory) before initialization of tests and after completion of tests, outcome of C.F.D. tests on each element is translated into thrust and torque. H.E.S. method data could be utilized by different proposes such as vibration, structural and aerodynamic performance analysis. Information of each element could be separated from whole blade's data and analyzed to investigate behavior of a certain part of blade due to a special change in that part.

Breadth of horizontal elements is one of aspects of H.E.S. method, which is now under dispute. These elements must be small enough to plot exact location of any changes on distribution profiles, cause minimum error in further calculations, and yet have reasonable quantity to prevent disturbance in outcome data and unnecessary calculations. Exact methods for calculation of lift, drag, thrust, torque, induced angle, solidity, and other parameters of each element are irrelevant to this study. But for instance, in order to calculate torque of each element after calculation of element initial resistance force, actual resistance force comes from:

$$R_{real} = R_{Int} \sec \xi \quad (1)$$

In which R is resistant force and ξ is shaft angle. Then torque is calculated by the following equation:

$$Q = R_{real} r_c \quad (2)$$

Where r_c defined as surface center could be obtained from:

$$r_c = \frac{\int_{r_0}^{r} R_{Real} dr}{R_{Real}} \quad (3)$$

By substituting resistance force:

$$r_c = \frac{1/2 \, \rho V^2 S}{R_{Real}} \int_{r_0}^{r} (C_l \sin(\frac{V}{r\,l} + \phi) - C_d \cos(\frac{V}{rl} + \phi))\, dr \quad (4)$$

In which l is element length and S is element surface.

In this investigation, basic blade's span was divided into 20 elements in order to compare effects of tip vortex on each model. This method was utilized in different occasions to analyze distribution of aerodynamic forces along blade of different models. As an instant this method was successfully utilized by same authors to model effects of fanlets on twisted unducted axial fans [21].

As it is proved in former experiences [15], k-ε: R.N.G. method is a valid mean to gain data about performance of axial fans and propellers. But as an extra precaution in this research, use of k-ε: R.N.G. method was validated by comparing C.F.D. results of a 2-blade fresh model, with results of blade element theory analysis.

Usually thrust or torque given by B.E. calculations is nearly 10 percent more than experimental results [19], this variance is generally due to limitations of B.E. theory to calculate exact effects of tip vortex or consideration of blade vibration effects on propeller performance. Since accuracy of various computational methods have been determined by former investigators in many occasions, in order to validate usage of C.F.D. tools in this study, it was just necessary to compare thrust and torque orders and behaviors of distribution profiles.

Total values for thrust, torque, and efficiency were fair close in a 7 percent range [table 1] and distribution profiles demonstrated almost same behavior [Fig. 1]. In tip region, there was a significant drop in C.F.D. profile, which is due to better capabilities of C.F.D. methods to illustrate tip losses due to tip vortex effects as it was predicted.

Table 1. NUMERICAL METHOD VALIDATION

parameter	T (N)	Q (N.m)	η
Calculated (BE)	0.48	9.6e-3	0.31
Numerical method	0.4538	9.99e-3	0.2891

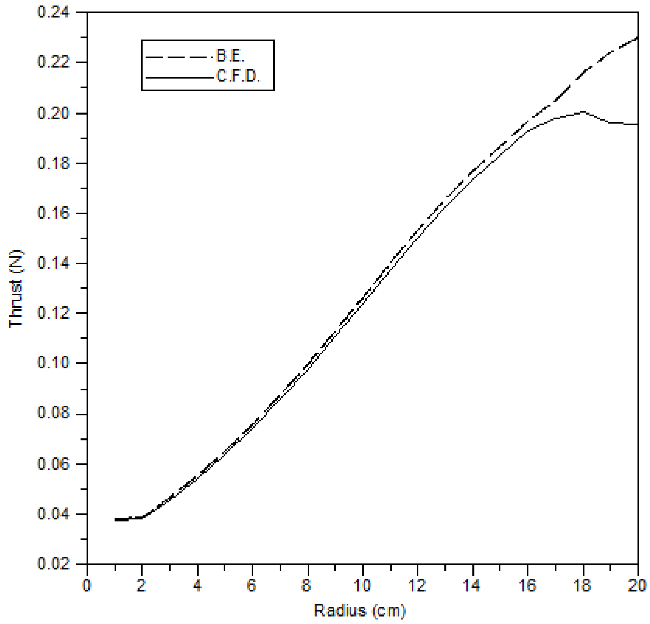

Figure 1. Comparison of Blade Element and C.F.D results

IV. MODELS AND CONCEPT

To investigate the effects of different fanlet arrangments, a basic blade was designed and utilized in 2, 4 and 6-blade fans. Then up-let, and down-let fanlets were applied separately to the basic (fresh model). Fig. 2 demonsgtrates 3 different configuration of fanlets applied to 2, 4 and 6-blade models.

Design method of a non-twisted axial fan is the same as regular twisted models. to design a non-twisted fan, flow characteristics for the Lock's refrential element (at 0.7 of relative radius) would be calculated and then specifications of the element would be generalized to whole span.

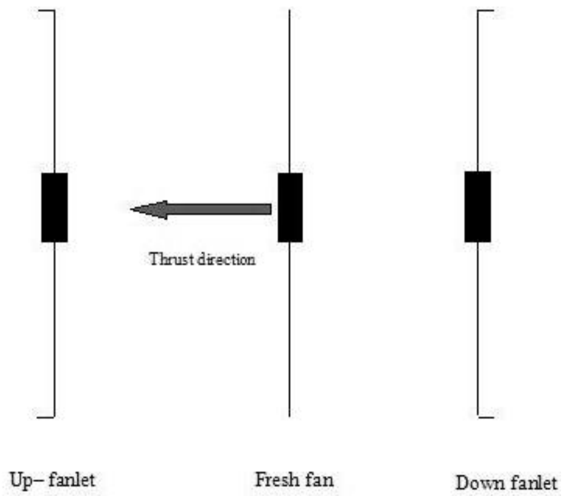

Figure 2. Fanlet arrangements

V. RESULTS

The major results of this project have been attained by studying distribution profiles along the blade span. Tip vortices evidently cause a slight drop in ending points of thrust distribution profiles. The amount of this drop and the extent of the area affected by can show how powerful tip vortices are. In thrust distribution profiles, which are plotted using C.F.D. and H.E.S. methods, slight drop in ending points of fresh model profile is perceptible. However, in up-let models, there is no drop in ending points of thrust profiles. This indicates that using up-let fanlet reduces the negative effects of tip vortices in these models. The analysis of thrust distribution profiles, shown in figures 3, 4 and 5, demonstrates that utilization of up-let arrangement improves the proficiency of the models. However, the change in thrust is not significant in down-let models.

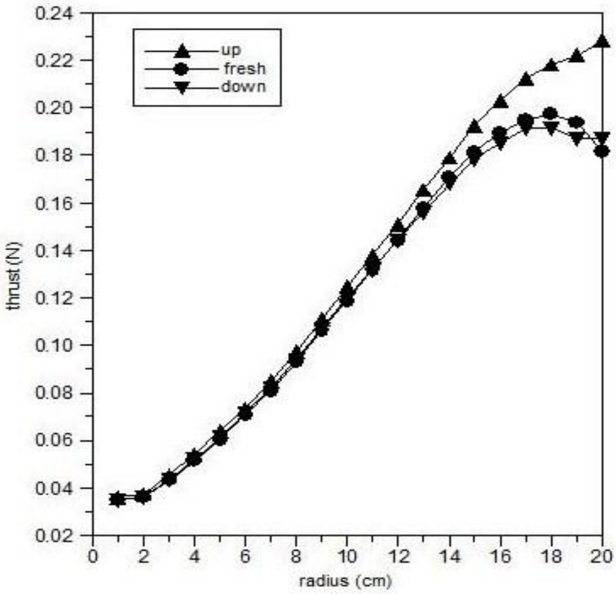

Figure 3. Thrust distribution profiles in 2-blade models

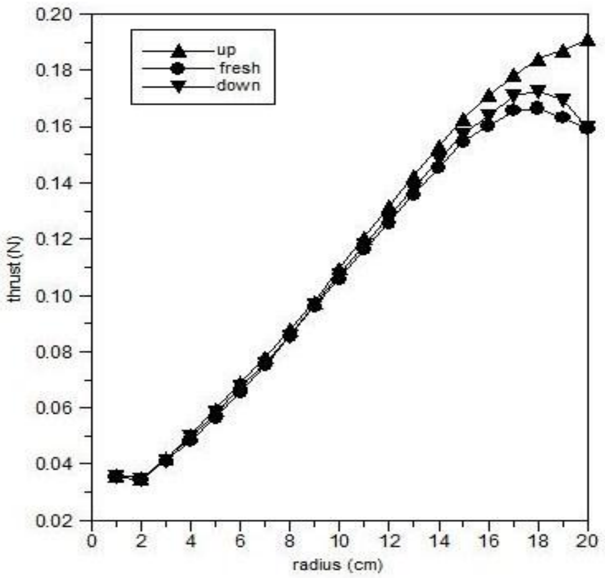

Figure 4. Thrust distribution profiles in 4-blade models

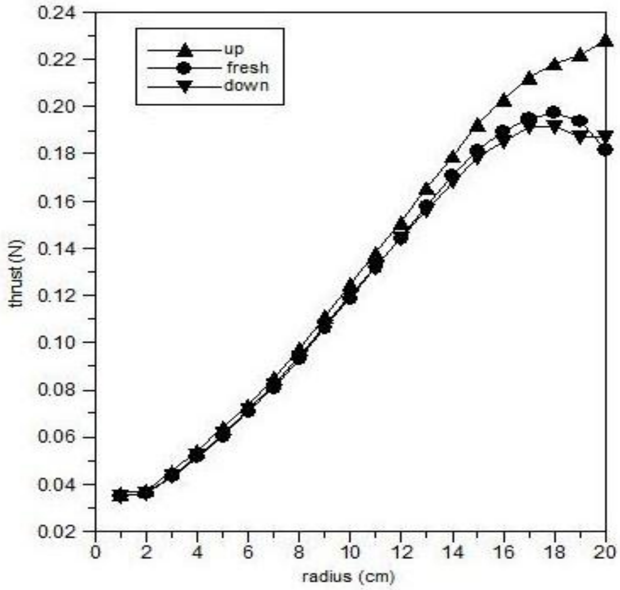

Figure 5. Thrust distribution profiles in 6-blade models

Just like thrust distribution profiles, tip vortices decrease ending points of the torque profiles. However, in torque profiles this reduction is much more negligible than in thrust profiles. In torque distribution profiles plotted for this investigation, models with fanlets show higher amounts in ending points and the increment is more notable than thrust profiles. Like thrust profile cases, up-let models function more efficiently than down-let models.

A comparison of torque profiles in 2-blade [Fig. 6], 4-blade [Fig. 7] and 6-blade [Fig. 8] models demonstrates that just like thrust distribution profiles, effects of using fanlet is more significant in 4-blade fans.

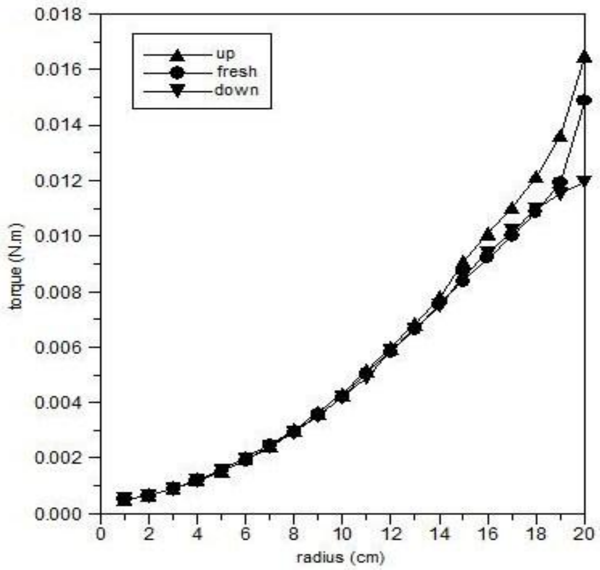

Figure 6. Torque distribution profiles in 2-blade models

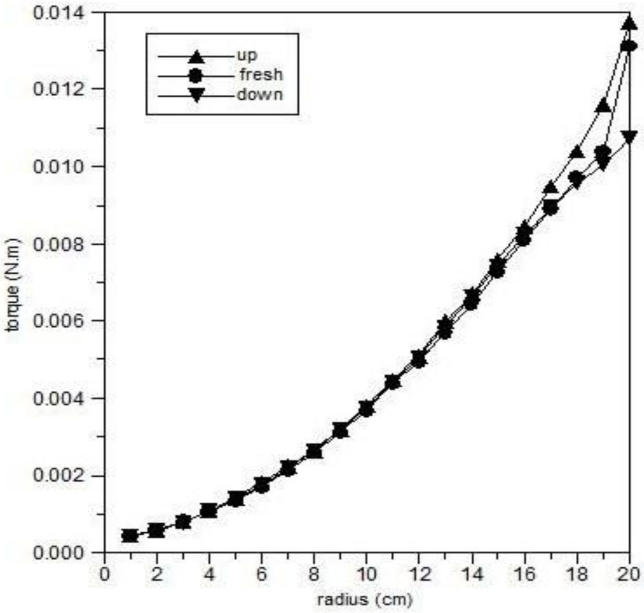

Figure 7. Torque distribution profiles in 4-blade models

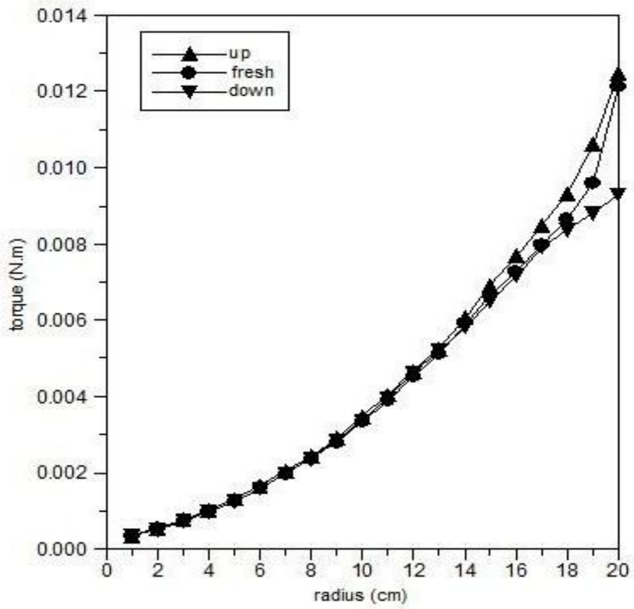

Figure 8. Torque distribution profiles in 6-blade models

With an over look to all diagrams, It can be also concluded that by increasing the number of blades, more elements of the blade are affected by down-let in torque distribution profiles. This is due to stronger tip vortices and capability of down-let in controlling resistant force.

Overall results [table 2] indicate that both configurations improve the efficiency of the models. In down-let models, the improvement in efficiency is a result of decreased torque, while in up-let models this improvement is gained by increased thrust and torque simultaneously, but with different proportions. The improvement in efficiency by down-let configuration is more than up-let arrangement. Models with down-let have an average relative improvement near 3.4 percent while this amount for models with up-let is about 1.4 percent.

Table 2. OVERALL CHARACTERISTICS

No. of blades	Configuration	Thrust (N)	Torque (N.m)	Efficiency (%)
2	Up	2.63	0.118	26.5
	Fresh	2.42	0.110	26.2
	Down	2.43	0.107	27.1
4	Up	2.28	0.101	26.9
	Fresh	2.13	0.096	26.5
	Down	2.17	0.094	27.4
6	Up	2.07	0.092	27.0
	Fresh	1.95	0.087	26.6
	Down	1.92	0.083	27.4

Results of distribution analysis emphasize that thrust distribution on fans with different arrangements of fanlets is similar to the lift distribution on wings with different arrangements of winglets [22], which also point that consideration, and basic rules that are used to optimize geometry of winglets can be also utilized to optimize geometry of fanlets.

VI. Conclusion

Results show that efficiency of axial fans can be improved by 3.6 percent by using fanlets. Both configurations of fanlets enhance the performance, but the boost gained by down-let arrangement is more than up-let. As it is proved that one of the major reasons of blade vibrations is a tip vortex effect, another benefit of using fanlets is the reduction of vibration of fans, specially by using down-let. It reduces the resistant force acting on the tip elements of the blade. Therefore, it is predictable that vibration and noise of the samples with down fanlets are less than the other samples.

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