Axial Fan Design Using Multi-Element Airfoils to Minimize Noise

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ABSTRACT

Axial fans are one of the most harmful sources of noise due to their close proximity to occupied areas and widespread use. The prolonged exposure to hazardous noise levels can lead to noise-induced hearing loss. Consequently, there is a critical need to reduce noise levels from ventilation fans. Since fan noise scales with the 4-6th power of the fan tip speed, minimizing the fan tip speed is an effective method to reduce fan noise. However, reducing the fan speed results in a decrease in aerodynamic performance. To this end, the present study uses multi-element airfoils to increase the aerodynamic characteristics of the fan blades to enable lower fan speeds and noise relative to fan blades with single element airfoils. Additionally, a control vortex design method has been implemented to increase the effectiveness of the blade outer sections, i.e. spanwise varying axial flow. The resulting blade geometry has been shown to reduce noise levels while maintaining the same volumetric flow rate.

Keywords: Multi-element, Fan, Noise
I-INCE Classification of Subject Number: 30

1. INTRODUCTION

Axial ventilation fans are used extensively to control the temperature, humidity, and to remove and dilute contaminants from occupied areas. However, their close proximity to occupied areas and widespread use are a significant threat to the immediate and long term health and hearing. Long term exposure to harmful noise levels can lead to irreversible hearing damage, i.e. noise-induced hearing loss (NIHL). Consequently, the National Institute for Occupational Safety and Health (NIOSH) recommends an exposure limit of 85 dBA for an 8-hour time-weighted average[1]. The short term exposure to high noise levels can create physical and psychological stress, reduce work efficiency, and contribute to workplace accidents and injuries from difficulty to hear warning signals[2]. Consequently, there is a critical need to reduce noise form ventilation fans.

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Ventilation fans are often loud and have poor aerodynamic performance due to poor design features e.g. flat plates of constant chord blades, support struts too close to the fan and so forth. The main driver in the design and fabrication of most ventilation fans is lower cost. Therefore, there are opportunities to significantly reduce fan noise by better design of the fan blades. Since fan noise scales with the 4 to 6th power of the fan tip speed[3], an effective approach to reducing fan noise is to reduce the fan tip speed, i.e. reducing the fan tip speed by half can reduce noise levels by up to 18dB. However, decreasing the fan tip speed typically corresponds to a decrease in the fan aerodynamic efficiency, i.e. the design requires a trade-off between the aerodynamic efficiency and the fan noise. Hence, the approach here is to reduce the fan tip speed while maintaining the same volumetric flow rate by increasing the aerodynamic characteristics of the fan blades. To this end, the blade spanwise chord and twist distribution are designed to maximize the volumetric flow rate contribution of the outer radii, i.e. the axial flow velocity increases from the fan hub to the tip. However, a non-uniform spanwise axial flow is susceptible to radially outward flow that increases the fan tip losses[4]. Consequently, radial equilibrium is implemented into the design process using a control vortex design (CVD) approach. This allows for a reduction of the fan tip speed and noise while reducing the complexity of the blade, i.e. the chord and twist distribution are reduced along the blade[5]. The resulting blade geometry is ideally suited to implement multi-element airfoils that can further improve the aerodynamic characteristics of the fan blades. Multi-element airfoil configurations outperform single element airfoils by preventing flow separation and subsequent stall[6] that lead to higher lift characteristics. This is possible due to the accelerated flow in the gap of the multi-element airfoil that increases the kinetic energy of the flow on the suction surface of the subsequent airfoil[7]. Consequently, the use of multi-element airfoils in a tandem configuration has been previously investigated to improve the aerodynamic characteristics of compressor blades[8,9,10]. However, to the best of our knowledge, they have not been used for the design of commercial portable low-pressure axial ventilation fans. To this end, this paper demonstrates the use of multi-element airfoils as a promising solution to increase the aerodynamic characteristics of the fan blades to enable lower fan speeds and noise while maintaining the same volumetric flow rate. The multi-element airfoil blade design presented here represents a "proof of concept" design. Future work will focus on validating the results experimentally and optimizing the multi-element airfoil geometry.

2. AIRFOIL DESIGN

A method for improving the aerodynamic performance of the blades is to implement high lift airfoil geometries. However, most airfoils specifically designed for high lift have been designed to operate at high Reynolds numbers[11,12]. At low Reynolds numbers ($10^5 < Re < 10^6$) these high lift airfoils show a dramatic decrease in the maximum lift coefficient that does not make them suitable airfoils to use for the design of the blades. However, some high lift airfoils such as the S1223 have been designed to operate at low Reynolds numbers. The airfoil was designed by Selig et al. by making use of a concave pressure recovery with aft loading that delays separation of the turbulent boundary until it is close to the trailing edge[13]. The resulting airfoil geometry ensued a complex shape with a sharp trailing edge that is difficult to fabricate. Consequently, the use of multi-element airfoils to achieve high lift has become increasingly more popular for UAV[14] and sail boat[15] applications which operate at low Reynolds numbers. However, the available literature of high lift multi-element airfoil configurations at low Reynolds numbers is limited. To this end, the approach here is to conduct a trade study to design the multi-element airfoil configuration at a chord Reynolds number of 200,000 using the viscous/inviscid MSES/MSIS[16] solver. The airfoil geometry used for this study is restricted to the E214 airfoil geometry which has been shown to have good aerodynamic characteristic at low Reynolds numbers[5,17]. Additionally, the number of airfoils is limited to two. Consequently, hereafter the multi-element airfoil will be referred simply as a tandem airfoil.

2.1 Airfoil trade study

The design parameters for the tandem airfoil used in the trade study are shown in Figure 1. They are the chord ratio ($c2/c1$), airfoil angles ($\delta_1$and δ_2), and gap size (defined when $\delta_1 = \delta_1 = 0$). A total of 21 different airfoil configurations with different parameters were investigated in the trade study. The selection of the best airfoil configuration was based on (a) a high lift coefficient for angles of attack between 0-10 deg. and (b) a high lift to drag ratio at lift coefficients greater than 1.5. The geometric and aerodynamic characteristics of the best resulting airfoil are shown in Table 1 for a chord Reynolds number of 200,0000.

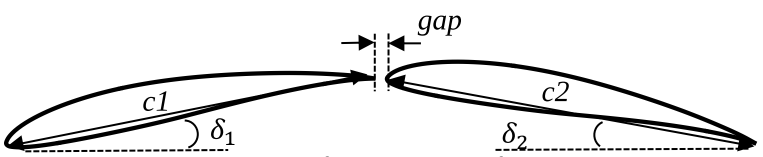

Figure 1: Design parameters for the tandem airfoil geometry.

Table 1: Geometric and aerodynamic characteristics of the tandem airfoil design.

Parameter	
Airfoil geometry	E214 airfoil
c_2/c_1	0.88
Leading airfoil angle (δ_1)	16.4 deg
Trailing airfoil angle (δ_2)	13.9 deg
Gap size	0
Maximum lift coefficient	1.96
Maximum lift to drag ratio	73.5

The coefficient of lift and drag of the tandem airfoil are compared to a single element airfoil with the same chord in Figure 2. Here it can be illustrated that the tandem airfoil results in an increase of lift while also increasing the drag.

(a) (b)

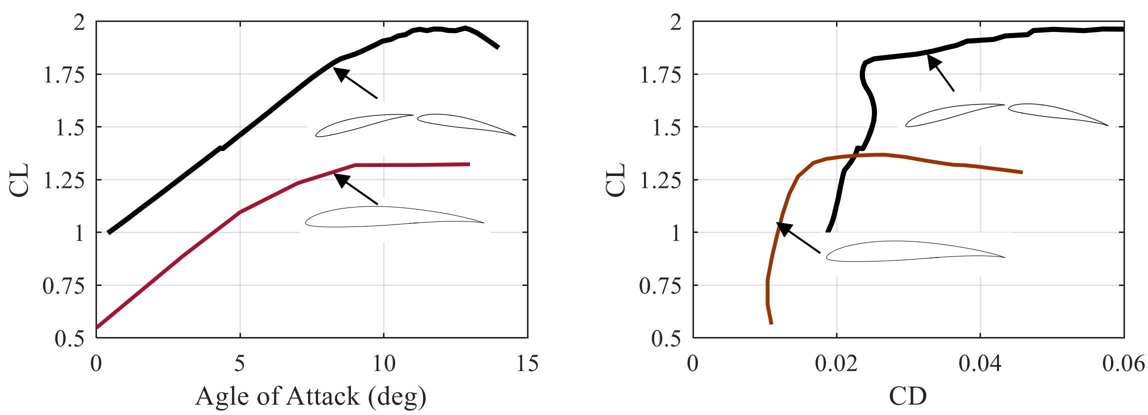

Figure 2: (a) Lift and (b) drag polar for the tandem airfoil and single element airfoil for a chord Reynolds number of 200,000.

Furthermore, Table 2 presents a comparison of the single and tandem airfoil at their maximum lift to drag ratio, i.e. 77 and 75 respectively. As illustrated here, at this point the tandem airfoil increases the lift coefficient by 132% while also increasing the drag by 140%. However, the penalty caused by the increase in drag is more than offset by the gain in the lift coefficient since the fan noise scales with the 4-6th power of the fan tip speed.

Table 2: Tandem and single element airfoil characteristics at the maximum lift to drag ratio.

Airfoil	AOA	CL	CD
E214-airfoil	8.25	1.80	0.024
Tandem airfoil	2	0.77	0.01

3. FAN DESIGN

A comparison between three fan designs is presented in this section to investigate the use of tandem airfoils in the blade design. Two of the fans were designed using the control vortex design methodology described by Hurtado et al.[5] using a single element airfoil and a tandem airfoil. The third fan is a baseline fan designed using the conventional free vortex design and a single element airfoil. Therefore, the three fans will be referred to as ***FVS*** (Free-vortex single), ***CVS*** (Control-vortex single), and ***CVT*** (Control-vortex Tandem). Here the first two letters indicate the swirl velocity distribution (free vortex or control vortex) while the last letter indicates the airfoil geometry (**S** for single element airfoil and **T** for tandem airfoil). The ventilation fans have been designed to generate a target volumetric flow rate of 1030 CFM. To this end, a multi-objective Genetic Algorithm (GA) has been implemented to design the velocity profile that satisfies the volumetric flow rate requirement. Next, an inverse design is implemented that uses the classical blade-element/vortex formulation to design the blade geometry that results in the desired velocity profiles. Lastly, the broadband noise of the three fans is computed using the semi-empirical model developed by Mugridge and Morfey[18].

3.1 Fan velocity profile design

The design of the velocity profile involves finding the hub-to-tip ratio (v) and the tip tangential velocity (M_{tan}) that result in the target volumetric flow rate. The tip tangential velocity is

$$M_{\tan} = \Omega r_t / c_{air} \qquad (1)$$

where Ω is the angular velocity, r_t is the tip radius, and c_{air} is the speed of sound. The hub-to-tip ratio defined as

$$v = r_h / r_t \qquad (2)$$

where r_h is the hub radius. Additionally, the velocity distribution is also an important parameter as it can be used to further improve the aerodynamic characteristics of the blades. To this end, the velocity profile is designed to increase from the hub to the tip while maintaining radial equilibrium using the control vortex design methodology presented by Hurtado, et al.[5]. Here, radial equilibrium is incorporated into the design of the velocity profile by solving the radial equilibrium equation assuming a swirl velocity power law distribution defined as

$$v_\theta(r) = ar^n \qquad (3)$$

where a is the swirl velocity coefficient and n is the swirl velocity exponent. The resulting axial velocity distribution that maintains radial equilibrium is

$$v_a(r) = \sqrt{2a\Omega(r^{n+1} - r_h^{n+1}) - R(r) * a^2(n+1) + v_h^2} \qquad (4)$$

where

$$R(r) = \ln(\frac{r}{r_h})^2 \text{ for } n = 0$$

$$R(r) = \frac{r^{2n} - r_h^{2n}}{n} \text{ for } n \neq 0$$

The velocity at the hub is defined as $v_h \simeq \Omega r_h / 0.6$ which is the minimum velocity while maintaining a high aerodynamic efficiency[19].

Therefore, the aim of the design of the velocity profile is to define the hub-to-tip ratio (v), the tip tangential velocity (M_{tan}), and the velocity distribution (swirl velocity coefficient a and exponent n). To this end, a Multi-objective Genetic algorithm (GA) from the MATLAB toolbox[20] has been implemented to investigate the trade-offs between hub-to-tip ratio and tip tangential velocity for a target volumetric flow rate of 1030 CFM. Hence the objective functions to be minimized are the tip tangential velocity (M_{tan}), and the hub-to-tip ratio (v) defined in Equation (1) and Equation (2) respectively. Lastly, a constraint function is used to limit the solutions to velocity distributions, i.e. swirl velocity coefficient a and exponent n, that result in the target volumetric flow rate of 1030 CFM. The non-dominating set of feasible solutions (Pareto front) are presented in Figure 3. Here the minimum tip tangential velocity for a range of hub-to-tip ratios that result in the target volumetric flow rate is shown. It can be illustrated here that as the hub-to-tip ratio decreases, the required tip tangential velocity to generate the target volumetric flow rate increases.

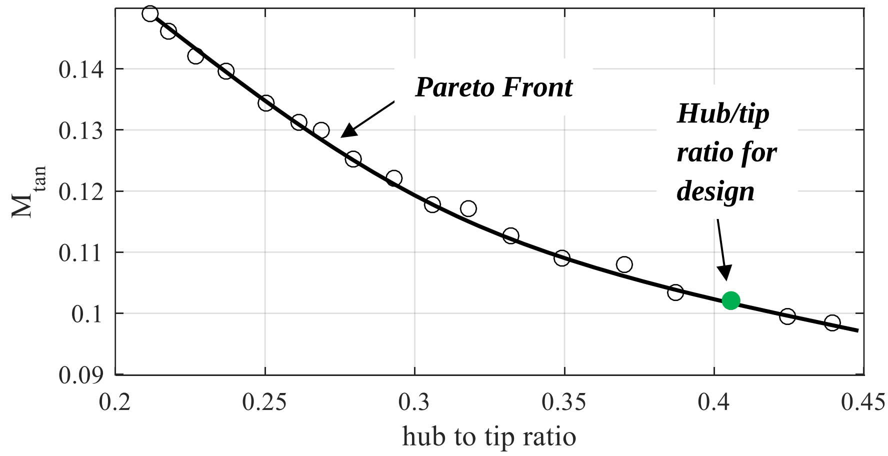

Figure 3: Multi-objective GA Pareto front.

The hub-to-tip ratio and corresponding tip tangential velocity selected for the design of the control vortex velocity profiles are 0.405 and 0.1 respectively. Here, the swirl velocity coefficient and exponent for Equations (3) and (4) are 4.48 and -0.1922 respectively. The resulting axial and swirl velocities are shown in Figure 4. Additionally, the free vortex axial and swirl velocity profiles to generate the target volumetric flow rate are also shown in Figure 4. As illustrated here, the velocity distribution using the control vortex design results in a lower swirl velocity and hence fewer losses near the hub of the blade.

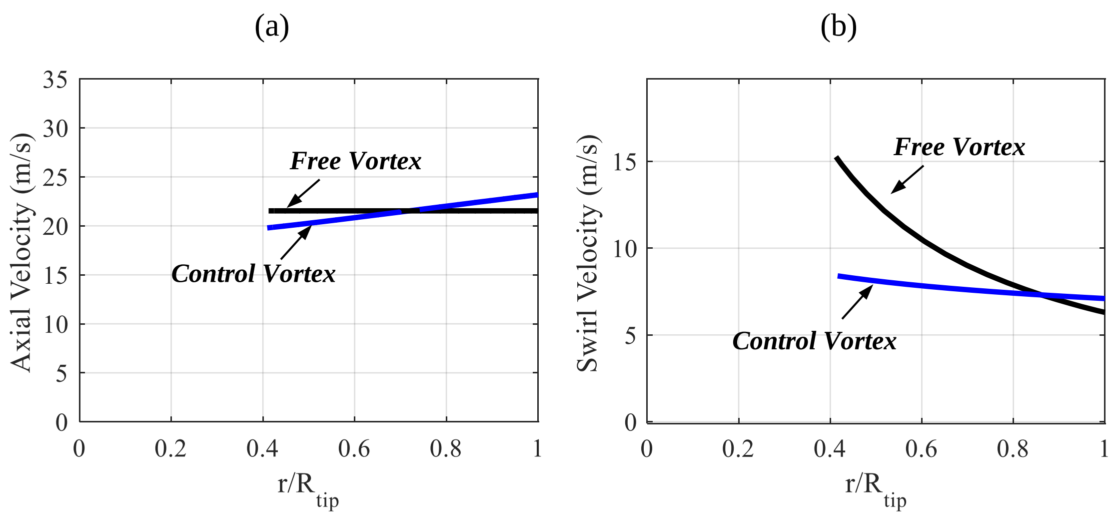

Figure 4: (a) Axial and (b) swirl velocities for the free vortex and control vortex designs.

3.2 Fan geometry design

An inverse design method has been implemented to design the blade chord and twist distribution for the FVS, CVS, and CVT fans that generate the velocity profiles shown in Figure 4. The constraints imposed on the design of the blades are (a) a chord at the hub less than the hub radius, (b) a chord at the tip greater than 40% of the hub radius, and (c) a twist at the hub less than 85deg. These constraints were imposed to limit the blade designs to realistic blade geometries that are practical to fabricate. The baseline FVS fan was designed with a single element airfoil to generate the free vortex axial and swirl velocity profiles shown in Figure 4. The design fan tip speed and the number of blades for the FVS fan are 0.125 and 7 respectively. The resulting chord and twist distribution for the blades of the FVS fan are shown in Figure 5.

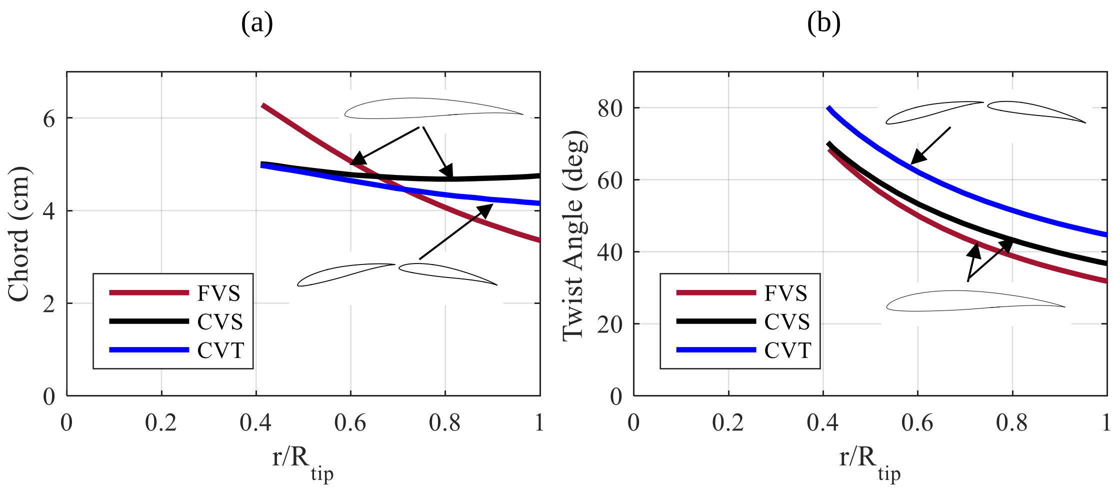

Figure 5: (a) chord and (b) twist distribution for the FVS, CVS, and CVT fan designs.

The CVS and CVT fans were designed to generate the control vortex axial and swirl velocity profiles shown in Figure 4 with a single element airfoil and tandem airfoil respectively. The chord and twist distribution for the CVS fan which results in a realistic blade geometry while generating the control vortex axial and swirl velocity profiles are shown in Figure 5. The design fan tip speed and number of blades for the CVS fan are 0.115 and 7 respectively. Similarly, the CVT fan was designed with 5 blades and a fan tip speed of 0.1 to generate the control vortex velocity profiles. The resulting chord and twist distribution are shown in Figure 5. As illustrated in Figure 5(a), the chord variation along the blade span is smaller for the CVT fan relative to the CVS fan although it has fewer blades due to the higher lift coefficient. Additionally, Figure 5(b) shows that the twist of the CVT blade increases given that it operates at higher angles of attack using the tandem airfoil configuration. However, the overall change in the twist from the hub to the tip is the same as that of the CVS fan as illustrated in Figure 5(b). Furthermore, Table 3 shows that the CVT fan results in a 15% decrease in the fan tip speed relative to the CVS fan while generating the same axial and swirl velocity profiles. Similarly, the CVS fan design resulted in a 9% decrease in the tip speed relative to the FVS fan. Consequently, it has been shown that the design of the velocity profile and the use of multi-element airfoils can be used to enable lower fan speeds and noise while generating the same volumetric flow rate.

Table 3: Fan design features.

Fan Design	***Airfoil***	***Velocity distribution***	***Number of blades***	***Fan tip speed***
FVS	E214 airfoil	Free vortex	7	0.125
CVS	E214 airfoil	Control vortex	7	0.115
CVT	E214 tandem airfoil	Control vortex	5	0.1

The blade geometry of the three fan designs is shown in Figure 6. It is apparent here that the low twist and chord variation of the blades designed using the control vortex design approach is more suitable to implement multi-element airfoils. On the contrary, the free vortex design approach makes it difficult to implement multi-element airfoils as a small chord at the tip will result in airfoils with a very small chord that are difficult to fabricate. Additionally, Figure 6 shows that the tandem airfoil blades of the CVT fan reduce the total volume of the blades relative to the single element airfoil blades. Therefore, reducing the amount of material required for fabrication of the blades. Moreover, the tandem blades reduce the blade thickness noise associated with the thickness of the blades.

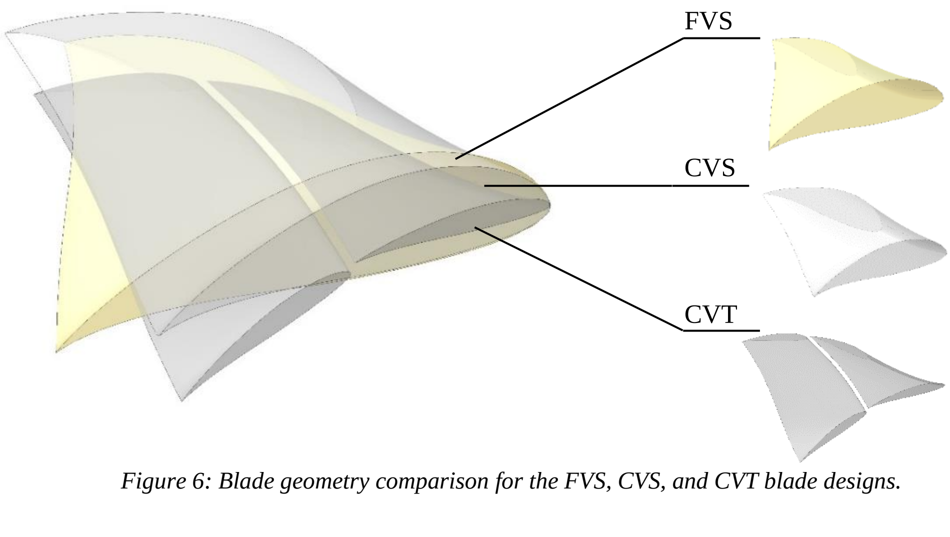

Figure 6: Blade geometry comparison for the FVS, CVS, and CVT blade designs.

The CAD geometry of the FVS, CVS, and CVT fans is presented in Figure 7. Additionally, a rotating shroud has been added to the blade geometry to control the tip clearance noise[21]. Additionally, Figure 7 illustrates the decrease in the solidity of the fan when tandem airfoils are used instead of single element airfoil.

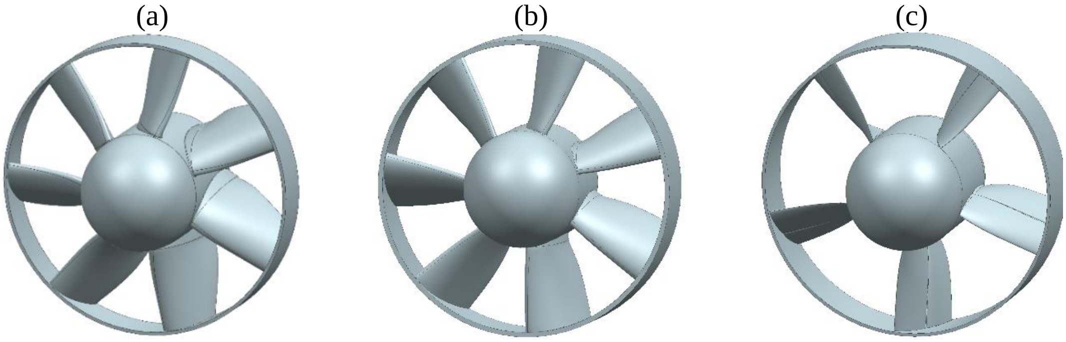

Figure 7: CAD geometry of the (a) FVS, (b) CVS, and (c) CVT fan designs.

The performance of the three fan designs at their respective design speed is presented in Table 4. As illustrated here, the CVT fan reduces noise levels by 5.6 dB relative to the baseline FVS fan and 4.2 dB relative to the CVS fan. However, as illustrated in Table 4 the CVT fan increases the power consumption by 5.7% relative to the CVS fan. The increase is the CVT fan power consumption is associated with the increase in the drag of the tandem airfoil relative to the single element airfoil as shown in Table 2.

Table 4: Fan performance comparison at the fan design speed.

Fan design	*Fan speed [rpm]*	*Power [watts]*	*Sound power level [dBA]*
FVS	4338	158	59.9
CVS	4000	165	58.5
CVT	3500	175	54.3

Additionally, the volumetric flow rate as a function of the fan speed is presented in Figure 8. As illustrated here, the CVT fan design outperforms the CVS and baseline FVS fan designs for all fan speeds.

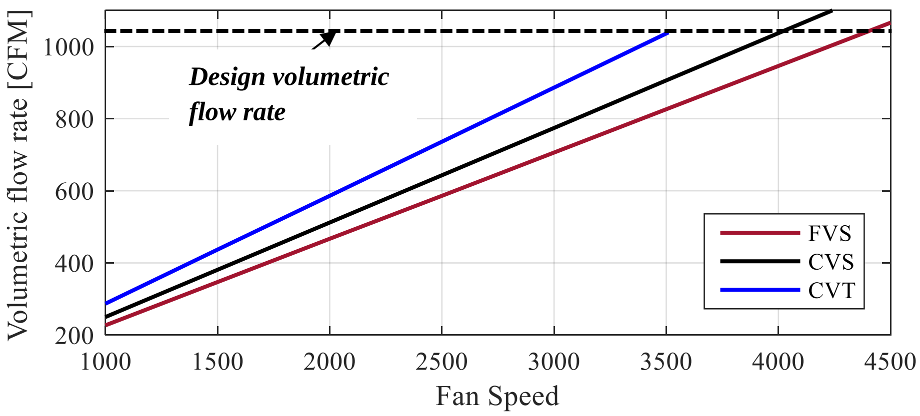

Figure 8: Volumetric flow rate vs fan speed for the FVS, CVS, and CVT fan designs.

Furthermore, mechanical power consumption is presented in Figure 9 as a function of the volumetric flow rate. As illustrated here, all fans have a similar power consumption (within 10%) for all volumetric flow rates shown, i.e. from 200 CFM to the design volumetric flow rate of 1030 CFM.

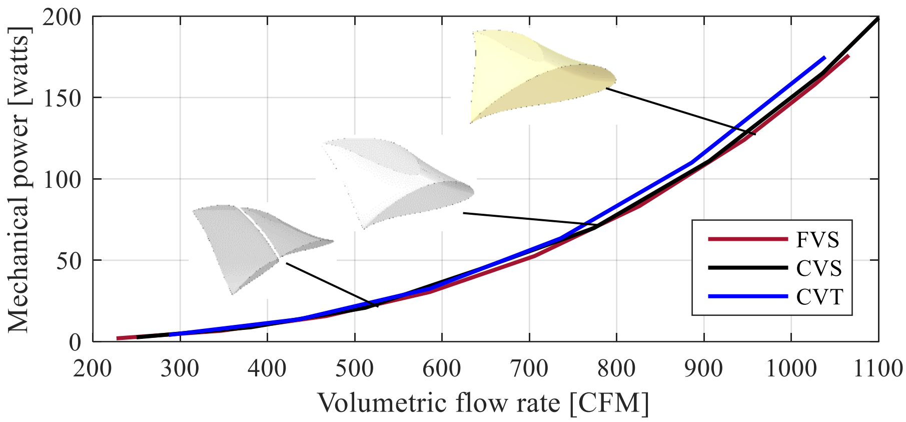

Figure 9: Mechanical Power vs Volumetric flow rate for the FVS, CVS, and CVT fan designs.

The sound power level as a function of the volumetric flow rate is presented in Figure 10. As illustrated here, the CVT fan results in lower noise while generating the same volumetric flow rate as the CVS and FVS fan designs. Consequently, the use of a tandem airfoil for the design of the fan blades has been shown to be an effective approach to significantly reduce noise levels while maintaining the same volumetric flow rate and similar power consumption.

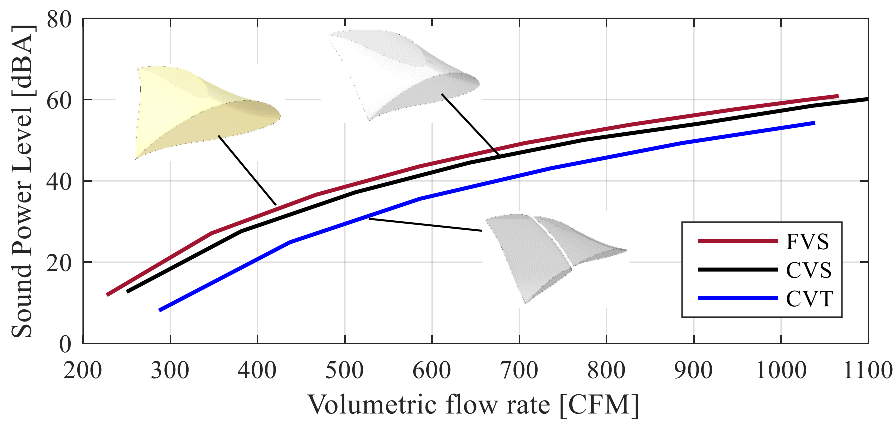

Figure 10: Sound Power Level vs Volumetric flow rate for the FVS, CVS, and CVT fan designs.

4. CONCLUSIONS

The use of multi-element airfoils has been explored as a method to enable lower fan speeds and noise. The design of the multi-element airfoil has been accomplished through a trade study using the viscous/inviscid MSES/MSIS solver at a chord Reynolds number of 2×10^5. The resulting airfoil was shown to increase the lift coefficient by 132% while also increasing the drag by a similar amount. However, the penalty caused by the increase in drag is more than offset by the gain in the lift coefficient. This is apparent from the 4.2 dB noise reduction in the fan designed using a multi-element airfoil relative to a single element airfoil. Additionally, a control vortex design approach was implemented to further increase the aerodynamic characteristics of the blades. The resulting blade geometry was shown to be ideally suited to implement multi-element airfoils. A total noise reduction of 5.6 dB was shown from the combination of the control vortex design and the multi-element airfoil blade relative to a baseline single element free vortex blade design. Consequently, it has been shown that the design of the velocity profile and the use of multi-element airfoils can be used to enable lower fan speeds and noise while maintaining the same volumetric flow rate and a similar fan power consumption.

5. ACKNOWLEDGEMENTS

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