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Effects of NACA 65-blade's trailing edge modifications on the performance of a low-speed tube-axial fan

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Abstract

NACA 65-series airfoils feature a cusped trailing edge impractical for mass-production manufacturing processes. The effects of two different trailing edge modifications on NACA 65-810 blades on the performance of a low-speed rotor-only axial fan were investigated. Two rotors were realized and experimentally tested at two different tip leakage values. Experimental data were compared each other and with results of CFD calculations performed on the ideal geometry. The comparison shows the performance losses of the actual geometries against the ideal one. These losses must be taken into account when blade design is based on cascade data. Indications on the best modification strategy are also suggested.

Keywords: axial-flow fan design; NACA 65; trailing edge; NACA 65 cusp; rotor-only; tube-axial

Nomenclature

p_t	total pressure: $p + \frac{1}{2}\rho C_a^2$	$[Pa]$	C_a	axial velocity	$[\frac{m}{s}]$
p	static pressure	$[Pa]$	Qv	volumetric flow rate	$[\frac{m^3}{s}]$
Δp_t	$= p_{t2} - p_{t1}$	$[Pa]$	D	fan external diameter	$[m]$
1,2	fan inlet and outlet sections		θ	flow turning angle	[°]
ρ	air mass density	$[\frac{kg}{m^3}]$	M	fan rotor torque	$[Nm]$
C_u	tangential velocity	$[\frac{m}{s}]$	c	chord length	$[m]$
ω	angular velocity	$[\frac{rad}{s}]$	th	airfoil maximum thickness	[-]

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1. Introduction

NACA 65-series airfoils are widely used in aeraulic turbomachinery. Of course one of the motivations is the great amount of data available for these profiles in the literature. In fact, they were extensively tested in cascade configurations with a constant chord-wise loading camber line (i.e., a = 1) since 1940's [1]. The databases resulted from these experimental campaigns are an important tool for any fan designer. However these tests were performed on airfoil sections featuring an extremely thin trailing edge TE (~ 0.15% of the chord length). In fact, the ideal aerodynamic airfoil shape features a cusped rear part (i.e., TE of zero thickness). In the fan industry bladings of relatively small sizes are usually obtained with mass-production techniques (e.g. casting or injection molding) and thin airfoil rear sections may not be realizable because of structural and manufacturing problems[†1]. Thus, as common practice, the rear part of the 65-series airfoils is modified to employ these sections for blading applications [2, 3], but this modification can decrease the characteristic "flap effect" of the original airfoil [3]. As a consequence, reduction on flow deflection capability is expected and differences respect cascade data as well. In spite of the widely accepted practice of modifying these airfoils' TEs for fan bladings, few references were found in the literature reporting the details of the shape actually manufactured and how these modifications affect fan performance.

As a general rule to reach a required deflection angle θ, it is expected that chord decrease should be avoided. Anyway a thickened TE blade is expected to suffer a reduction of the actual θ (i.e., of fan total pressure rise) as well, because of the consequent diffusion capability decrease on the suction side. Moreover, TE thickening is likely to increase the blade drag too, because of a wider wake. In this work two different strategies are adopted to provide a TE geometry technologically feasible when the constrain of a minimum thickness is imposed by the manufacturing process. In the first case (case 1) the airfoil geometry is truncated at 96% of the chord length (i.e., when the minimum thickness available is reached). In the second case (case 2) the tail geometry is modified by imposing a constant thickness equal to $0.02c$ to allow the manufacturing while maintaining the original chord length, as was done for specific cascade tests by Herrig at al. in [4]. Two series of bladings for a 315 mm rotor-only tube-axial fan are realized and fans performances compared to evaluate the effects of these modifications. The blades differ each other uniquely because of the TE shape. The two rotors are experimentally tested on a ISO 5801 category-A test bench to obtain the characteristic curves at two different tip leakage values. Experimental results are compared each other and with CFD calculations performed on the ideal blading (i.e. no TE modifications) as well. Aim of the paper is quantifying the performance decrease of the actual fans realizations respect to the ideal aerodynamic shape and to indicate the best modification strategy.

2. Fan and blade section modifications

The study is carried out on a 10 blades, 315 mm rotor-only axial fan with a hub-to-tip ratio $\nu = 0.44$ (see Figure 1 a)). Blades were designed to realize an arbitrary vortex flow (i.e., $C_u = constant$ along the span at rotor exit) and they present a quite simple geometry: as the required design flow deflection angle distribution $\theta(r)$ was roughly constant, a single NACA 65-810 section was chosen and applied with constant chord along the blade span. Mutual interference effects are expected due to blade solidity (in particular near the blade root) but the use of an unique profile allows to relate the effects of TE modifications to this singular airfoil. Stagger angles were chosen following the indications by Herrig

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[†1] 1. The cusped trailing edge of the NACA 6-series was a practical drawback for aeronautical applications as well. For this reason the modified 6A-series was developed; see as reference: Laurence K. Loftin. Theoretical and experimental data for a number of NACA 6A-series airfoil sections. *NACA Report No. 903*, 1947.

(later Emery) et al. [1]. The chord design value was supposed to be 52 mm and Figure 1 b) shows the differences among the three geometries considered. For case 1 (red line) the airfoil geometry was truncated around the 96% of the chord length, when the minimum thickness available by the manufacturing method was reached. For case 2 (black line) indications by Herrig et al. [4] were followed and the tail geometry was modified by fixing a constant thickness equal to 2% of the chord *c* to allow the manufacturing while maintaining the design value length. Circles of 1 mm diameter were centered along the airfoil mean line and their envelope was used to define the upper and lower geometry of the profile. This resulted in a modification of original tail geometry in the last 15% and 11% chord lengths on suction side and pressure side respectively. As previously mentioned, this modification is expected to reduce the flow diffusion on the upper part of the profile (the opposite on the pressure side) and to increase the wake size (i.e., the blade drag).

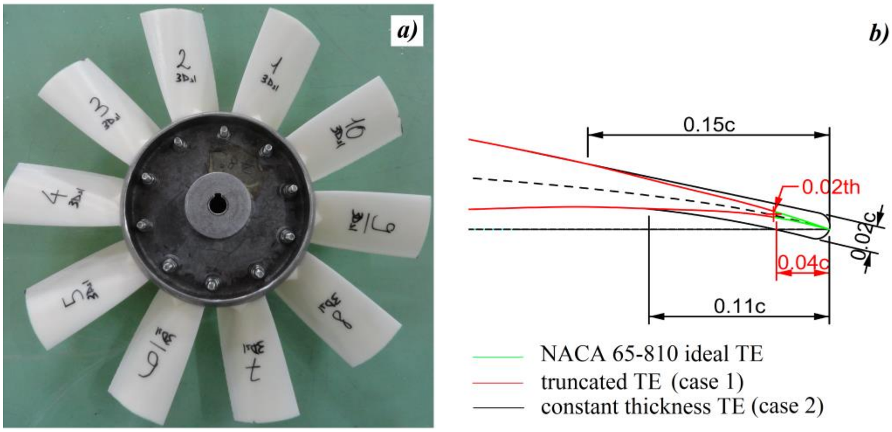

Fig. 1. (a) Fan rotor tested (case 1); (b) Graphical comparison of the TE modifications adopted.

3. Methods

Fan performance are evaluated through the dimensionless fan flow-rate coefficient Φ , fan total pressure coefficient Ψ and fan total efficiency η, defined as follows:

$$\Psi = \frac{\Delta pt}{\rho(\omega D)^2};\Phi = \frac{Qv}{\omega D^3};\eta = \frac{\Delta pt \cdot Qv}{M\omega}$$

As experimental tests on the ideal blading (i.e. no TE modifications) were not feasible, CFD simulations were performed; the numerical model is described in the proper sub- section.

3.1. Experimental Apparatus

Experimental tests were performed using a category-A ISO-5801 test rig [5]. The rig features a plenum chamber at the fan inlet and free delivery. Fan volume flow rate is evaluated using suitable orifice plates, stagnation pressure is acquired in the plenum chamber. Static pressure measurements at plenum chamber and at orifice plate pressure tappings are taken by using water micro-manometers. Efficiency was indirectly obtained by measurements of rotor shaft torque M. In fact, the motor is mounted on a swinging chassis which is part of the specifically designed torsion balance. Ball bearings friction was measured before and after each test and subtracted to compute M, as indicated in [7]. However some dispersion of data was observed and this caused the accuracy on rotor shaft torque values to be slightly higher than what allowed by the ISO standard (4% against 2%). All tests have been conducted, when possible, at a rotational speed of 1350 rpm. As the auxiliary fan was unable to overcome the pressure losses in the airway at higher flow rates, gradual reduction of the tested fan rotational speed up to about 850 rpm was required. As this reduction affects only higher flow rates performance while considerations are done at peak efficiency points, Reynolds effect can be effectively neglected for this work's purposes.

3.2. CFD Model

The CFD model used is the *M2* scheme presented in [6]. Although quite simple, this model demonstrated to be accurate enough in estimating fan's performance for engineering purposes [7]. In order to keep the description synthetic, only the main characteristics of the model are reported here whereas more details can be found in [6]. To take advantage of the geometrical periodicity of the 10 blades rotor volume, the fluid domain is constituted by an 1/10 azimuth section of a straight annular cylinder corresponding to the region surrounding a single blade. The sub-domain closer to the blade (named "*Rotor*") is able to simulate the rotor motion by means of the *Relative Reference Frame* approach (see [8]). The other parts of the domain and the upper surface of the sub-domain rotor (the external casing) are fixed. The blade features the actual tip clearance. In [6] the k-ε turbulence closure model was used. In order to reduce simulation time, here the k-ω with a low-y+ wall treatment [8] was used. In fact, respect to the k-ε, the k-ω model demonstrated to give similar results with half number of cells circa (about 267.000). Total and static pressures were measured at the entrance and at the exit of the sub-domain *Rotor*. Performance curves were obtained by running several simulations varying the volumetric flow rate, in a similar fashion as was done for the experimental curves. Simulations were performed with the CD-Adapco STAR-CCM+® CFD code, Version 8.2.

4. Results

Experimental curves Φ - Ψ and Φ - η for the two bladings at two different values of tip leakage are presented in Figure 2. Tests were performed at three blade positioning angles (23°, 28°, 33°). Tip leakages are 1.2 mm (1.4% of blade height) on the left case *a)* and 2.2 mm (2.5% of blade height) on Figure 2 *b)*, respectively. CFD data for a blade positioning angle of 27° are reported for case a) as well. As previously mentioned, experimental curves were obtained reducing fan speed at higher flow rates due to the limitation of booster capability. This occurrence affects especially the efficiency curves. In fact, a decrease of slope is clearly visible in the right hand side at higher flow rates. The effect on the pressure rise curves is less marked althoug present as well.

5. Discussion

Comparing case 1 and 2 on Figure 2a (tip leakage equal to 1.4% of blade height) things are pretty much as expected. In fact, the truncated TE rotor (red markers) reaches lower pressure rises respect to the modified TE one (blue markers) within the whole operation range. This is due to the reduced chord length which strongly reduce the blade "flap effect". On the contrary, case 1 geometry reaches slightly higher efficiencies. This asses the ability of the truncated TE geometry to reduce the wake size thanks to a less thick trailing edge. In Table 1 performance differences between case 1 and case 2 at peak efficiency points are reported.

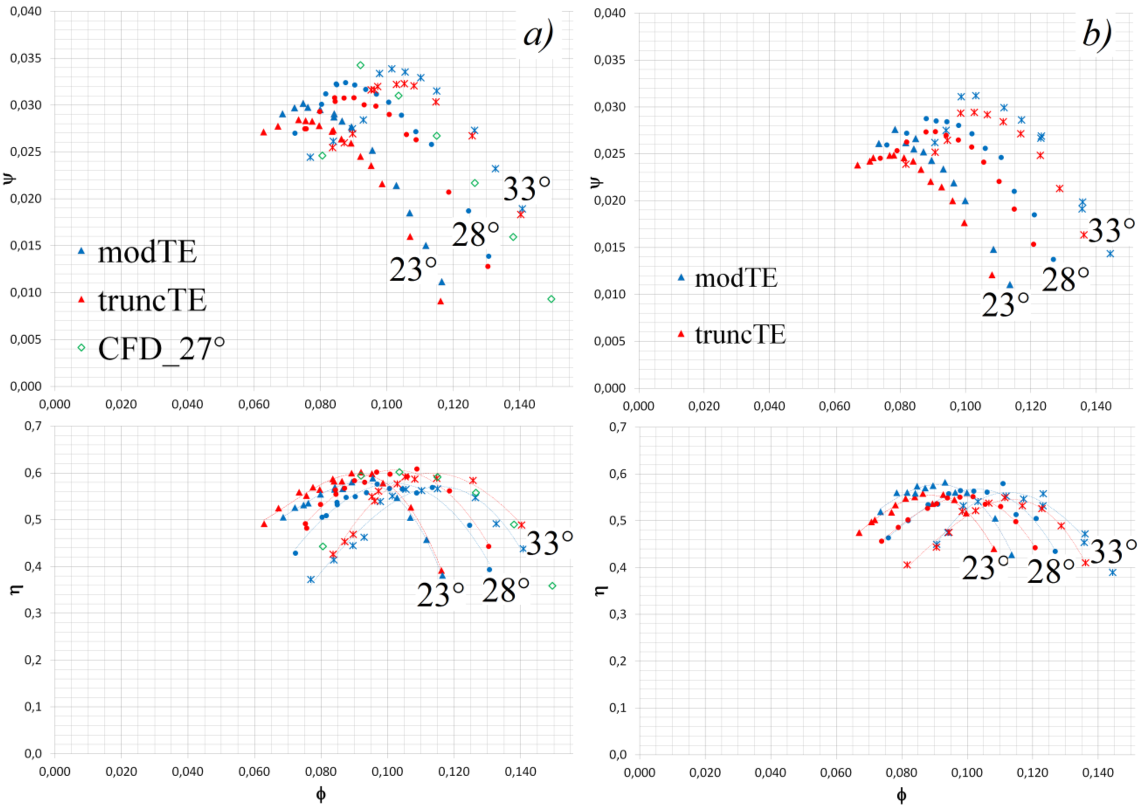

Fig. 2. Performance curves for case 1 (red markers) and 2 (blue markers) geometries at three blade positioning angles (23°, 28°, 33°). (a) Tip leakage equal to 1.4% of blade channel height; (b) Tip leakage equal to 2.5% of blade channel height. Data from CFD simulations (green markers) on the ideal geometry at blade positioning angle of 27° are reported on figure (a).

As expected both the modifications pay a performance loss respect to the ideal profile blade. The differences in terms of pressure rises at peak efficiency point are quite impressive: compared with CFD results, truncated geometry shows a decrease of 11.5% whereas the modified one only of 5%. In fact, Herrig et al. [4] observed a turning angle loss of 1-1.6° for NACA 65-series blades featuring a 0.02c thickened TE.

Table 1. Performance differences between case 1 and case 2 geometries at maximum efficiency points. Percentages refer to the truncated TE blade (i.e. performance of case 1 respect case 2).

	1.2 mm tip leak.		2.2 mm tip leak.	
	$\Delta\Psi_{1\text{–}2}$(%)	$\Delta\eta_{1\text{–}2}$(%)	$\Delta\Psi_{1\text{–}2}$(%)	$\Delta\eta_{1\text{–}2}$(%)
23°	- 6.0	+ 1.6	- 6.8	- 5.5
28°	- 6.1	+ 4.9	- 3.8	- 3.6
33°	- 3.3	+3.4	- 4.4	- 3.7

To reduce this performance drop Herrig et al. suggest a 1%c tail thickness, although this is not always feasible when structural, vibrational and manufacturing constrain must be satisfied.

On the other hand, the results obtained at a higher value of tip leakage (2.5% of channel height) showed in Figure 2 b) are quite surprising. The two geometries show the typical performance drop but the truncated tail blade is more affected than case 2. In fact, referring at the left side of Table 1, also case 1 efficiencies are lower than those featured by the modified blading (case 2). Moreover, case 1 peak efficiency points slightly slides at lower values of volumetric flow rate than case 2. Explanations of this phenomenon are not evident and require further investigations.

6. Conclusions

The effects of two trailing edge modifications on NACA 65-series section on the performance of a rotor-only tube axial fan were investigated. In the first case the airfoil trailing edge is truncated at the minimum manufacturing thickness available. In the second case the tail geometry is modified by imposing constant thickness. The main results are summarized as follows:

- Both the modifications pay a loss of pressure rise in comparison with the ideal geometry (i.e., no trailing edge modifications). The drop is around 5% for the constant thickness tail blade and higher for the truncated chord blade (more than 11%). This occurrence shall be taken into account when blade design are based on NACA 65-series cascade data.
- At small tip leakage values the truncated tail geometry show a drop of pressure rise respect to the thickened TE full chord length blade, while efficiencies are similar.
- At higher tip leakage values the truncated geometry is not advantageous at all. Both pressure rises and efficiencies are lower than those obtained with the full chord length constant thickness tail blade.

Acknowledgement

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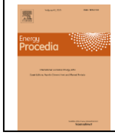
Biography



Stefano Castegnaro is PhD student at the School of Industrial Engineering of University of Padua. His research activity regards industrial axial flow fans; he is active on low-speed wings design as well. Before he worked on composite for nautical applications and participated in the construction of two sailing yachts.

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