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NUMERICAL ANALYSIS OF MODIFIED FANWING CONCEPT

Modification of the FanWing concept intended for the use at higher speeds of flight (over 20 m/s) is numerically analyzed. The principle of operation, basic aerodynamic characteristics, and the features in untypical flight situation (autorotation) are described and explained.

NOMENCLATURE

F_D	–	drag force (if less than zero airfoil is generating thrust),
F_L	–	lift force,
M	–	momentum on blades,
$r = 0.086$ m	–	radius on which center of the blades is placed,
u	–	flight speed,
$s = 1$ m	–	airfoils width,
ω	–	rotational speed of the fan,
$\rho = 1.225$ kg/m^3	–	air density,

1. Introduction

This work was inspired by the FanWing concept introduced by Patrick Peebles [1]. FanWing is a specific kind of aircraft propelling device, which has a fan attached along its wings. Rotating fan enables airfoil to generate thrust, so that no other kind of propulsion is needed. By now, several different prototypes of FanWing have been created proving that this solution can be

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brought to life. Time will show whether FanWing has enough advantages to be introduced to commercial flights.

The aim of this work was to check if there is a possibility of using the FanWing concept with a more traditional kind of airfoil. In the original concept (Fig. 2.b.), diameter of the fan is about a half of the total width of wings. This work presents results achieved by the use of one-meter wide airfoil and a 0.195 m diameter fan. The ratio of the rotor diameter to the cord is more than two times less than in the original Fan Wing concept. The use of so much smaller fan makes it impossible to work in the same way as the original one, and to provide enough thrust. That is why there had to be found a different airfoil and fan configuration. The most important was that the new setup had to create thrust; this was the main criterion rating its work and an essential condition. It was also intended that the airfoil should work properly at the flight speed of at least 20 m/s. The original FanWing is designed for lower speeds, up to 20 m/s.

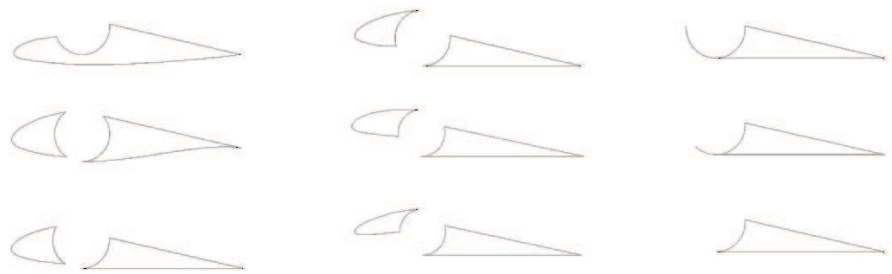


Fig. 1. Comparison of preliminarily considered modifications of the FanWing geometry

Fig. 1 is showing some of the airfoils studied before the final airfoil was achieved, one can see what different placements of the fan were taken into consideration and what changes and simplifications of the airfoil have been made. There have been performed analysis of the airfoils properties with different kinds of nose sections. The following solutions have been taken into consideration:

– complete lack of nose section
– a rigid windshield covering the fan up to different angles
– nose sections of different standard airfoils

Different kinds of blades also have been checked. Airfoil that produced the greatest thrust was selected for further examination; it was one with a part of an airfoil NACA6409 as a nose section. Some of its properties were also compared with an airfoil without the nose section.
The studied airfoil geometry with attached fan is shown in Fig. 2.a.

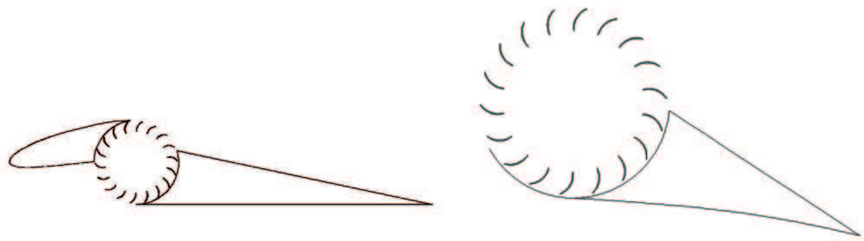


Fig. 2. a) Final geometry numerically analyzed; b) Original FanWing airfoil

All calculations were performed in Fluent, in two dimension and double precision solver version. The mesh contained 45 000 nodes, mainly concentrated near the blades of rotor.

The unsteady, two dimensional, turbulent flow model of incompressible fluid was used in the simulation. The Spalart-Allmaras model was applied in turbulence modeling due to the implementation of the wall damping functions tuned for external aerodynamic flows, and because of known, good performance in boundary layer with adverse pressure gradients [2].

Fan movement was modeled by the use of moving mesh, and the airfoil was connected with fan by the interface technique.

2. How does it work

The principle of operation is slightly similar to existing in cross-flow fans. Fan is rotating right, it makes the stream of air to move up, and go through the center of the fan, later blades direct the stream to flow round the right upper part of the airfoil. Below (Fig. 3 – Fig. 5) is an overview of some of the airfoils properties in the case of:

– flight speed: u = 20 m/s
– rotational speed of the fan: ω = 300 rad/s

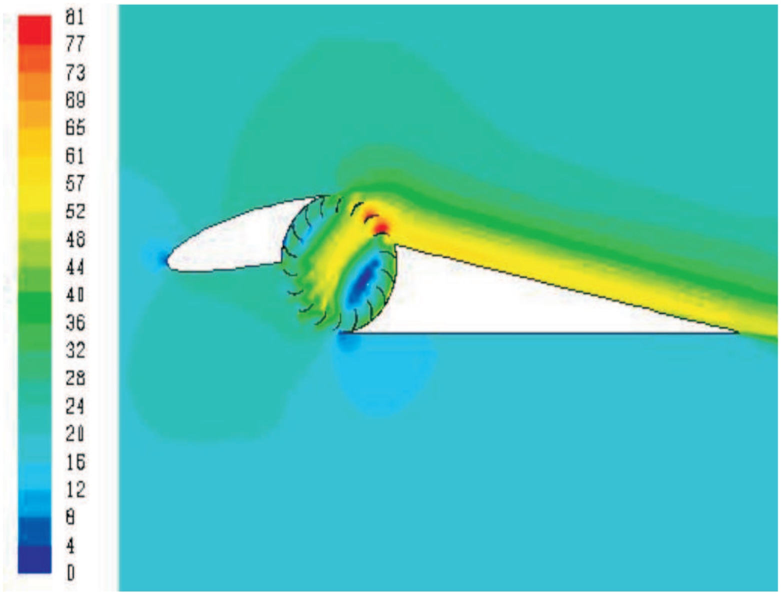


Fig. 3. Velocity magnitude distribution [m/s]

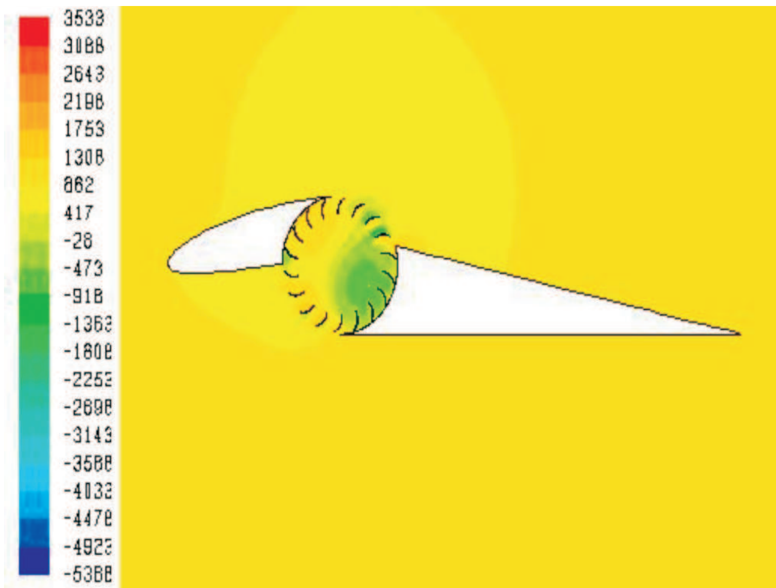


Fig. 4. Contours of static pressure [Pa]

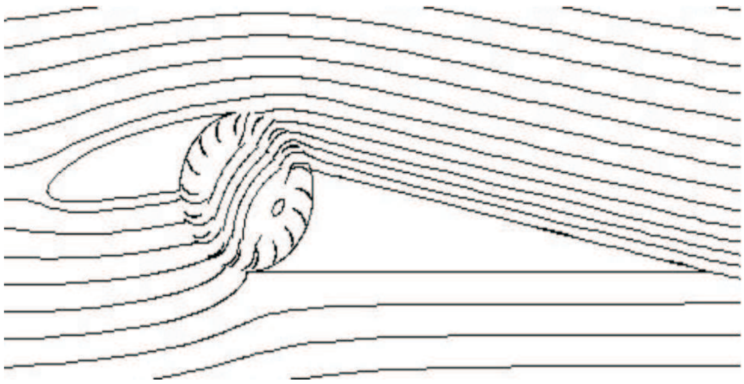


Fig. 5. Path lines

The diagrams of drag and lift forces are shown respectively in Fig. 7 and Fig. 8 in the function of blade rotation angle in the range of up to 120 degrees, which also represents time, in an indirect way. Each curve describes total force acting on the surface bounded by the characteristic points defined as shown in Fig. 6. It can be seen that the forces acting on each section of the airfoil have constant frequency and amplitude.

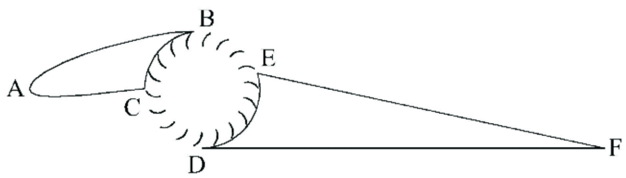


Fig. 6. Definition of characteristic points on the airfoil

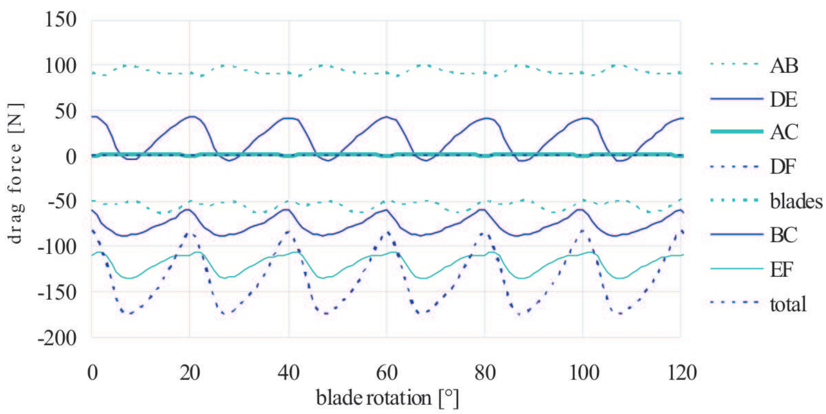


Fig. 7. Time course of drag force generated on each section of the airfoil

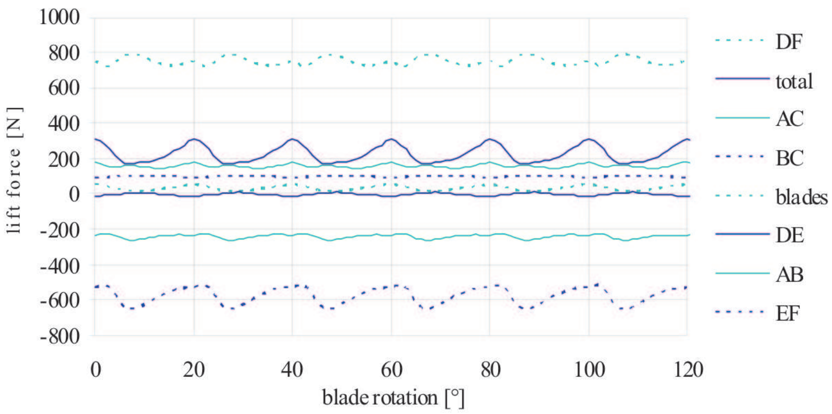


Fig. 8. Lift force generated on each section of the airfoil variation in time

The total drag force is below zero, it means that the airfoil generates thrust.

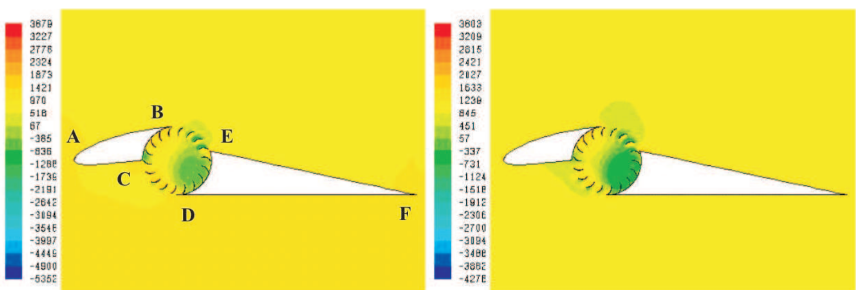
The total lift force reaches its maximum and minimum at the same time as the total drag force.

It is worth noticing that curve BC, representing the force acting on the surface between points B and C, generates a substantial part of the thrust as well as the lift force. The blades also generate some thrust, both forces on surface D-E are around zero, and the greatest portion of the thrust is generated on surface E-F. The lift is generated mainly on surface D-F and also on surface A-C.

An overview of average forces acting on each part of the airfoil is presented in Table 1.

Table 1.

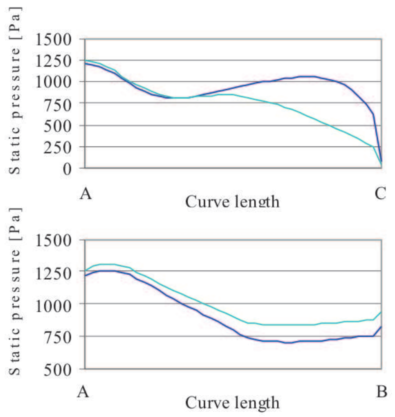
section	AC	AB	EF	DF	BC	DE	blades	total
Average lift [N]	159	–240	–575	751	100	–2	33	226
Average drag [N]	2	93	–119	1	–76	20	–55	–134



a) b)

Fig. 9. Contours of static pressure in the case of: a) Maximum lift / drag, b) Minimum lift / drag

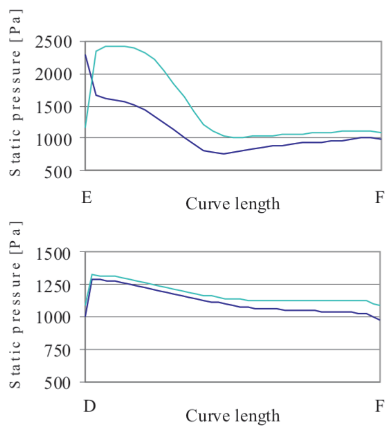
Pressure contours at the phase of rotor rotation corresponding to maximum values of the lift and drag are shown in Fig. 9a and those corresponding to minimum values – in Fig. 9 b.



	A-C	Total
Average lift	159 N	226 N
Average drag	2 N	-135 N

	A-B	Total
Average lift	-240 N	226 N
Average drag	93 N	-135

Fig. 10. Diagrams of static pressure for front airfoil section surfaces A-C and A-B, when the total lift and drag forces are max/min



	E-F	Total
Average lift	-575 N	226 N
Average drag	-119 N	-135 N

	D-F	Total
Average lift	751 N	226 N
Average drag	1 N	-135 N

Fig. 11. Diagrams of static pressure for rear airfoil section surfaces E-F and D-F, when the total lift and drag forces are max/min

	Blades	Total
Average lift	33 N	226 N
Average drag	–55 N	–135 N
Momentum on blades	28 Nm	
Power needed to run the fan	$M \cdot \omega = 28 \cdot 300 = 8.4$ kW	

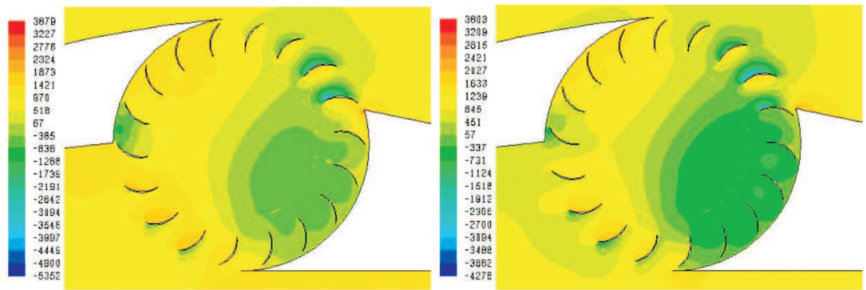
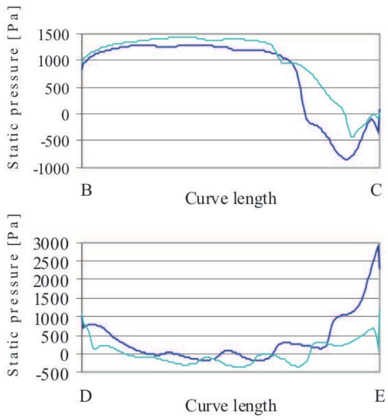

a) b)

Fig. 12. Contours of static pressure in the case of: a) Maximum lift / drag, b) Minimum lift / drag



	B-C	Total
Average lift	100 N	226 N
Average drag	-76 N	-135 N

	D-E	Total
Average lift	-2 N	226 N
Average drag	20 N	-135 N

Fig. 13. Diagrams of static pressure for internal airfoil surfaces B-C and D-E , when the total lift and drag forces are max/min

3. Lift an drag forces dependences on rotational speed

The aerodynamic device characteristics (drag and lift versus rotational speed) for a set of flight speeds are presented in Fig. 14 and Fig. 15. Nondimensional drag and lift force coefficients are shown in Fig. 16 and Fig. 17.

Lift force grows along with rotational speed and drag force becomes smaller, what was expected. In the case of low rotational speeds, the drag force is lower when the flight speed is low, and in the case of higher rotational speeds it is lower when the flight speed is high, as well.

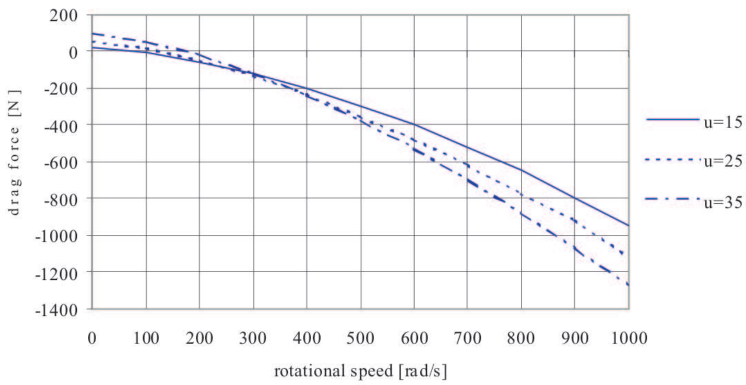


Fig. 14. Drag force in the function of rotational speed

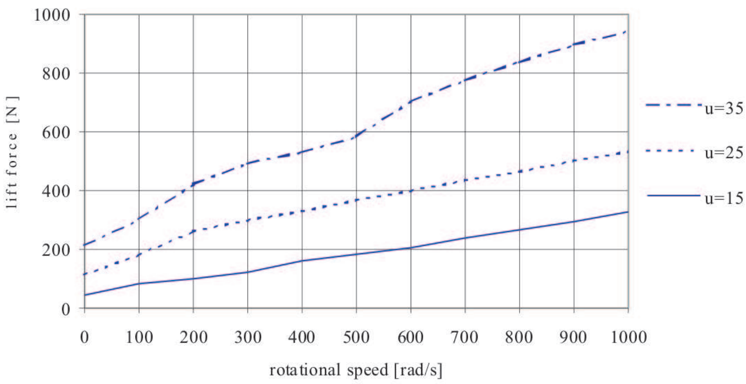


Fig. 15. Lift force in the function of rotational speed

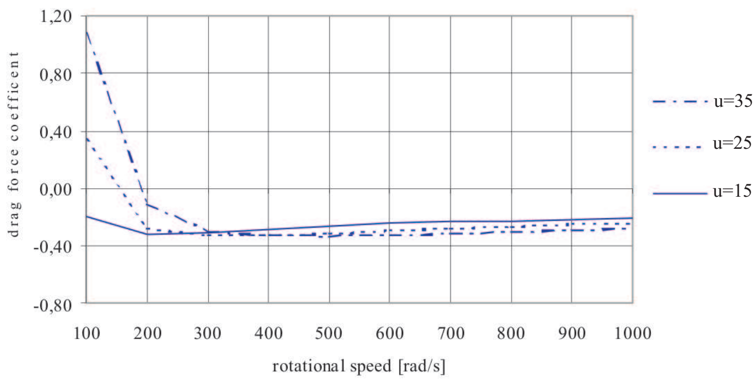


Fig. 16. Drag force coefficient in the function of rotational speed

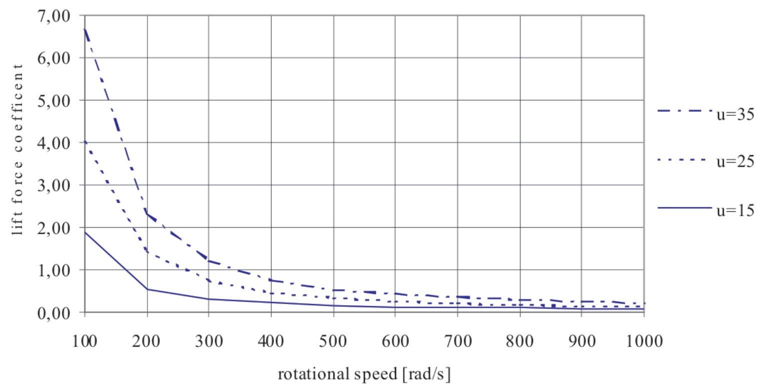


Fig. 17. Lift force coefficient in the function of rotational speed

Drag force and lift force coefficients are obtained from the equations:

$$C_D = \frac{2 \cdot F_D}{\rho \cdot (\omega \cdot r)^2 \cdot s} \qquad C_L = \frac{2 \cdot F_L}{\rho \cdot (\omega \cdot r)^2 \cdot s}$$

Both coefficients converge to constant values with the growth of rotational speed. Fig. 16 and Fig. 17 are showing that the airfoil properties are deteriorating with growth of rotational speed, because lift coefficient is falling and drag coefficient is going up. The comparison of aerodynamic characteristics of two geometric configurations of the device (with and without nose airfoil section) are presented in Fig. 18 and Fig. 19.

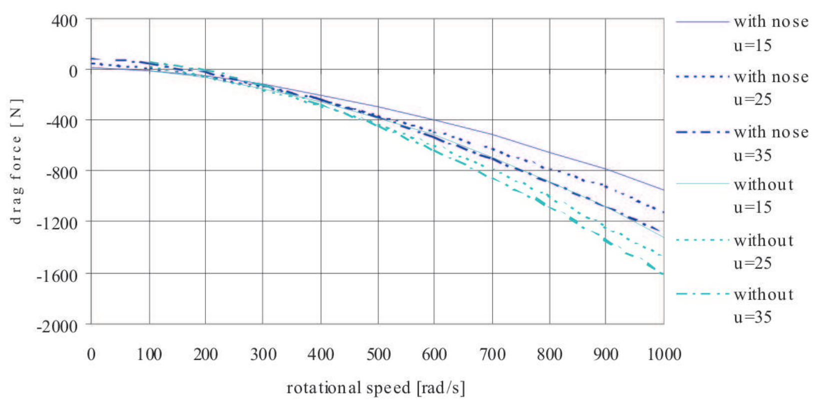


Fig. 18. Drag force comparison of profiles with and without nose section

The above diagrams (Fig. 18 and Fig 19) show that the lift force, as well as the thrust, grow faster in the case of airfoil without nose section. Their

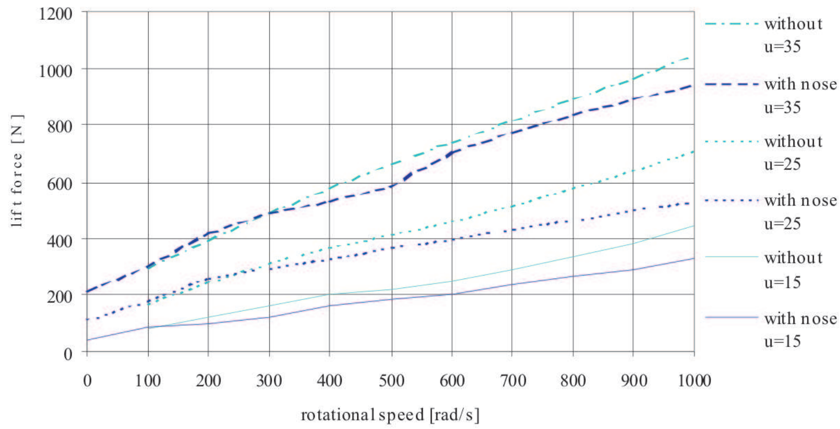


Fig. 19. Lift force comparison of profiles with and without nose section

values are higher than those in the case of airfoil with the nose section after a certain critical rotational speed is reached. This critical speed is unique for each flight speed and is slightly different for drag and lift forces.

4. Dependences of lift an drag forces on flight speed

Similar aerodynamic device characteristics, drag and lift versus flight speed, for a set of rotor rotational speeds are presented in Fig. 20 and Fig. 21. Nondimensional drag and lift force coefficients are shown in Fig. 22 and Fig. 23.

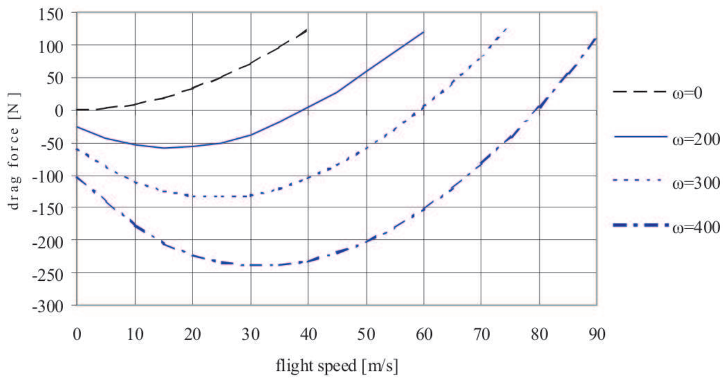


Fig. 20. Drag force in the function of flight speed

In the diagram of drag force (see Fig. 20) it can be seen that for each rotational speed, the drag force reaches its minimum for a specific flight speed. It means that for each rotational speed there is an optimal flight speed

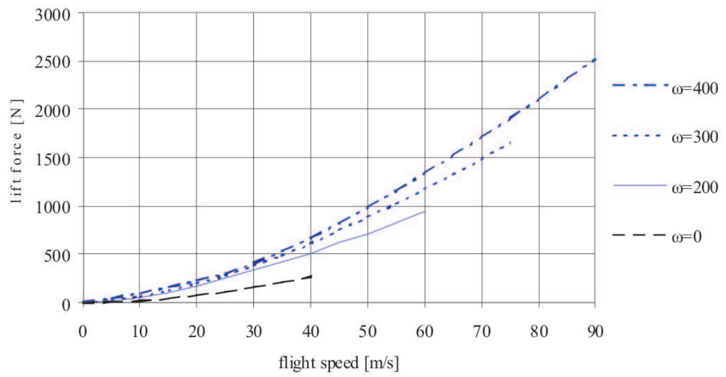


Fig. 21. Lift force in the function of flight speed

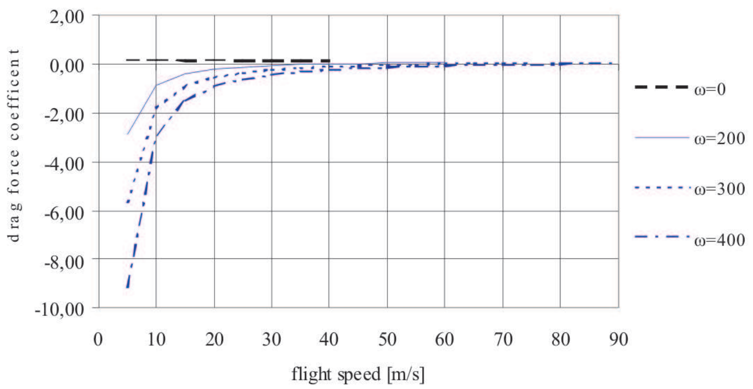


Fig. 22. Drag force coefficient in the function of flight speed

at which the aircraft should be moving. Its value grows along with the growth of rotational speed. It can also be seen that for each rotational speed there is a specific critical flight speed at which drag force value reaches zero (when the airfoil does not produce the thrust anymore), its value also grows along with growth of rotational speed. The lift force (Fig. 21) grows along with the growth of flight speed, and it grows faster for higher rotational speeds.

Drag force and lift force coefficients can be obtained from the equations:

$$C_D = \frac{2 \cdot F_D}{\rho \cdot u^2 \cdot s} \qquad C_L = \frac{2 \cdot F_L}{\rho \cdot u^2 \cdot s}$$

Both coefficients (see Fig. 22 and Fig. 23) have an almost constant value for rotational speed equal zero, just like for a typical airfoil, and for rotational speeds above zero, both of them seem to converge to that value. It can be

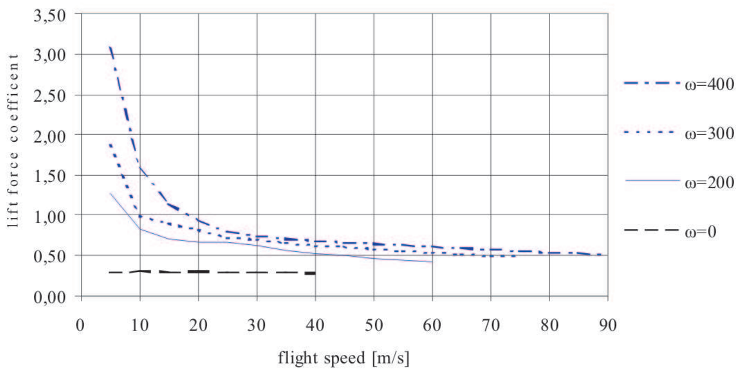


Fig. 23. Lift force coefficient in the function of flight speed

seen more clearly after the critical speed of flight is reached, when the thrust is no longer produced.

Comparison of aerodynamic characteristics of two geometric configurations of the device (with and without nose airfoil section) are presented in Fig. 24 and Fig. 25.

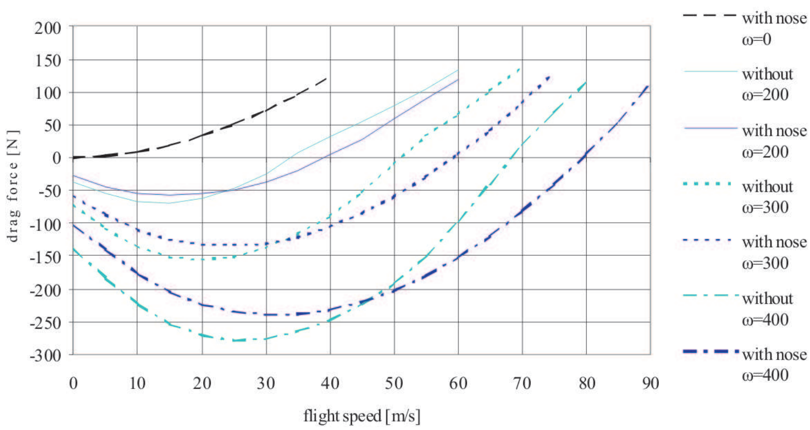


Fig. 24. Drag force comparison of profiles with and without nose section

The diagrams (Fig. 24 and Fig. 25) show that, at lower flight speeds, the airfoil without the nose section has better properties, greater lift force and thrust. At higher flight speeds it changes to the advantage of the airfoil with the nose section. One can observe a critical flight speed for each rotational speed at which this change occurs, and this speed is slightly different for lift and drag force. It can be also seen that the maximum thrust produced at a certain rotational speed is greater in the case of the airfoil without the nose section.

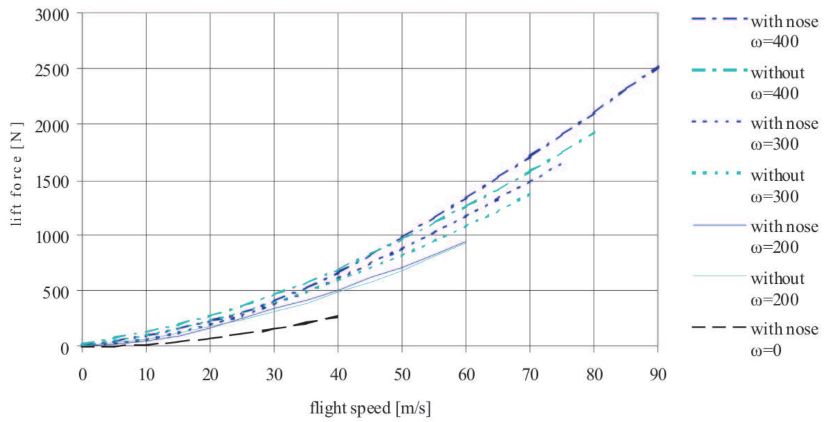


Fig. 25. Lift force comparison of profiles with and without nose section

The calculations for the airfoil without the nose section and rotational speed equal zero have not been performed in this study, because an unmoving fan creates so much disturbance in the flow that it was hard to obtain any solution and airfoil properties nowhere near the case of the working fan.

5. Thrust efficiency

One of most important device parameters is the efficiency of thrust generation. In specific configuration, negative drag represents generated thrust. The dependence of the thrust on the flight speed and rotor rotational speed is shown in Fig. 26. Thrust generation efficiency is presented in Fig. 27 and Fig. 28.

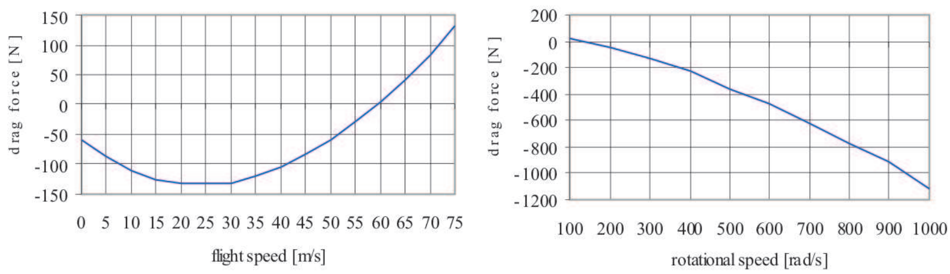
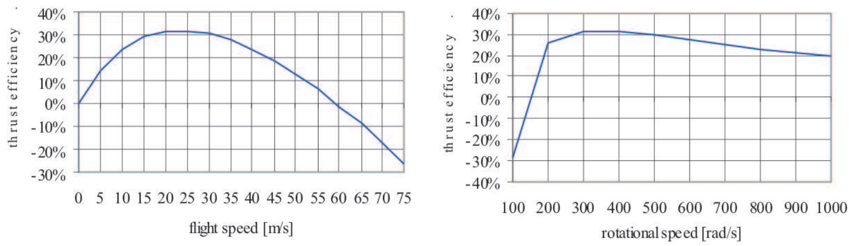


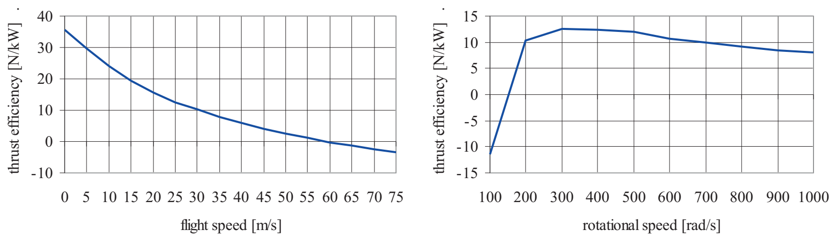
Fig. 26. Drag force in the function of: a)– flight speed, ω = 300 rad/s, b)– rotational speed of the fan, u = 25 m/s

Thrust efficiency is obtained from the equation: $\eta_T = \dfrac{F_D \cdot u}{M \cdot \omega}$ [%]



a) b)

Fig. 27. Thrust efficiency in the function of: a)– flight speed, ω = 300 rad/s, b)– rotational speed of the fan, u = 25 m/s



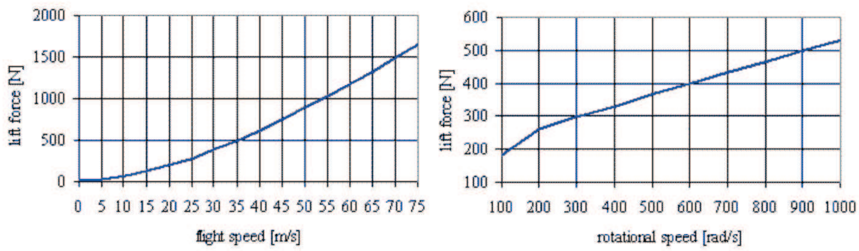
a) b)

Fig. 28. Thrust efficiency in the function of: a)– flight speed, ω = 300 rad/s, b)– rotational speed of the fan, u = 25 m/s

Thrust efficiency can be obtained from the equation: $\eta_T = \dfrac{F_D \cdot 1000}{M \cdot \omega} \left[\dfrac{N}{kW}\right]$

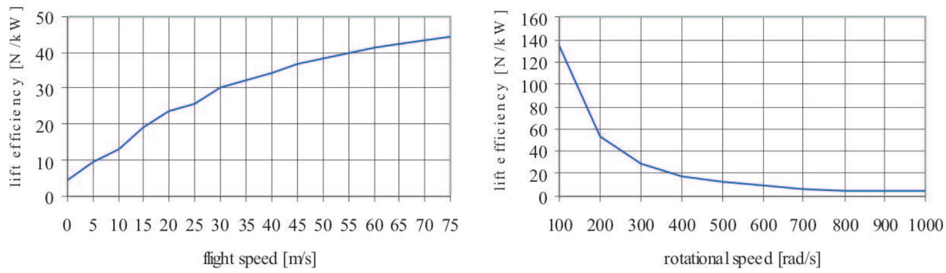
6. Lift efficiency

Rotation of the rotor changes the flow conditions around the steady part of the device and generates additional lift. The dependence of the lift on the flight speed and rotor rotational speed is shown in Fig. 29. The lift generation efficiency is presented in Fig. 30.



a) b)

Fig. 29. Lift force in the function of: a)– flight speed, ω = 300 rad/s, b)– rotational speed of the fan, u = 25 m/s



a) b)

Fig. 30. Lift efficiency in the function of: a)– flight speed, ω = 300 rad/s, b)– rotational speed of the fan, u = 25 m/s

Lift efficiency can be obtained from the equation: $\eta_L = \dfrac{F_L \cdot 1000}{M \cdot \omega} \left[\dfrac{N}{kW} \right]$

Looking at the thrust efficiency diagrams (Fig. 27 and Fig. 28), we can see that there is an optimal combination of rotational and flight speed at which airfoil produces the greatest thrust. Maximum efficiency, expressed in percentage terms, is equal to 30%, which is very small.

The lift efficiency (Fig. 29 and Fig. 30) grows along with the growth of flight speed and drops down very quickly when the rotational speed grows. In the case of flight speed u = 25 m/s and rotational speed ω = 100 rad/s, one can obtain a decent value of 140 N/kW, but at the same time drag is above zero, which means that the airfoil does not produce any thrust.

The main reason of low efficiency is very simple. The stream of air forces the fan to rotate anticlockwise, whereas to generate thrust and lift it should rotate clockwise. So that, some part of the energy must initially be wasted only to stop the fan rotating in the wrong direction. In the original concept of the FanWing, this problem did not occur, then the efficiency could be higher. For example, in the case of flight speed u = 20 m/s with stopped fan, the momentum on the blades is equal to 5 Nm, and when the fan rotates at the speed of ω = 300 rad/s, it equals 28 Nm.

There is also one more cause of low efficiency. It is the result of simplifications that have been made, concerning the right part of the airfoil. This airfoil is just an example of how can the FanWing concept be modified, and it wasn't optimized to achieve the best results. After some modifications, applied mostly to the right part of the airfoil, the lift as well as the thrust efficiency should be much higher.

7. Autorotation

As it was mentioned earlier, the presented airfoil generates thrust and lift if the fan rotates clockwise. The question arises, what happens if the fan is not moving or is rotating freely left, pushed by the stream of air? Below you can see how the flow around the airfoil changes in such cases.

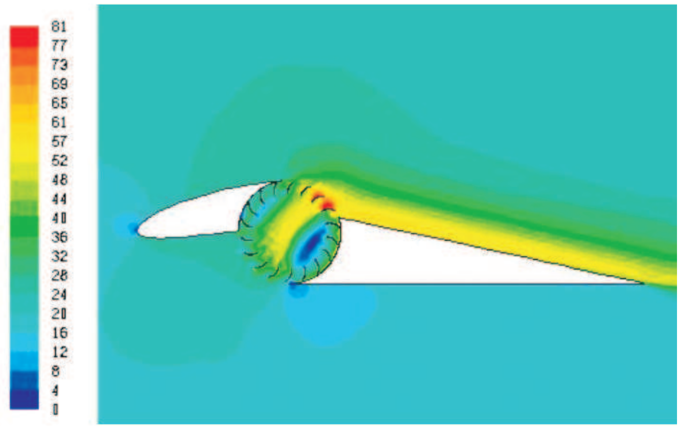


Fig. 31. Contours of velocity in the case of flight speed u = 20 m/s and rotational speed ω = 300 rad/s, (fan rotates clockwise)

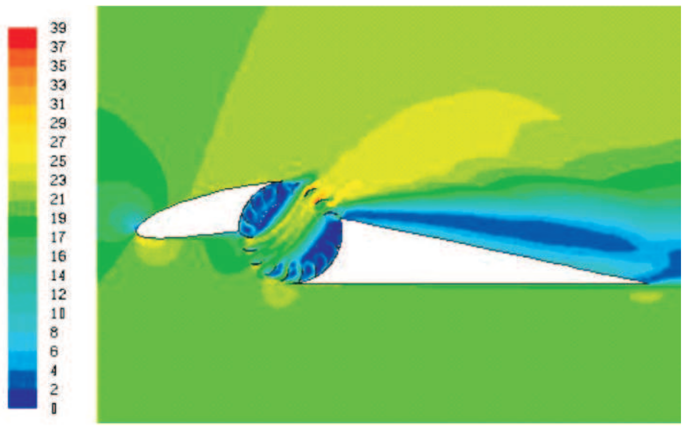


Fig. 32. Contours of velocity in the case of flight speed u = 20 m/s and rotational speed ω = 0 rad/s, (fan is not moving)

A set of average lift and drag forces generated by selected airfoil surface in the case of flight speed u = 20 m/s and different rotor rotational speeds is presented in Tables 2, 3 and 4.

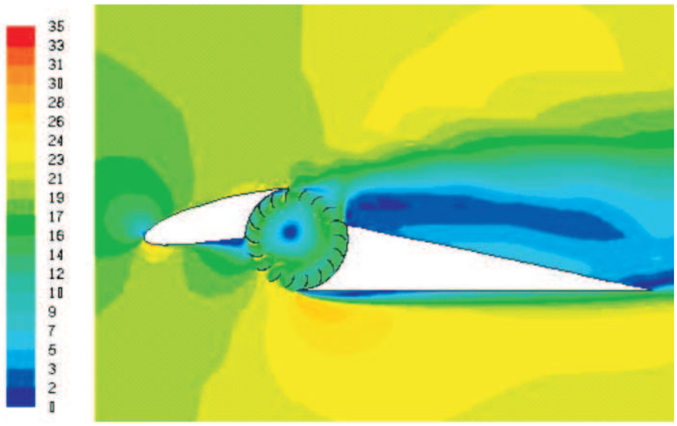


Fig. 33. Contours of velocity in the case of flight speed u = 20 m/s and different rotational speed ω = –126 rad/s, (fan rotates anticlockwise freely)

Table 2.

ω = 300 rad/s fan rotates clockwise

section	AC	AB	EF	DF	BC	DE	blades	total
Average lift [N]	159	–240	–575	751	100	–2	33	226
Average drag [N]	2	93	–119	1	–76	20	–55	–134

Momentum on blades is equal 28 Nm

Table 3.

ω = 0 rad/s fan is not moving

section	AC	AB	EF	DF	BC	DE	blades	total
Average lift [N]	–5	0	61	7	–7	–5	22	73
Average drag [N]	–3	7	13	1	8	6	2	34

Momentum on blades is equal 5 Nm

Table 4.

ω = –126 rad/s fan rotates anticlockwise freely

section	AC	AB	EF	DF	BC	DE	blades	total
Average lift [N]	49	–73	–66	83	14	–31	1	–23
Average drag [N]	–4	31	–14	0	–19	38	7	39

Momentum on blades equals 0 Nm

The above data show that the presented airfoil is worthless when the fan is not working properly, that means rotating clockwise at a certain speed.

When there is no power delivered to the fan, it rotates anticlockwise freely, pushed by the stream of air. The result is that the airfoil does not generate any thrust or even lift anymore. So, if a failure of the fan occurs, the result of it will be an uncontrollable falling down to the earth.

8. Effect of the angle of attack

Up to now all the presented device characteristics have been calculated for the zero angle of attack. The values of the lift and drag forces in a wide range of angles of attack are shown in Fig. 34. Two cases were checked:

– fan rotating at speed ω = 300 rad/s
– fan turned off ω = 0 rad/s

The diagram in Fig. 34 shows that there aren't any sudden changes of airfoil properties when the angle of attack changes. One can notice a maximum of the lift coefficient at very high angle of attack (30 deg) and a relatively high lift at angles reaching 50 deg. The changes of lift force are more significant, which proves only that the airfoils shape could be improved to generate much more lift force. Whilst creating the airfoil, the changes of angle of attack haven't been taken into consideration, but the airfoil still remains quite stable.

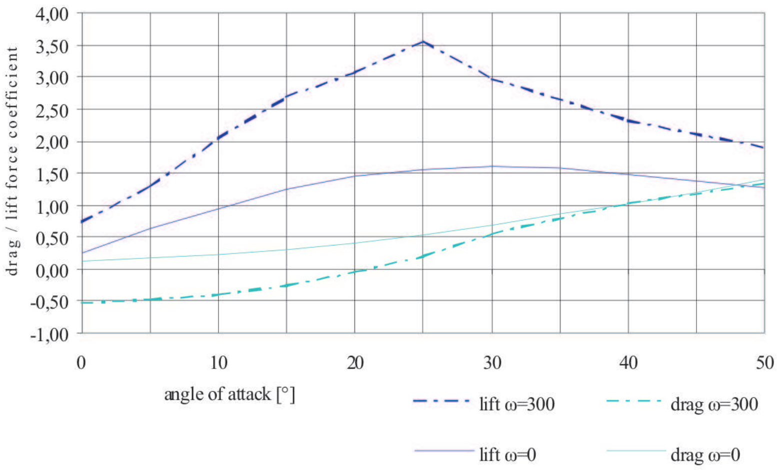


Fig. 34. Drag and lift force coefficients in the function of the angle of attack, flight speed u = 20 m/s

Drag / lift force coefficients can be obtained from the equations:

$$C_D = \frac{2 \cdot F_D}{\rho \cdot u^2 \cdot s} \qquad C_L = \frac{2 \cdot F_L}{\rho \cdot u^2 \cdot s}$$

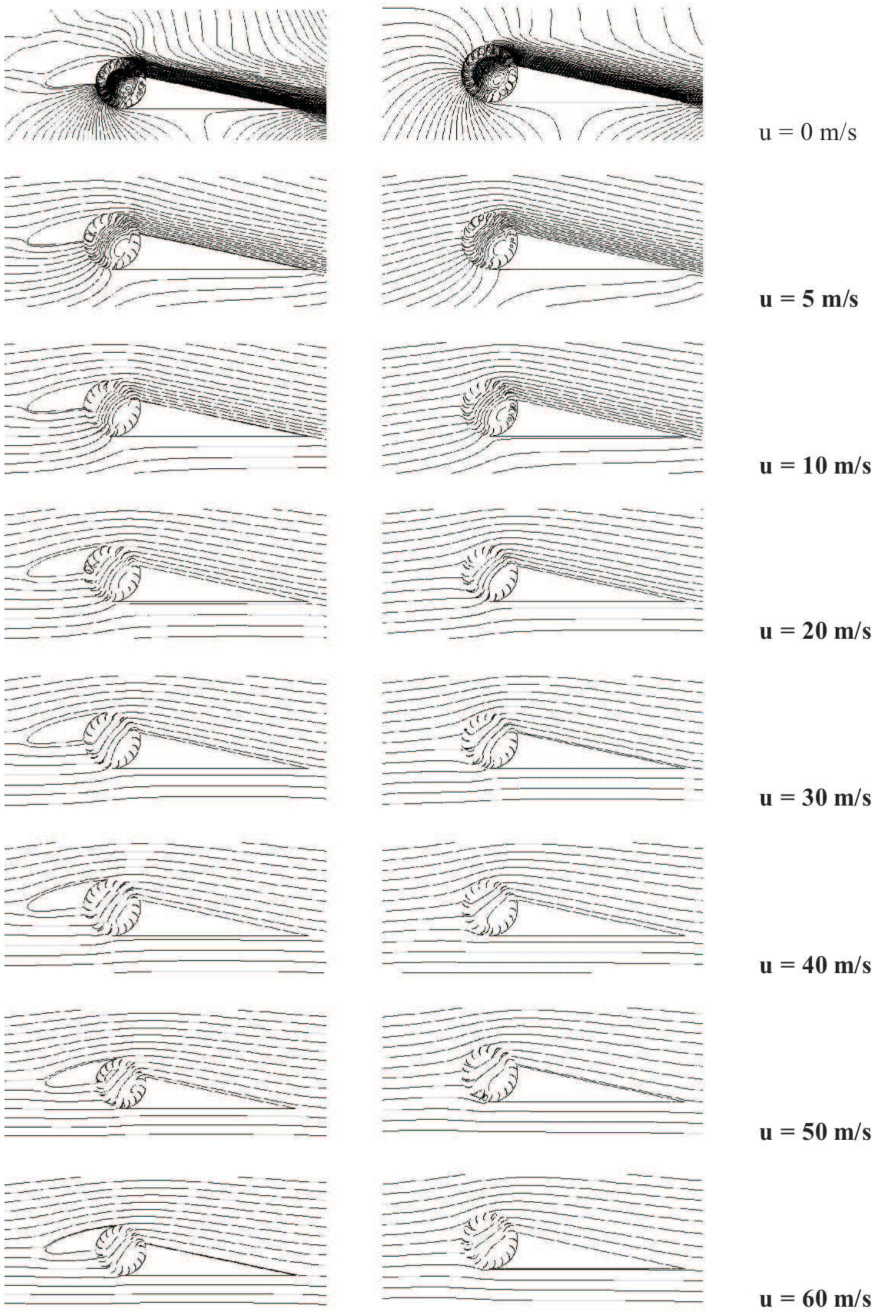


Fig. 35. Path lines – airfoil with and without nose section, rotational speed of the fan ω = 200 rad/s

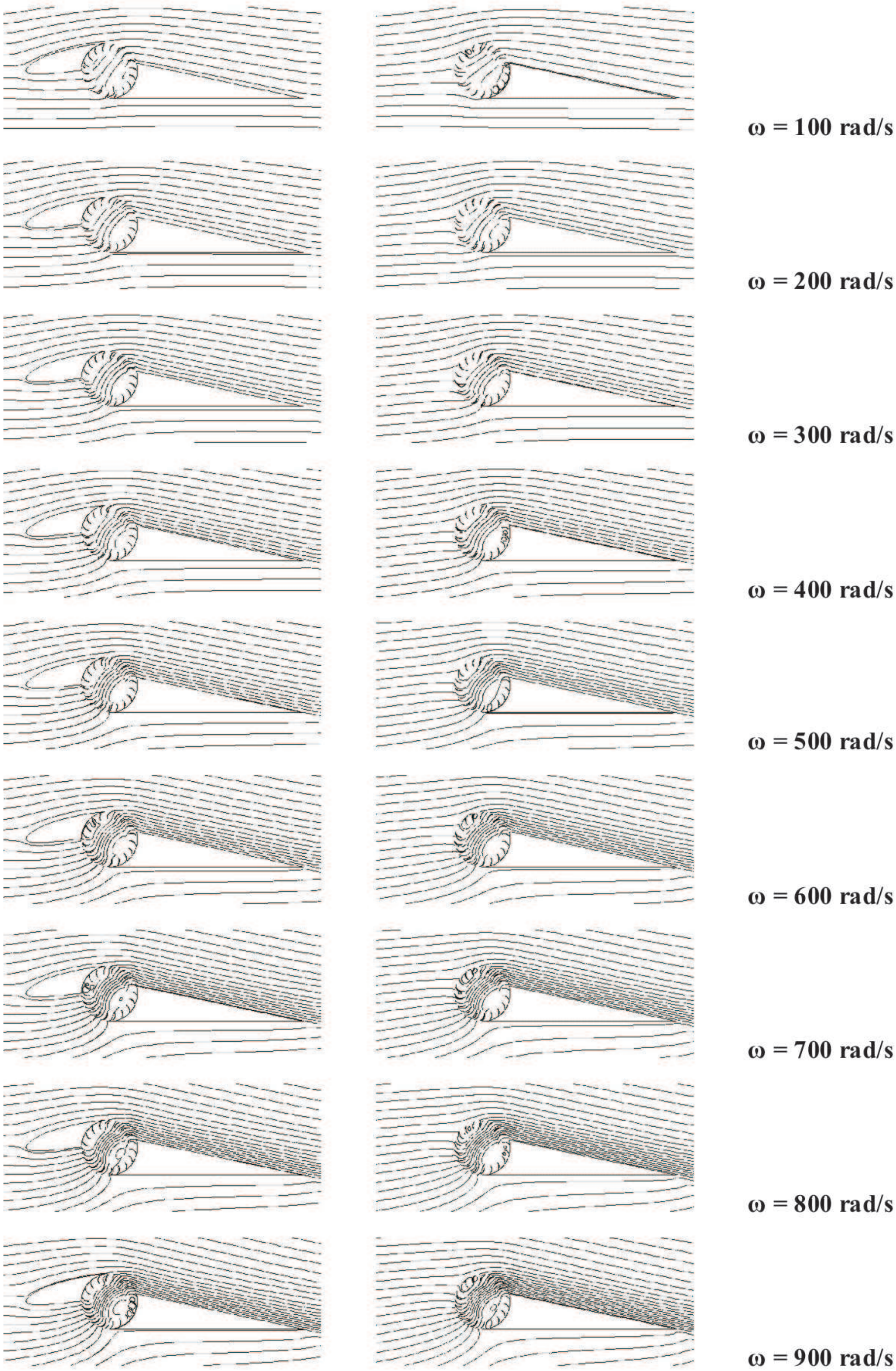


Fig. 36. Path lines – airfoil with and without nose section, flight speed u = 25 m/s

To explain the details of the flow conditions for two different device geometric configurations (with and without nose section), a set of path-line visualizations for different flight speeds is presented in Fig. 35. A similar path-lines visualization for the flight speed of 25 m/s and different rotor rotational speeds is presented in Fig. 36 for both considered geometrical configurations.

The increase of the flow speed over the rear upper airfoil section is clearly seen, as well as the lowered air speed below the rear airfoil section.

9. Conclusion

This work presents a modification of the FanWing concept, which shows that a fan attached as a propulsion system along a wing is an interesting solution. It might be possible that there are more such set-ups of fan and wing that give advantageous results. The one presented in this work fulfills one essential condition, which is the requirement to generate thrust and lift. However, it has two significant disadvantages, which are: low efficiency and impossibility of safely emergency landing with the use of autorotation. Both of them result from the necessity to put some extra energy forcing the fan to rotate in the direction opposite to the natural one.

The comparison of airfoils with and without the nose section showed that more thrust and lift can be produced by the airfoil without the nose section. The advantages of the airfoil with the nose section were observed only when the flight speed was higher. It means that to improve this airfoil, the nose section should be excluded, and an optimization process should be preformed at lower speeds of flight. Eventually, it might lead to the original FanWing concept, but still it doesn't mean that it must be the only possible solution for this problem.

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Numeryczna analiza koncepcji zmodyfikowanego skrzydła wentylatorowego

S t r e s z c z e n i e

W pracy przedstawiono koncepcję modyfikacji skrzydła wentylatorowego przeznaczonego do lotów z większymi prędkościami (ponad 20 m/s) niż oryginalne skrzydło wentylatorowe. Wykorzystując program Fluent dokonano symulacji opływu skrzydła dla kilku konfiguracji geometrycznych, szeregu prędkości obrotowych wirnika i prędkości lotu. Przedstawiono i przeanalizowano podstawowe charakterystyki aerodynamiczne skrzydła. Wskazano zarówno na zalety rozwiązania jak i jego słabe strony. Analizy zachowania skrzydła zilustrowano szeregiem rozkładów ciśnień jak też wykresów nieustalonych sił aerodynamicznych. Zasugerowano dalsze kierunki badań.