Deutscher Luft- und Raumfahrtkongress 2009
DocumentID: 121284

AERODYNAMIC ANALYSIS OF A NEW HYBRID ROTOR

J. Seifert, Bauhaus Luftfahrt e.V., Germany
Boltzmannstr. 15, 85748 Garching

Abstract

A Hybrid Rotor [1] consisting of a cycloidal propeller [2], [3] and a rotating cylinder [4] for VTOL application is presented.
Recent research projects demonstrated a tethered flight of an unmanned air vehicle, propelled by a cycloidal blade system [3]. Lightweight structures and high performance electric motors were used to hover in ground effect. The propulsive efficiency has to be increased in the future to realize a forward flight and to carry additional payload.
The Hybrid Rotor is the combination of two devices for cruise flight – a propulsion system such as the cycloidal propeller and an additional lift generating device such as a rotating cylinder.
The Magnus Effect is a well known phenomenon, which produces aerodynamic forces on a rotating cylinder nearly perpendicular to the motion through the air. Some applications for ships demonstrated that very high thrust coefficients could be realized and utilized in commercial shipping. An application in aviation seems to be possible, however other physical effects like drag and gyroscopic forces have to be taken into account. Furthermore a rotating cylinder is like a wing without control surfaces. For application in aeronautics control devices are essential for flight. One favorable solution is presented here, that is able to provide thrust, lift and control power. It is a two-dimensional propulsor with 360 degree thrust vector control.
Aerodynamic analyses were performed to study the flow characteristics and to calculate forces and moments in cruise flight and hovering. First results are presented which characterize the interactions between both rotor subsystems. Possible advantages and main challenges for an application in aeronautics will be discussed.

1. INTRODUCTION

The idea of cycloidal propulsion goes back to the beginning of the 20th century. One of the pioneers was Frederik Kurt Kirsten, who proposed cycloidal propulsion for Ligther-Than-Air vehicles and for aircraft as replacement to the wings [6]. James H. Boschma demonstrated the efficiency for the cycloidal propeller, that was higher than helicopter rotors [2]. He proposed the cycloidal propeller as propulsion system for airships, providing excellent maneuverability and low noise. Seung Kim built an UAV with four cycloidal propeller providing enough lift for a tethered flight [3]. However, a free flight of a cyclogiro, that is the name for an air vehicle using cycloidal propeller, was not reported till now. Some issues seem to be unsolved today, such as fatigue endurable kinematics and an appropriate flight control system.

In the 1920th a revolutionary vessel, equipped with rotating cylinders instead of a sail, crossed the atlantic ocean [8]. Anton Flettner was the inventor of the propulsion system. His success was supported by the wind tunnel experiments of Ludwig Prandtl, who found out, that end plates improve the aerodynamic forces of rotating cylinders in cross-flow [9]. This invention represents an application of scientific principles known for many years; an early English Paper titled “The irregular flight of a tennis ball” was published in 1878 by Lord Rayleigh, using the same principle in explanation. In the 1920th, the application of rotating cylinder in aeronautics was regarded as inefficient means compared to a wing [10]. Ten years later, the Scottish engineer Alexander Thom published a paper, showing the possibility to devise fencing sufficiently effective to enable lift-to-drag ratios of over 30 to be attained. Instead of using fences only at the end, Thom built a model rotor with discs of three times rotor diameter spaced every 0.75 rotor diameters [11], [12].

Pictures of rotorplanes exist, documenting the application of rotating cylinders to aircraft in the 1930th. There is few literature available, documenting a successful flight of a rotorplane. Friedrich Wilhelm Weissheimer reported recently about his flight trails with a radio controlled flight model in [13]. A powered aircraft needs thrust, lift and control for a sustained flight. The cycloidal propeller as propulsion system with control mechanism and the rotating cylinder as lifting device could be a solution. Both rotors are rotational symmetric, so they can be easily technically integrated.

The motivation for the development of a hybrid rotor is the need for new air vehicles in the future, with VTOL capability and less fuel consumption than nowadays. Gologan et. al. proposed a VTOL concept to address the demand of highly flexible transportation in the short range segment [14].

This contribution will describe the functional principle of the hybrid rotor and the results of the aerodynamic analysis. The challenges for future applications will be discussed.

2. ROTORS

The cycloidal propeller and the rotating cylinder are not new in aeronautical application. However, some important features, benefits and disadvantages of these rotors will be summarized here.

2.1. Cycloidal Propeller

The aerodynamic of a cycloidal propeller compared to the conventional screw propeller is quite different. The uniform distribution of the flow around a propeller blade increases the aerodynamic efficiency. On the other hand, the unique design of a cycloidal propeller leads to structural and mechanical challenges. The centrifugal forces combined with the oscillating aerodynamic forces lead to alternating loads and moments. A stiff and light weight structure is required for the propeller blades to compensate these loads [15]. The design of the connecting parts, especially the bearings of the propeller blades seem to be a challenging task in order to get them rated for endurance strength.

Hwang et. al. applied a swash plate to the rotor system to improve the rotor performance and control mechanism [3]. The purpose of using the swash plate is to decrease the whirling of the cantilever shaft by enlarging the shaft diameter, to make the control devices compact, and to be located inside the fuselage. This new mechanism enables easier yawing control of the aircraft, in addition to the performance improvement of converting the flying mode from hovering to forward flight. Furthermore, this control mechanism shows a faster response than the previous control design.

The cycloidal propeller is one part of the hybrid rotor. The design parameter, which are used, are listed in TABLE 1.

Propeller Airfoil	NACA 0012
Setting angle (max)	± 30 deg
Propeller diameter	0.8 m
Propeller span	1.0 m
Propeller chord lenght	0.15 m
Rotating speed	400 revs/min
Freestream velocity	0 m/s

TABLE 1: Design parameter of the cycloidal propeller used for the hybrid rotor.

A typical flow-field around such a propeller operating without inflow is given in FIGURE 1. The aerodynamic and the performance of a cycloidal propeller was investigated by Ioslevskii et.al. [17], [18] and Kim et.al. [5].

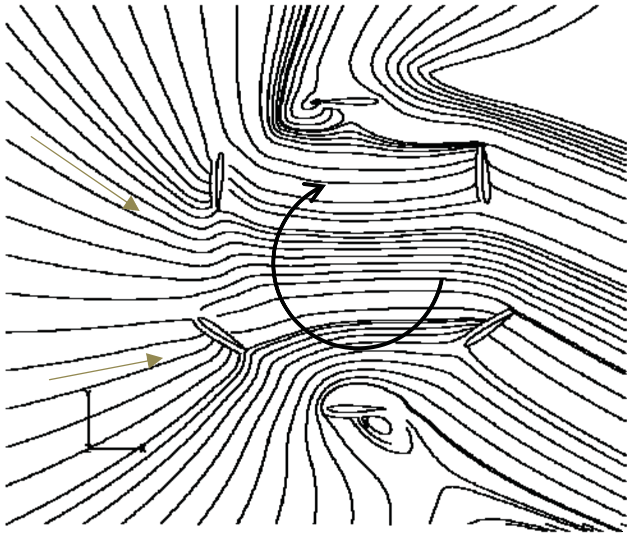

FIGURE 1. Streamlines around a cycloidal propeller (freestream velocity equals zero)

2.2. Rotating Cylinder

The primary characteristic of this flow is the generation of a transverse force, at right-angle to the flow direction, which is produced by the rotation. This phenomenon has commonly come to be known as the “Magnus effect” and is generally identified with the 1853 experiments of Gustav Magnus [5].

As mentioned above, rotating cylinder entered the field of aeronautics only rudimentary. Weissheimer reported recently about the flight characteristics of an aircraft possessing two rotating cylinders, taking advantage of the Magnus effect [13]. The handling qualities were poor, due to gyroscopic effects of the rotors spinning at high revolutions.

Research has shown the aerodynamic characteristics of rotating cylinders in crossflow to be highly dependent on a number of parameters (TABLE 1). The most important parameter that has major influence on the flow around a rotating cylinder is the velocity ratio α between the free flow v_0 and the rotational speed u of the cylinder.

$$\alpha = \frac{u}{v_0} \tag{1}$$

All aerodynamic coefficients are dependent from this velocity ratio. For example, the lift coefficient for a rotating cylinder without endplates reaches the maximum of 4.5 at $\alpha \approx 3$ [4].

The maximum lift and maximum lift-to-drag ratio can be widely extended applying discs along the cylinder. The maximum $L/D = 40$ was reported by Thom on the basis of experimental analysis [12].

The rotating cylinder is the second part of the hybrid rotor. The design parameter, which are used in chapter 3, are listed in TABLE 2.

Number of discs	0
Endplate diameter	-
Cylinder span	1.0 m
Cylinder diameter	0.2 m
Cylinder RPM	7000 revs/min

TABLE 2: Design parameter of the rotating cylinder

The flow around a circular cylinder produces a large wake, producing a lot of drag. However, the flow characteristics change with an increasing velocity-ratio. FIGURE 2 illustrates the flow-field at $\alpha = 3.5$.

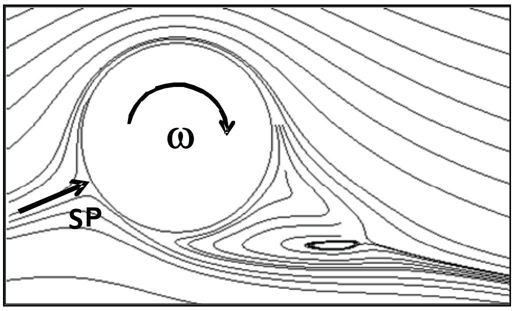

FIGURE 2: Streamlines around a rotating cylinder in crossflow

2.3. Hybrid Rotor

The Hybrid Rotor was published in [1]. It consists of a cycloidal propeller and a rotating cylinder, which are realized in one coaxial assembly. This is done in order to improve the cruise efficiency, as the rotating cylinder is able to produce lift in forward flight.

The functional principle is pointed out in FIGURE 3.

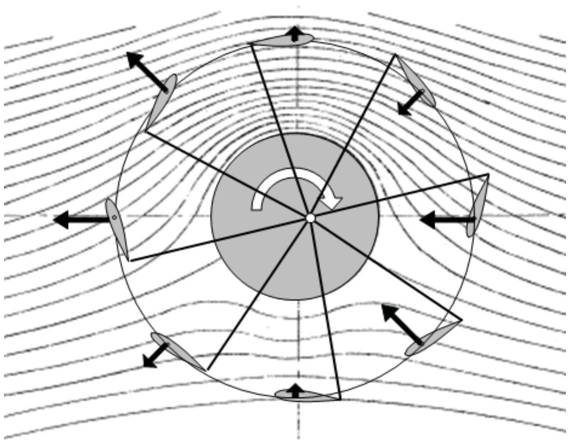

FIGURE 3. Shematic representation of the hybrid rotor

The functionality of each rotor is regarded as independent from each other in the first instance. As described above, the thrust and control is provided by the cycloidal propeller and lift and drag is produced by the rotating cylinder due to the incoming flow of the cycloidal propeller.

3. AERODYNAMIC ANALYSIS

The aerodynamics of both rotor systems is documented in the literature. The aerodynamic of the hybrid rotor is analyzed in this chapter. As the Magnus Effect is important for the aerodynamic analysis, the theory of ideal flow is briefly summarized.

3.1. Magnus Effect

A rotating cylinder in cross-flow shows a flowfield as illustrated in FIGURE 4. The superposition of a laminar flow with a circular flow results in different velocities at the cylinder surface with radius r:

$$v_1 = v_0 + \omega r$$
$$v_2 = v_0 - \omega r$$

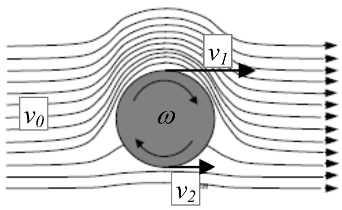

FIGURE 4: Theoretical flowfield around a rotating cylinder

The varying velocities around the cylinder lead to a difference in the static pressure. According to Bernoulli's theory of potential flow the pressure difference is calculated:

$$(2) \quad \Delta p = \frac{1}{2}\rho\left(v_2^2 - v_1^2\right)$$

The maximum velocity around a non rotating cylinder in crossflow is twice the freestream velocity. Equation (2) leads to:

$$(3) \quad \Delta p = 4 \cdot \rho \cdot \omega \cdot r \cdot v_0$$

To estimate the resulting force, the reference area A ($A=2rl$) has to be multiplied with the pressure difference:

$$(4) \quad F = A \cdot \Delta p = 8 \cdot \omega \cdot r^2 \cdot \rho \cdot l \cdot v_0$$

As the pressure distribution is not uniform around the rotating cylinder, the real force should be calculated by equation (5).

$$(5) \quad F = 2\pi \cdot \omega \cdot r^2 \cdot \rho \cdot l \cdot v_0$$

3.2. Numerical investigation

The numerical investigation of the hybrid rotor is the first step to get a proof of concept. Many parameters can be varied to define the geometry, the kinematic and the flow around the rotor. The analysis was done with a parameter setting depicted in TABLE 1 and TABLE 2. The propeller blades have a setting in order to produce thrust to the left side.

A two dimensional hybrid grid was built out of 44000 elements, consisting out of triangle and rectangular parts. A moving mesh is necessary, to model the motion of the propeller blades.

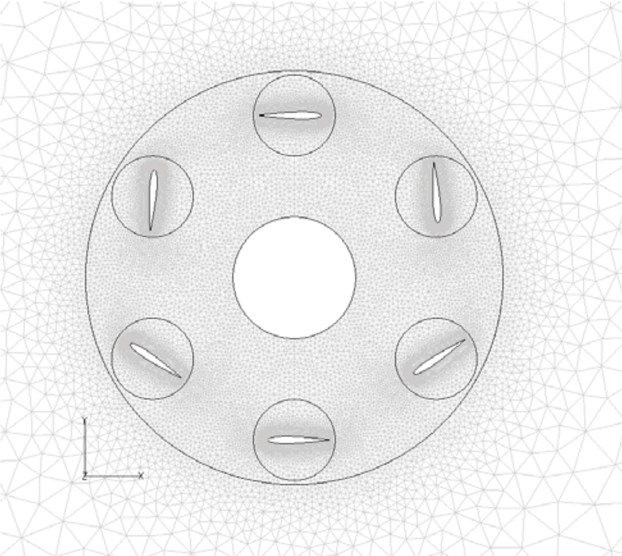

FIGURE 5. Grid of the hybrid rotor comprising six blades and one rotating cylinder in the middle

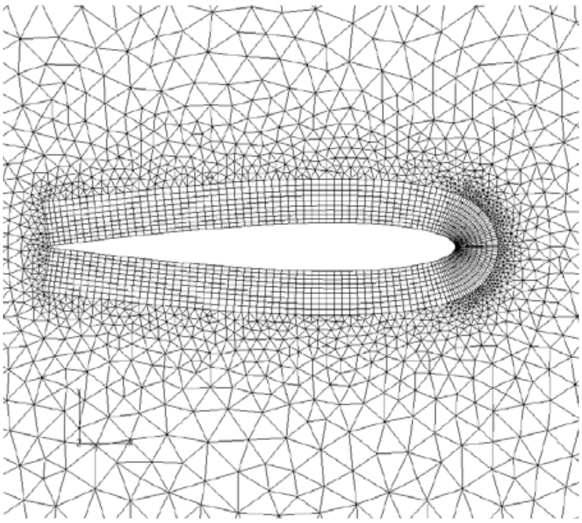

FIGURE 6. Detail of the propeller grid

The turbulence was specified by a $\kappa-\varepsilon$ model. The software Gridgen rel. 15.10, Fluent rel. 6.216 and Fieldview 11 was used for the aerodynamic analysis. Ten revolutions were calculated in order to get a quasi-stationary flow.

3.3. Flow characteristics

The flow characteristics inside and outside the cycloidal propeller will be described now,.

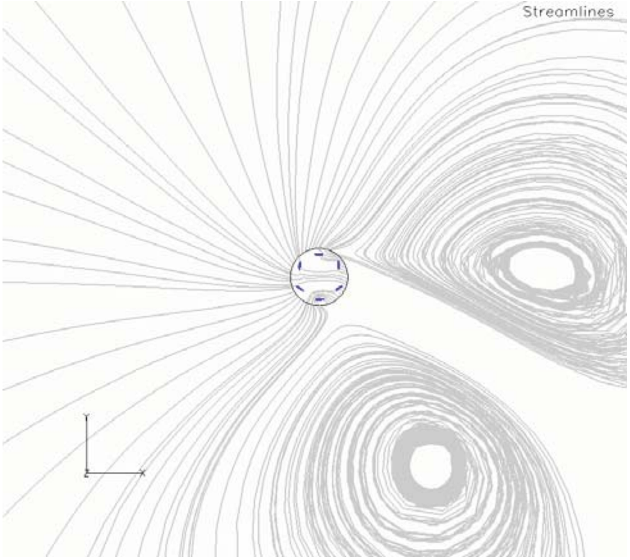

FIGURE 7. Streamlines of the hybrid rotor (stationary operation)

The streamlines around the rotors show two counteracting vortices. The characteristic of the flow is not different compared to the propeller alone. Therefore, the presence of the rotating cylinder has minor influence to the streamlines, if the hybrid rotor is operated stationary.

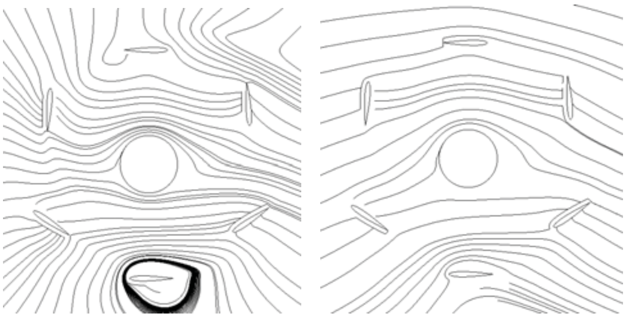

FIGURE 8: Streamlines through the hybrid rotor - stationary operation (left) and in flight operation (right)

The flowfield changes, if the hybrid rotor is operated under cruise condition. In FIGURE 8 both situations can be compared each other. In forward flight, the streamlines are strongly curved by the circulation around the rotating cylinder.

3.4. Pressure

The pressure distribution of the hybrid rotor in forward flight is presented in FIGURE 9.

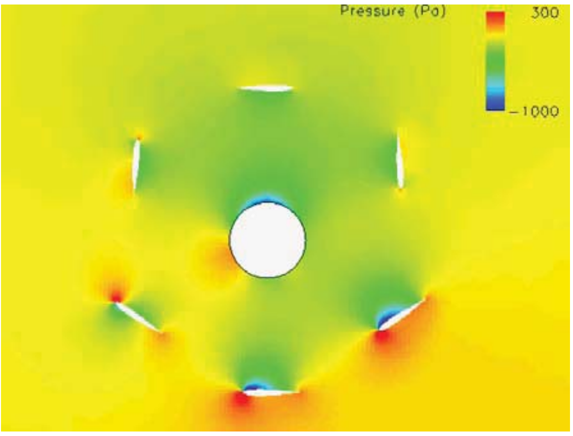

FIGURE 9. Pressure distribution in forward flight

The low pressure on the upper side of the rotating cylinder indicates lift. The propeller blades which rotate against the flow, contribute to the total lift.

3.5. Velocity

The velocity contours of the flow around the hybrid rotor in forward flight are presented in FIGURE 10.

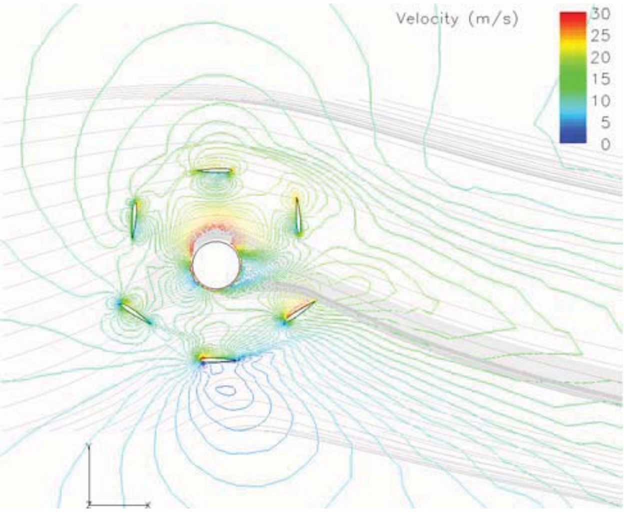

FIGURE 10. Velocity contours and streamlines

3.6. Propeller/Cylinder Interactions

Research in the area of flapping wing propulsion demonstrated a positive effect on a wing, if a propulsor is mounted close to the trailing edge of the wing. The entrainment effect caused by the oscillating airfoils turns out to be sufficiently strong to prevent boundary layer separation on the stationary wing, making such a configuration surprisingly gust insensitive and stall resistant [16].

A similar effect is observed in the wake of the rotating cylinder. The large wake as presented in FIGURE 2 has totally disappeared in the hybrid rotor (see FIGURE 11).

The stagnation point (SP) is marked by an arrow.

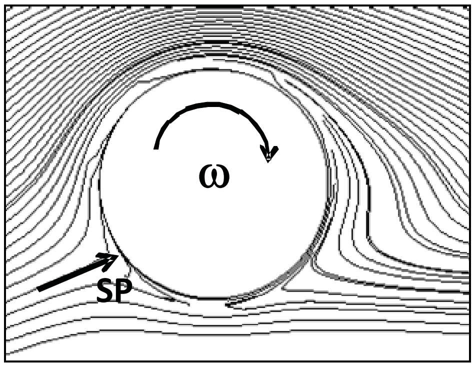

FIGURE 11: Flowfield around a rotating cylinder in the presence of a rotating cycloidal propeller

4. DISCUSSION

4.1. Aerodynamic Forces

The aerodynamics of the hybrid rotor is more complex, as both rotor systems counteract each other. However, the aerodynamic coefficients for the rotating cylinder were derived from the total force acting on its surface.

The forces were calculated for a hybrid rotor with a span of 1m. No 3D effects were taken into account.

u	V_∞	V_0	$\alpha = \frac{u}{V_0}$	c_L	c_D
73 m/s	0 m/s	14m/s	5.2	3.2	1.8
73 m/s	10 m/s	14m/s	5.2	4.4	0.6
105 m/s	10 m/s	14 m/s	7.5	7.3	0.6
133 m/s	25 m/s	25 m/s	5.3	4.1	0.8

TABLE 3: Aerodynamic coefficients under different operating conditions

The forces in x- and z- direction are presented in a polar plot for one propeller blade during one revolution. The forces of the cycloidal propeller alone are plotted in FIGURE 12.

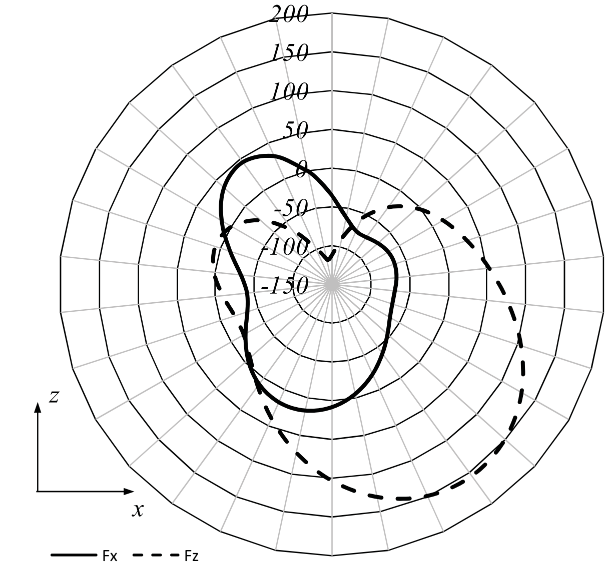

FIGURE 12: Polar plot of the forces of the cycloidal propeller in stationary operation

Regarding Fx, it is interesting, that the maximum force is in the rear part. Close to the upper position the propeller produces drag (positive sign).

Regarding Fz, the propeller produces a force downwards, if the blade is in the upper position.

The magnitude of the aerodynamic forces is oscillating from positive to negative. Such an oscillation would be an issue for the structural design of the cycloidal propeller. But in addition to the aerodynamic forces the centrifugal forces have to be taken into account.

In FIGURE 13, the polar plot of the forces acting on the hybrid rotor in cruise condition is presented.

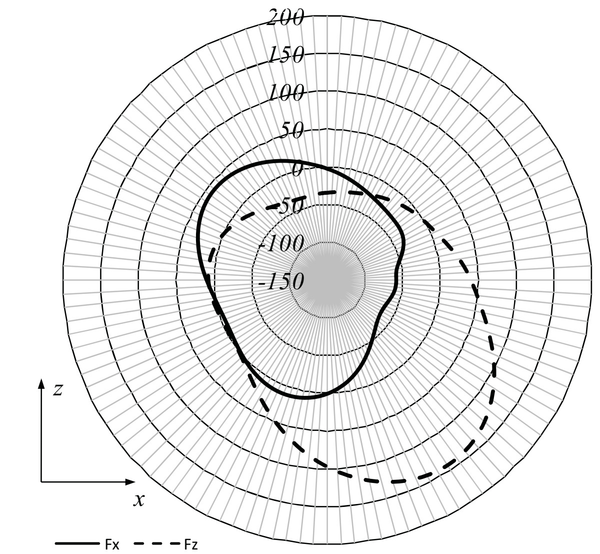

FIGURE 13: Polar plot of the forces of the hybrid rotor in cruise flight

The magnitude of the oscillation is less than presented for the cycloidal propeller alone. As mentioned chapter 3.3, the rotating cylinder has strong influence on the flowfield around the propeller. This effect influences the angle of attack of the propeller during one revolution and therefore the acting force.

4.2. Power measurement

The required power to turn both rotors was calculated based on the CFD results. In TABLE 4 the power is listed for different operating conditions. The total thrust is the vector sum of the resulting forces from each rotor.

V_∞ [m/s]	n_{prop} [1/min]	n_{cyl} [1/min]	P_{prop} [W]	P_{cyl} [W]	T_{total} [N]
0 m/s	400	7000	2032	70	208
10 m/s	400	7000	976	58	303
10 m/s	400	10000	850	150	344
25 m/s	800	12700	7356	339	1198

TABLE 4: Power measurement of propeller and cylinder

It has to be mentioned, that a thrust to power ratio of T/P = 35 kg/kW is calculated for a hybrid rotor in cruise condition (v_∞=10m/s, n_{cyl} = 10000 1/min).

4.3. Noise

Gibbens et. al. reported that the cycloidal propeller is relative quiet compared to screw propellers. Due to its design and unique operation, no two airstreams are of the same length passing through the blades, therefore there are no rhythmic impulses and very little noise. The quiet operation of these propellers has been confirmed by full scale test of a 15 foot diameter propeller, driven by a 400 H.P. engine [2].

However, no conclusion can be drawn from these experiments, as the hybrid rotor has different structural and aerodynamic characteristics.

4.4. Challenges

The major challenges for the hybrid rotor are not different to the cycloidal propeller alone. The dynamic loads and the centrifugal forces are a major issue for the structural design. The rotating cylinder is usually rotated at high rotational speeds leading to gyroscopic effects, which have to be taken account. The hybrid rotor has limitations concerning the geometry. The surface of the cylinder should not be too close to the cycloidal propeller. Otherwise, the flow around the cylinder and consequently the magnus effect would be affected.

5. CONCLUSIONS

The aerodynamic analysis on the basis of computational fluid dynamics presents favorable results. It is the first time, that such a hybrid rotor is investigated and the calculated aerodynamic forces and the flowfield around the rotor provide a proof of concept. However, the numerical investigations and results have to be validated by experimental tests.

SYMBOLS AND ABREVIATIONS

A	Reference Area
c_D	Drag coefficient
c_L	Lift coefficient
l	Length of cylinder
p	Pressure
P	Power
r	Radius
T	Thrust
u	Rotational velocity
v_0	Freestream velocity
α	Velocity ratio
δ	Air density
ω	Angular velocity
L/D	Lift to Drag ratio
SP	Stagnation point

REFERENCES

[1] SEIFERT, J.: *Fluggerät mit rotierenden Zylindern zur Erzeugung von Auftrieb und/oder Vortrieb*, Patentschrift DE102007009951B3, 2008

[2] GIBBENS, R.P., BOSCHMA, J.H., SULLIVAN C.: *Construction and testing of a new aircraft cycloidal propeller*, AIAA-1999-3906, 1999

[3] HWANG, I.S., MIN, S.Y., LEE, C.H., KIM, S.J.: *Development of a Four-Rotor Cyclocopter*, Journal of Aircraft, Vol. 45, No. 6, 2008

[4] BADALAMENTI, C., PRINCE, S.A.: *The Effects of Endplates on a Rotating Cylinder in Crossflow*, AIAA-2008-7063, 2008

[5] KIM, S., YUN, C., KIM D., YOON, Y., PARK, I.: *Design and Performance Tests of Cycloidal Propulsion Systems*, AIAA-2003-1786, 44th AIAA/ASME/ASCE/ AHS/ASC Structures, Structural Dynamics, and Materials Conference, Norfolk, Virginia, 2003

[6] KIRSTEN, F.K.: *Cycloidal Propulsion Applied to Aircraft*, Transactions of the American Society of Mechanical Engineers, 50 (AER-50-12): pp 25-47, 1928

[7] BOSCHMA, J.H.: *Cycloidal Propulsion for UAV VTOL Applications*, Final Report for Government Technical Liaison Naval Air Warfare Center – Aircraft Division, Patuxent River, Maryland, 1998

[8] FLETTNER, A.: *Mein Weg zum Rotor*, Köhler & Amelang, Leipzig 1926.

[9] PRANDTL, L.: *Application of the Magnus Effect to the Wind Propulsion of Ships*, NACA-TM-367, from *Die Naturwissenschaft Vol XIII*, 1925

[10] L., B.: *Rotor Ships*, Nature, No. 2873, Vol. 114, 1924

[11] NORWOOD, J.: *Rotors*: Amateur Yacht Research Society 120, 21st Century Multihulls, chapter 7, pp. 77-96, London, 1995/96

[12] THOM, A.: *Effect of Discs on the Air Forces on a Rotating Cylinder*, Aeronautical Research Committee Reports and Memoranda No. 1623, London, Cranfield University, Januar 1934

[13] WEISSHEIMER, F.W.: *Aircraft*, WO 89/07073, 1989

[14] GOLOGAN, C., HEISTER, C., KELDERS, C., KUHLMANN, A., SEIFERT, J.: *Perspectives of Vertical/ Short Take off and Landing in Commercial Aviation*, 1st CEAS European Air and Space Conference, CEAS-2007-298, Berlin, 2007

[15] HWANG, I.S., HWANG, C.S., KIM, S.J.: *Structural Design of Cyclocopter Blade System,* 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, AIAA-2005-2020, Texas, 2005

[16] PLATZER, M.F., JONES, K.D.: *Flapping-Wing Aerodynamics: Progress and Challenges*, AIAA Journal Vol.46, No.9, pp 2136-2149, 2008

[17] IOSILEVSKII, G., LEVY, Y., *Aerodynamics of the Cyclogiro*, AIAA-2003-3473, 33rd AIAA Fluid Dynamics Conference and Exhibit, Orlando, Florida, June 23-26, 2003

[18] IOSILEVSKII, G., LEVY, Y.: *Experimental and Numerical Study of Cyclogiro Aerodynamics*, AIAA Journal, Vol. 44, No.12, pp 2866-2870, 2006

[19] Magnus, G., "*On the Deflection of a Projectile*," *Poggendorf's Annalen der Physik und Chemie*, Vol. 88, 1853, pp. 804-810

[20] BAIRSTOW, L.: *The Rotor Ship and Aeronautics*, Nature, Vol. 115, No. 2891, pp 462-464, 1925

[21] ACKERET, J.: *Recent Experiments at the Göttingen Aerodynamic Institute*, aus Zeitschrift für Flugtechnik und Motorluftschiffahrt, 1925.