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ELECTRICAL DRIVE AND REGENERATION IN GENERAL AVIATION FLIGHT WITH PROPELLERS

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Abstract

Electric flight has the potential for a more sustainable and energy-saving way of aviation compared to fossil fuel aviation. The electric motor can be used as a generator inflight to regenerate energy during descent. Three different approaches to regenerating with electric propeller powertrains are proposed in this paper. The powertrain is to be set up in a wind tunnel to determine the propeller efficiency in both working modes as well as the noise emissions. Furthermore, the planned flight tests are discussed. In preparation for these tests, a yaw stability analysis is performed with the result that the aeroplane is controllable during flight and in the most critical failure case. The paper shows the potential for inflight regeneration and addresses the research gaps in the dual role of electric powertrains for propulsion and regeneration of general aviation aircraft.

Keywords

Inflight Regeneration, Recuperation, Electrical Flight, Flight Mechanics, Flight Tests, Propeller Aerodynamics

1 INTRODUCTION

Modern-day aviation focuses to a large extent on the reduction of air travel's environmental impact. Significant efficiency improvements are expected from employing electric or hybrid-electric propulsion systems. Electric drivetrains offer new unconventional solutions for aircraft configuration as well as for the integration of new technologies. General Aviation profits most from implementing electric powertrain components because of their versatile intended use for short-haul flight missions. As battery mass does not diminish like fuel mass during the flight, short-haul flights are less affected by the lower energy density of batteries than long-haul flights.

Modern converter electronics also allow the use of electric motors as generators without constructive changes by reversing the electrical polarity. This system enables the propeller to be used as a windmill to regenerate power.

A lot of research addressing propellers was conducted in the first half of the last century, and wind turbines have been of high research interest since around 1970. In both areas, blade designs have been investigated separately for their intended use. However, an efficient way of combining the propulsion and regeneration mode in one system has not been established yet. This is because the propeller and the drivetrain needs to be designed for separate design points: propulsion and regeneration mode. That yields a conflict of interest in creating the shape of the propeller blade.

Conventional propellers are designed for either aircraft thrust generation or complete

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regeneration on a wind turbine. Variable pitch propellers have a small range of pitch variations within service. Some propellers can vary the pitch up to a maximum of 90° into feathering mode in the case of engine failure or for gliding. How a pitch variation can help achieve the trade-off must be investigated.

Three different approaches to switching the operating mode from propulsion to regeneration with the same powertrain are discussed in this paper:

1. Static propeller blade, change of rotation speed
2. Pitch variation towards negative angle of attacks, same rotation direction
3. ≈180° pitch variation, change of rotation direction

Furthermore, the planned flight tests and thus a yaw stability analysis for the most critical failure case are described.

2 LITERATURE REVIEW

In recent years, the interest in electrically propelled aircraft experienced a boom. According to Roland Berger [1], the number of electrically-propelled planes grew by 30% in 2019.

The first fully-electric retro-fit planes like the Magnix Beaver [2] and the Cessna Grand Caravan [3] emphasise this trend. But not only fully electric design studies are recent, but also the integration of hybrid concepts with a combustion engine and an electric motor has been high on the research agenda in recent years [4, 5].

Electrically powered aircraft are particularly suitable for short-haul missions. The local zero-emissions around the airfields and the higher efficiency in the energy conversion chain underline the potential of electric flight [6]. Glauert advised to "consider the case of a windmill on an aeroplane". The idea of regenerative battery-augmented soaring was described in 1998 by MacCready [7]. The author already describes the challenge of designing a propeller for propulsion and regeneration and suggests using two separate propellers to achieve the highest efficiency in both modes and fold them into the fuselage when not in use while soaring.

Glassock developed a conceptual design of a hybrid-electric aircraft optimised for skydiving missions [8], already taking the option of regeneration during the descent into account. However, the author already identifies that the efficiency during the windmill operation state is of low efficiency due to the incorrect propeller shape. Barnes reviews the advantages of regenerative electric drives for extracting energy from atmosphere updrafts, descent flight, or parked on the airfield aligned upwind [9].

Pipistrel achieved the first certification of their fully electric aircraft Velis in 2020 [10]. It was developed as a trainer aircraft and specially designed for traffic circuit missions. With the propeller, the plane can regenerate energy during the descent phase. This function reduces the net energy consumption by 19% and increases the number of traffic circuits flown with one battery charge by 27% [11]. The propeller blade shape is optimised for the climb and regeneration phase. The result is a blade with a long chord length [12].

However, there is no efficient variable pitch propeller and controller optimised for both thrust and regeneration.

3 METHODOLOGY

The potential of in-flight regeneration with propellers has already been mentioned. In this study, the case of an electric drivetrain, including one propeller, is described and analysed. The use of one propeller for propulsion and regeneration creates the demand for an efficient and safe transition phase between the working modes.

The transition between the propulsion and regeneration mode is influenced by different topics and parameters, as depicted in FIG 1.

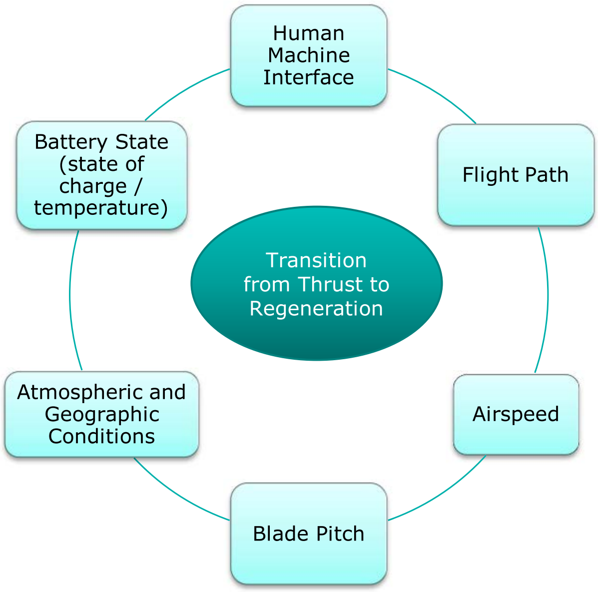

FIG 1: Influences on the inflight transition between propulsion to regeneration mode

The human-machine interface is one of the critical factors because the system must be easy to handle but additionally avoid critical flight mechanical cases. Furthermore, the mission aim is an essential factor. Maybe the pilot wants to regenerate with lower power but flies with a reduced sink rate, enabling a steady descent to the mission waypoint. The current airspeed is another critical parameter because the drag relates quadratic to the instream velocity. This has to be considered when pitching the blades to stay within the allowed force region. Also, the atmospheric and geographic conditions play a role as it is economic to fly slowly during updrafts and thermals but to fly faster in areas of downwash.

We identified the three approaches in FIG 2 to transition the propeller from propulsion to regeneration mode. The initial state is the same for all three approaches and depicts the thrust generation. Because of a positive angle of attack (AoA), the resulting thrust force *T* points in the flight direction, and the propeller pulls the plane forward. The blade incident angle is higher at the blade root (depicted in green) and lower at the blade tip (shown in orange) because the rotational velocity component increases from the blade root to the tip. This enables an AoA in the range of the airfoil's best lift-to-drag ratio along the entire blade.

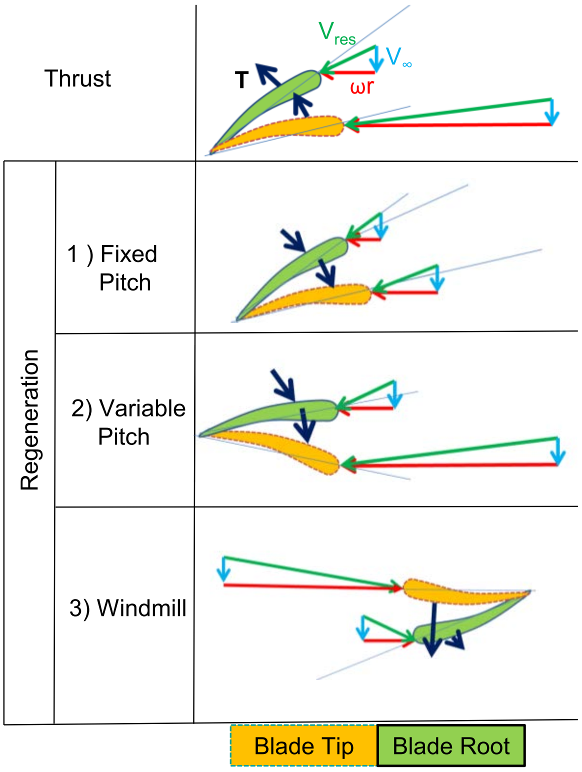

FIG 2: Identified transition approaches from thrust to regeneration mode with V_{res} = resulting velocity vector, V_∞ = incoming freestream velocity and ωr = rotational velocity component

During the regeneration phase, the propeller must be driven by the resulting wind forces. Therefore, a negative AoA at the propeller blade causing a negative torque is necessary. The first approach achieves a negative AoA by reducing the rotational speed. The propeller blade will not be changed in pitch; the negative

AoA is solely achieved by changing the velocity triangle.

For the second approach, the propeller blade pitch is changed until a negative AoA results. This maintains a high rotational speed and therefore results in higher forces.

In the third approach, the propeller blades are turned around to work like a windmill blade. Additionally, the rotation direction must be changed accordingly. Though, the blade twist distribution is the wrong way around now and causes high angles of attack at the blade root leading to a stall.

The goal of the E-DARIT project is to design and optimise a propeller for both working modes. We choose a three-pronged approach: First, we conduct calculations using the low-order blade element method. Promising design results regarding blade shape are then validated with high-order CFD simulations. The blades will then be manufactured by Helix Carbon GmbH and tested in a wind tunnel before being integrated into our flying testbed, the research plane Stemme S-10 VTX.

3.1 Flight Experiment Equipment

One of the project's aims is to integrate the propulsion and regeneration drive into our flying testbed Stemme S-10 VTX of the University of Applied Sciences Aachen. Thus, validating the low order calculation results with wind tunnel tests is an important upstream objective. The wind tunnel tests will allow to accurately simulate real-world flow conditions.

These tests will be conducted in the subsonic wind tunnel (USK) at the Institute of Aerospace Systems (ILR) of the RWTH Aachen University. The facility has an open test section with a diameter of 1.5 m and a length of 3 m. It is a Göttinger-type wind tunnel with a maximum wind speed of 250 km/h.

For the first tests and quantification of regeneration energy, a paramotor propeller of Helix-Carbon GmbH is used. The propeller is shortened from 1.2m to 1m to guarantee a clean inflow for the whole propeller within the measurement section of the wind tunnel. The propeller is continuously variable ground-adjustable, allowing a precise simulation of the transition.

A brushless 20 kW motor from Geiger Engineering is chosen as the motor and generator. The engine is already used as an electrical motor for several trikes, paragliders, sailplanes and light aircraft. The company offers the entire electric powertrain, including electric motor, motor management system, motor control interface, batteries and charger. The motor can also be used as a generator and feed energy via the battery management system back into the battery. The electric signals from the system are read out, enabling quantification of the rotation speed, the electrical power consumed or generated, and the amount of energy fed into the battery.

To measure the thrust and drag forces as well as the torque, bidirectional axial force and torque sensors are used with a range of +/- 1000N and +/- 100NM of ME-Meßsysteme GmbH.

A digital mock-up is shown in FIG 3. In addition to the above-mentioned parts, a modular aluminium frame and adapter flanges are necessary.

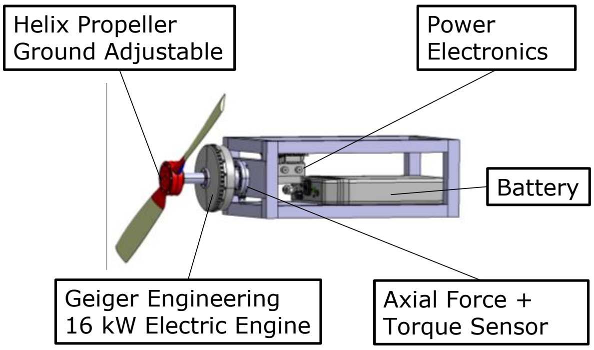

FIG 3: Digital mock-up for wind tunnel tests of electrical drive and regeneration

3.2 Planned Flight Tests and Flying Testbed

The FH Aachen flying testbed is well suited for the planned flight tests. The aircraft is a touring motor glider (TMG) with self-launch capability with its combustion engine (CE). The main propeller can be retracted during the flight, and the propeller hub seamlessly closed. In this flight state, no further drag of the CE propeller is produced, and the aircraft is a high-performance glider. This also means that solely the electrical drives can be measured without other influences. A possible flight test profile is shown in FIG 4.

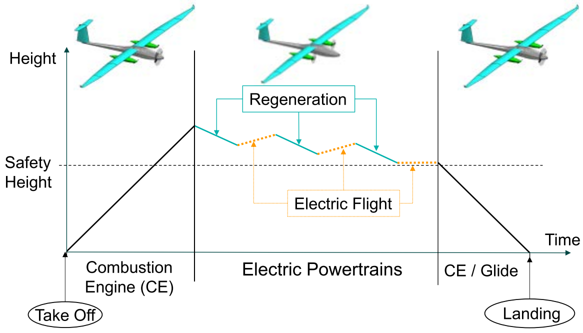

FIG 4: Possible flight test profile for regeneration and propulsion tests of the electric engines

First, the research plane will ascend with the main combustion engine over a safety height that enables a safe return to the airfield. Afterwards, the CE will be shut down, and the main propeller will be retracted. Then the electric experiment platforms can be tested in alternating propulsion and regeneration mode. Different flight velocities, sink and climb rates are tested, and the data is collected until the safety height is reached again. The electric engines will then be switched off again, and the pilot can either ascend higher again with the CE or land. Even if the CE does not restart, the plane can still glide back and land like a glider.

3.3 Yaw stability analysis

During all flight phases, the research plane has to be in a safe and controllable flight. When integrating multiple engines outside the rotation axis into one aircraft. The one engine inoperative (OEI) case is usually a critical flight mechanical situation. The OEI case must be recoverable with the rudder to ensure a safe return, approach and landing. For this project, it is also to be considered that one electrical engine works fully in propulsion mode and the other entirely in regeneration mode. This case is depicted in FIG 5. The x-axis points into the direction of flight, the y-axis along the right wing and the z-axis downward from the plane's centre of gravity. In this example, the left electrical powertrain produces a thrust force T causing a positive Moment M_T around the z-axis. The right powertrain creates the drag D_{Reg} due to regeneration and therefore creates a positive Moment M_{Reg} around the z-axis. The two moments of the powertrains add up and must be counteracted by the rudder force F_R, causing the negative rudder moment M_R around the z-axis.

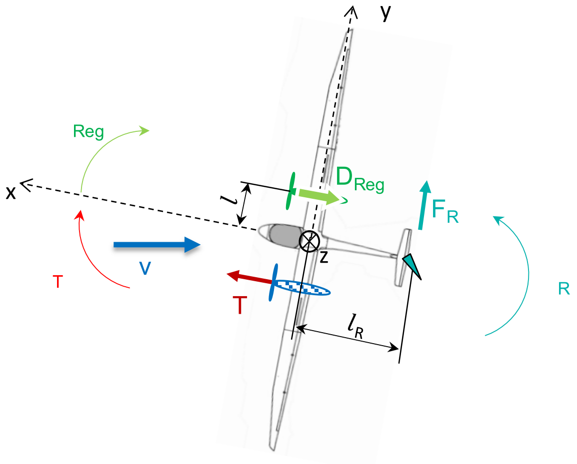

FIG 5: Critical flight mechanic case during research flights with two engines: One electric motor creates maximum thrust (T), the other maximum regeneration drag (D_{Reg}).

Thus, one limiting factor for the propeller size and electric motor power is the maximum possible moment created by the rudder deflection. The critical design case is the lowest possible flight speed, the stall speed, resulting in the smallest rudder yaw moment M_R. Essential for the moment calculation is the rudder coefficient and the rudder deflection. The applied rudder airfoil is a FX71-L-150/35 airfoil [13]. The airfoil has a thickness of 15% (150) with a chord control surface of 35% (35). In the publication from Wortmann, the values for the airfoils listed in TAB 1 are given. According to the maintenance manual of the aircraft, the minimum allowable rudder deflection is 205mm ,leading to a adeflection angle δ_n of 26° [14]. Therefore, the values for 25 and 30 degrees are listed in the table. As the FX71-L-150/35 airfoil values are not available, the most conservative value of $c_n = 1$ is used. When being in full slip and counteracting with the rudder, the value for c_n is greater [15]. But the most critical case is, when in approach, no sideslip and having to overcome the moment of the electric engines.

TAB 1: Values from the Stuttgarter Airfoil Cataloque [15]

Airfoil	Rudder Deflection δ_n	Rudder Coefficient c_n
FX 71-L-150/30	25°	1,15
	30°	1,1
FX 71-L-150/25	25°	1
	30°	1
FX 71-L-150/20	25°	1,05
	30°	1,05

The calculation is done with a very conservative load combination, thus not considering additional overlaying yaw effects caused by aircraft roll.

4 RESULTS

Following the maximum measured values of the wind tunnel, tests are shown, and the flight mechanical manoeuvrability calculation is done.

The equation $M_R > M_{Reg} + M_T$ must be fulfilled to maintain the manoeuvrability of the plane. The rudder moment M_R must be larger than the sum of the moment caused by the regenerating propeller M_D and the propelling propeller M_T. This equation is based on the equilibrium of forces acting on the aircraft. The rudder torque M_R results from the multiplication of rudder force F_R and distance l_R from the centre of gravity to the force acting point at the rudder.

$$M_R = F_R * l_R \tag{1}$$

The rudder force is given by

$$F_R = \frac{\rho}{2} * v_{s0}^2 * c_n * A_R \tag{2}$$

Underlying values are the stall velocity of the Stemme S-10 v_{s0}, the rudder coefficient c_n and the rudder reference area A_R. The yaw moment caused by the regenerating propeller is given by

$$M_{Reg} = D_{Reg} * l \tag{3}$$

M_{Reg} results from the multiplication of the regeneration drag D_{Reg} and distance l from propeller to the centre of gravity. The maximum thrust at stall speed T is also multiplied with l.

$$M_T = T * l \tag{4}$$

The underlying values for the calculation are listed in TAB 2.

TAB 2: Yaw manoeuvrability study

	Symbol	Value	Unit
Density (MSL)	Rho_{Air}	1,225	kg/m³
Stall Velocity	v_{s0}	23,6	m/s
Rudder Coefficient	C_n	1	
Rudder Area	A_R	1,51	m²
Leverarm Rudder - CG	d_R	6,122	m
Equation	$F_R = \frac{\rho}{2} \cdot v_\infty{}^2 \cdot c_n \cdot A_R$		
Rudder Force	F_R	515,12	N
Rudder Moment	$\mathbf{M_R}$	**3153,55**	**Nm**
Leverarm Wingpod-CG	l	2,5	m
Max Trust measured in Wind Tunnel	T	380	N
Max Regeneration Force meas. in Wind Tunnel	D_{Reg}	218	N
Equation	$M_T = T \cdot l$		
Trust moment	M_T	-950	Nm
Regeneration Moment	M_{Reg}	-545	Nm
Summed Trust + Regeneration Force	$\mathbf{M_T + M_{reg}}$	**-1495**	**Nm**
Remaining Rudder Moment		1658,55	Nm

If we now compare the values of the torques using the initial equation, we can conclude that the most critical case in terms of yaw steering is covered. Furthermore, a considerable amount of rudder moment is still available.

5 CONCLUSION AND OUTLOOK

The paper gives an overview of the research project EDARIT. The integration of two electric powertrains into the underwing compartments of the research plane Stemme S-10 VTX of the FH Aachen UAS is discussed. Different approaches to changing the working mode of the propeller from propulsion to regeneration are described. The measurement equipment for the project and the planned flight tests are discussed. The performed manoeuvrability study outlines that the aircraft is controllable for the most critical failure case. Future publications will address a detailed aerodynamic survey detailed survey of the propeller blade and the construction of the underwing compartment combining lightweight and fire protection requirements.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Robert Thomson, *Electrically Propelled Aircraft Developments Exceed 200 For The First Time.* [Online]. Available: https://www.rolandberger.com/en/Point-of-View/Electric-propulsion-is-finally-on-the-map.html (accessed: Oct. 26 2020).

[2] David Tulis, *Harbour Air flies first electric Beaver: MagniX Electric Engine-Powered Seaplane Takes Off Amid Cheers.* [Online]. Available: https://www.aopa.org/news-and-media/all-news/2019/december/10/harbour-air-flies-first-electric-beaver (accessed: Sep. 14 2020).

[3] Dominic Gates, *Redmond startup powers all-electric first flight of a Cessna commuter plane.* [Online]. Available: https://www.seattletimes.com/business/boeing-aerospace/redmond-startup-powers-all-electric-first-flight-of-a-cessna-turboprop/ (accessed: Sep. 14 2020).

[4] F. D. Finger *et al., Eds., An Approach to Propulsion System Modelling for the Conceptual Design of Hybrid-Electric General Aviation Aircraft*, 2019.

[5] E. Frosina, C. Caputo, G. Marinaro, A. Senatore, C. Pascarella, and G. Di Lorenzo, “Modelling of a Hybrid-Electric Light Aircraft,” *Energy Procedia*, vol. 126, pp. 1155–1162, 2017, doi: 10.1016/j.egypro.2017.08.315.

[6] M. Hepperle, *Electric Flight - Potential and Limitations*, 2012. [Online]. Available: http://elib.dlr.de/78726/#?; http://elib.dlr.de/78726/; http://www.cso.nato.int/Meetings.aspx?RestrictPanel=1

[7] P. B. MacCready, “Regenerative Battery-Augmented Soaring,” *TECHNICAL SOARING*, vol. 23, no. 1, pp. 28–32, 1999.

[8] R. Glassock, M. Galea, W. Williams, and T. Glesk, “Hybrid Electric Aircraft Propulsion Case Study for Skydiving Mission,” *Aerospace*, vol. 4, no. 3, p. 45, 2017, doi: 10.3390/aerospace4030045.

[9] J. P. Barnes, “Regenerative Electric Flight Synergy and Integration of Dual-role Machines (AIAA 2015-1302) Aerospace sciences meeting,” *Papers American Institute of Aeronautics and Astronautics*, 1289-1446; Jg. 2015, pp. 9982–9996, 2015.

[10] AOPA, *Pipistrel first to certify electric airplane: EASA grants Velis Electro type certificate.* [Online]. Available: https://www.aopa.org/news-and-media/all-news/2020/june/17/pipistrel-first-to-certify-electric-airplane

[11] Erzen, David|Andrejasic, Matej|Kosel, Tadej|Lapuh, R.|Tomazic, J.|Gorup, C., D. Erzen, M. Andrejasic, and T. Kosel, “An Optimal Propeller Design for In-Flight Power Recuperation on an Electric Aircraft (AIAA 2018-3206),” *Papers American Institute of Aeronautics and Astronautics*, 3044-3354, pp. 1028–1036, 2018.

[12] Erzen, David|Andrejasic, Matej|Kosel, Tadej|Lapuh, R.|Tomazic, J.|Gorup, C., D. Erzen, M. Andrejasic, and T. Kosel, “An Optimal Propeller Design for In-Flight Power Recuperation on an Electric Aircraft (AIAA 2018-3206),” *Papers American Institute of Aeronautics and Astronautics*, 3044-3354, pp. 1028–1036, 2018.

[13] Stemme GmbH & Co. KG, “Flughandbuch Stemme S10-VT,” 1997.

[14] P. ontag, “Wartungshandbuch Motorsegler Stemme S10-VT,” 1998.

[15] F. X. Wortmann, “Symmetrical Airfoils Optimized for Small Flap Deflection,” in *13. OSTIV-Congress*.