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Bolam, R.C., Roque, J.P.C., Vagapov, Y., and Dianov, A.

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Prototype Testing of Rim Driven Fan Technology for High-Speed Aircraft Electrical Propulsion

Robert Cameron Bolam
Wrexham University
Wrexham, UK

Jhon Paul C. Roque
Wrexham University
Wrexham, UK

Yuriy Vagapov
Wrexham University
Wrexham, UK

Anton Dianov
Wenzhou Jiangcheng Automotive Parts Co., Ltd
Wenzhou, China

***Abstract*—This paper presents the findings of the preliminary testing that has been conducted on a rim-driven fan, electric jet-engine device at Wrexham University (WU). The purpose of the testing was to demonstrate the feasibility of WU's electrical Fast-fan technology and to verify its performance and mechanical integrity. The results have demonstrated that the Fast-fan design is robust and operates very smoothly with minimum vibration. The fan also exhibited very good efficiency characteristics both electrically and thermodynamically. An overview of the fan's design and the test conditions is provided accompanied with a discussion of the results and conclusions. The testing also demonstrated that to obtain a high efflux velocity an element of the thrust must be sacrificed, or input power increased and discusses how the Fast -fan design is optimised to satisfy both of these conditions. This paper should provide confidence to individuals and organisations wishing to investigate or adopt rim-driven technology for aircraft electrical propulsion solutions.**

***Keywords*—rim driven fan, RDF, electric jet-engine, fast-fan, electrical propulsion, zero-emission**

I. Introduction

It is widely recognised that the onboard generation and storage of electrical energy is considered the primary obstacle to aircraft electrical propulsion. However, the conversion of electrical power to propulsive thrust still presents a significant challenge when considering ways to efficiently achieve propulsion for high-speed flight.

Conventional civil aircraft use propellors for regional operations to attain speeds of up to Mach 0.6 and altitudes ranging up to 30 kft. For longer journeys, ducted by-pass fans are used to achieve higher speeds and altitudes up to Mach 0.9 and 45 kft. Both technologies are hub-driven with the main propulsive airflow passing over a central energising unit. This is normally a gas turbine engine with the propulsive drive being transmitted via rotating shafts. Traditional hub-driven architectures present a familiar technology and appear to provide lower development risks and this reason might explain why the aerospace industry automatically considers hub-drives for aircraft electrical propulsion solutions.

The aim of Wrexham University's Fast-fan Project [1] was to construct and test a concept demonstration electrical Rim-Driven Fan (RDF) device to verify the feasibility of applying rim drive technology for high-speed flight applications. The Fast-fan is a patented electrical jet engine configuration [2] that has resulted from research conducted at Wrexham University [3]-[5]. The concept demonstrator/ prototype, that underwent testing, is shown in Fig. 1. The objectives of the testing conducted were both qualitative; to prove the mechanical design of the Fast-fan device up to rotational speeds of 10,000 rpm and quantitative; to collect data relating to the fan's aerodynamic performance and motor efficiency.

II. Prototype Design

The Fast-fan is a rim-driven, dual motor, contra-rotating ducted fan as shown in Fig. 2. At its core, is the contra-rotating Energiser Unit that transfers torque from the motors to the air via the fan blades. The pressure rise across the fan determines the achievable efflux velocity and depends on the amount of energy (torque) transferred per swept volume. Therefore, the air is entrained in a duct of gradually decreasing volume to achieve the desired pressure rise over the dual fan stages. The closed fan-tips minimise pressure leakages and contra-rotation of the fans ensures that there is no energy lost in efflux swirl as the air flows through the nozzle to generate high-speed thrust. The relative rotor speeds can be independently modulated to control fan performance and cooling-air enters from vents on the outer surface of the intake and is drawn over the motor windings by the motive flow of the air exiting the fan (efflux).

The Fast-fan motors each have a nominal power rating of 15 kW (i.e. 30 kW in total) and are based on AC synchronous permanent magnet technology and incorporate minimal iron stators, aluminium windings, and iron-less rotors to minimise weight. Multi-slotted distributed

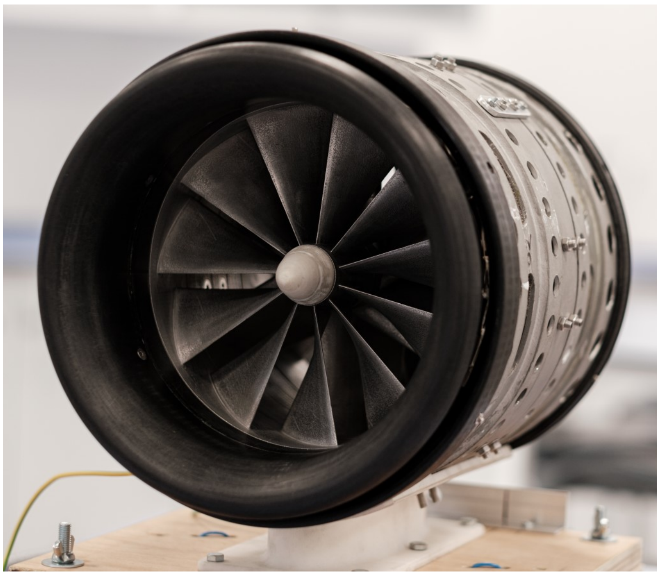

Fig. 1. Concept demonstrator Fast-fan.

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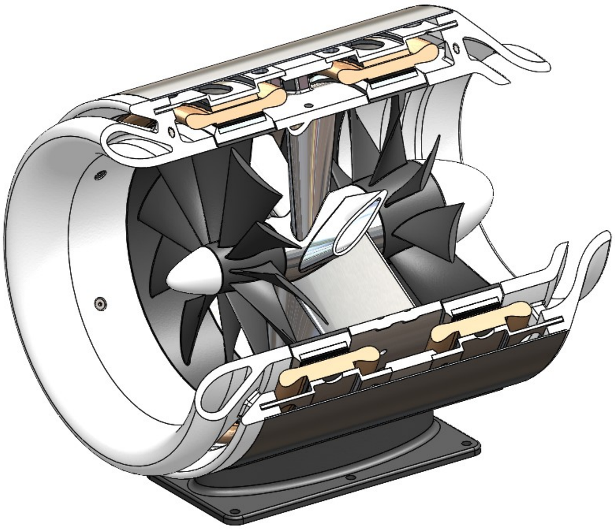

Fig. 2. Fast fan assembly cutaway view.

windings are used to minimise torque ripple and vibration. The motors are only subjected to relatively low currents, because of their relatively high supply voltage (nominal 400 VDC) and lower rim force requirements. This significantly reduces the resistive heating of the air-cooled windings and increases the attainable motor efficiency. The resulting compact concept demonstrator design has a nominal maximum power rating of 30 kW which provides an overall nominal Specific Power of 2.5 kW/kg. This includes the active (circuit) and non-active (structural) components (e.g. pylon, intake, nozzle, nacelle, and fans etc.).

Fig. 3. Fast fan set-up.

A. Design Theory

The design theory is based on Euler's Work Equation, which defines the rate of transfer of angular energy (torque) from a fan into the passing airstream and can be expressed as:

$$P = \dot{M} U \Delta C_W \tag{1}$$

where P is the fan shaft power [W]; $\dot{M}$ is the mass flow of air passing through the fan, measured in kilograms per second [kg/s]; U is the tangential velocity of the fan (which is normally taken at a mean radius position) measured in metres per second [m/s]; ΔC_W is the change in rotational (whirl) velocity of the airflow between the plane on which it enters the fan to that where it exits.

In eq. (1) the term $U\Delta C_W$ defines the total specific work done by the fan and can be expressed in Joules per kilogram [J/kg]. This term also represents the specific enthalpy rise of the air (Δh_0) and is widely given the symbol Y [6]. Total specific work Y is a very useful and versatile parameter in fan analyses and may be expressed in the following forms [7]:

$$Y = \frac{P}{\dot{M}} \tag{2}$$

$$Y = \frac{\Delta p}{\rho} \tag{3}$$

$$Y = U \Delta C_W \tag{4}$$

$$Y = C_p \Delta T \tag{5}$$

where Δp is the total pressure rise across the fan [Pa]; ρ is the average density of the air [kg/m^3], C_p is the specific heat capacity of air at constant pressure (taken as 1005 J/kg K); ΔT is the total temperature rise of the air across the fan [K].

To relate the specific work parameter (Y) to a particular fan device, for example, when considering the number, size, angles and shape of its blades etc., a dimensionless work coefficient (also known as the Stage Loading) ψ is used, where:

$$\psi = \frac{\Delta C_W}{\dot{M} U} \tag{6}$$

Therefore, from (4) and (6) it can be determined that:

$$Y = \psi U^2 \tag{7}$$

Typical values of work coefficient ψ for high-performance axial flow fans and compressors lie between $\psi = 0.4$ and $\psi = 0.75$ [8]. For radial (centrifugal) flow compressors, in which the airflow is turned through 90 degrees, a unity work coefficient can be assumed i.e. $\psi = 1$.

To relate the tangential speed of the fan U to the axial velocity C_x of the airflow through the fan the dimensionless flow coefficient, ϕ, is used, where:

$$\phi = \frac{C_x}{U} \tag{8}$$

An accepted value of flow co-efficient φ for high-performance axial flow fan and compressor designs is $\phi = 0.5$ [9].

The testing presented in this paper took place on the 20th of September 2023 and was conducted to establish the feasibility of the fan design operating at low to moderately high speeds up to 10,000 rpm (the Fast-fan design maximum being 15,000 rpm).

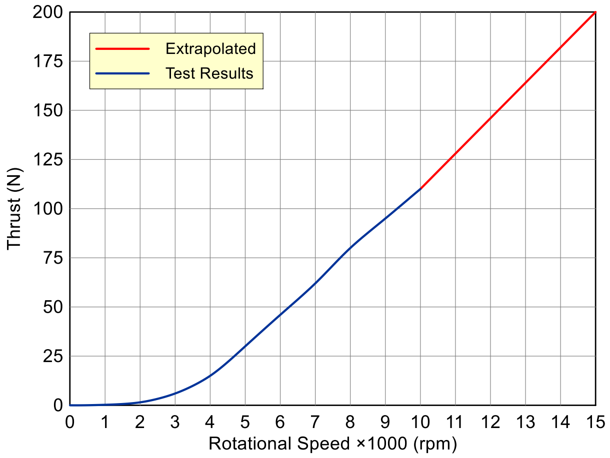

Fig. 4. Results of the fast-fan test and extrapolated curve.

B. Test Set-up

For safety reasons, the fan was configured to be remotely operated via a laptop computer with a bespoke graphical user interface (GUI) and an Ethernet connection. A video recording was made of the test so that post-test qualitative evaluations could be made of noise and vibration. Instrumentation was also fitted to record the fan thrust using a load cell and its efflux airspeed using a pitot tube positioned to sense pressure at the mean radial position of the fan on the nozzle exit plane. Fig. 3 shows the Fast-fan test set-up for the concept demonstration.

C. Test Procedure

Remote activation and speed control of the forward and aft fan motors was achieved via the GUI and for these initial tests the motor speeds were linked so that they were the same. Stepped test runs were made by running the fan at speeds from zero to 10,000 rpm in 1,000 rpm intervals. Above 5,000 rpm the tests were conducted with intervening visual inspections carried out whilst the fan was de-energised.

Table I contains the results of the fast-fan test runs up to 10,000 rpm and Fig. 4 shows these results plotted in graphical format with the curve extrapolated beyond 10,000 rpm up to the maximum fan design speed of 15,000 rpm. Fig. 5 shows a GUI image of the forward (left) and aft (right) motor currents and power consumption, and Fig. 6 is a still image taken from the test video of the Fast-fan operating at the maximum test speed of 10,000 rpm.

Table I. Results of the Fast-fan Test

Rotational Speed ×1000 (rpm)	Thrust (N)
0	0
1	0.25
2	1.5
3	6
4	15
5	30
6	46
7	62
8	80
9	95
10	110

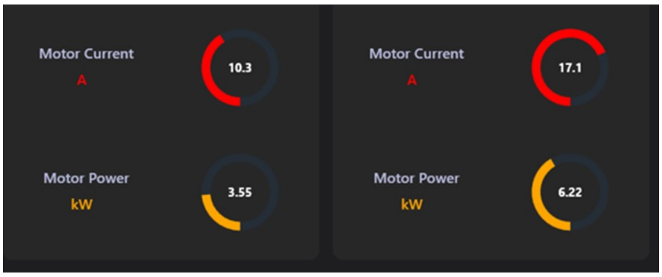

Fig. 5. GUI image.

III. Discussion

The results have provided a valuable insight into the operational nature and performance of the dual contra-rotational Fast-fan arrangement. From Fig. 4 it is evident that the fan performance graph demonstrates a quasi-exponential relationship between the fan's thrust and its rotational speed up to the maximum attained test speed of 10,000 rpm. This indicated that the fan was operating correctly and not in a stalled condition. The thrust and efflux velocity measured at the 10,000 rpm test point were 110.3 N and 70.07 m/s respectively. Therefore, an estimate of the propulsive power of the fan at this static test point could be calculated:

$$P_{OUT} = T \times V = 110 \times 70.07 = 7{,}707.7\text{W} \qquad (9)$$

where P_{OUT} is propulsive power (output) [W], T is thrust [N], V is relative efflux velocity [m/s].

The total motor power (P_{IN}) consumption indicated on the GUI (Fig. 5) was

$$P_{IN} = 3{,}550 + 6{,}220 = 9{,}770\text{W} \qquad (10)$$

A. Fast-fan Efficiency Analysis

A value for the overall fast-fan system efficiency was calculated as follows.

$$\eta_{TEST} = \frac{P_{OUT}}{P_{IN}} \times 100\% = \frac{7{,}707.7}{9{,}770} \times 100\% = 78.9\% \qquad (11)$$

where η_{TEST} is the overall system efficiency obtained from the test [%].

It was considered that this overall system efficiency value of 78.9% was a very good result especially when compared to current internal combustion engine (ICE) driven fans that have overall efficiencies typically below 40% [10]-[12].

Fig. 6. Still image taken from the test video of the Fast-fan operating at the maximum test speed of 10,000 rpm.

TABLE II. SPECIFIC WORK AND STAGE LOADING ESTIMATES AT 10,000 PRM.

Rotor Position	Y (J/kg)	ψ
Forward	1615.3	0.3
Aft	2830.2	0.53

The test efficiency value of 78.9% also gave a very close correlation with the design calculated values which were determined as follows for the overall system:

$$\eta = \eta_{DRIVE} \times \eta_{MOTOR} \times \eta_{FAN} = 95\% \times 93\% \times 90\% = 79.5\% \quad (12)$$

where η is the Fast-fan design efficiency chain [%], η_{DRIVE} is the electric drive efficiency [%], η_{MOTOR} is the electric motor efficiency [%], η_{FAN} is the fan efficiency [%].

These values exhibited less than 1% error between the predicted and achieved overall system efficiencies and demonstrated that the shrouded axial fan design and rim motor architectures were performing to design, providing a thrust to weight ratio of approximately 1.0 for the prototype design operating at 10,000 rpm. Beyond 10,000 rpm the curve has been extrapolated and is shown as a red line in Fig. 4. This has been done to anticipate the likely performance of the fan up to its maximum design speed of 15,000 rpm. At this point, the extrapolated fan thrust value is 200 N and the anticipated thrust to weight ratio is approximately 2.0. This suggests that if the same overall fast-fan efficiency is maintained, the efflux velocity will increase and is calculated as follows:

$$P_{OUT(15)} = P_{IN(MAX)} \times \eta_{TEST} = 30{,}000 \times 0.789 = 23{,}670\text{W} \quad (13)$$

where $P_{OUT(15)}$ is the Fast-fan propulsive power at 15,000 rpm [W], $P_{IN(MAX)}$ is the maximum input power (30kW).

$$V_{(15)} = \frac{P_{OUT(15)}}{T_{(200)}} = \frac{23{,}760}{200} = 118.35\text{m/s (256.1mph)} \quad (14)$$

where $V_{(15)}$ is the estimated Fast-fan efflux velocity at 15,000 rpm [m/s], $T_{(200)}$ is the estimated thrust (200 N).

B. Fast-fan Massflow ($\dot{M}$) Estimate at 10,000 rpm

To calculate the massflow of air through the engine an average efflux velocity value of 49.49 m/s and the fan swept area of 286 cm^2 was used.

$$\dot{M} = 49.49 \times 286 \times 10^{-4} \times 1.225 = 1.734 \text{ kg/s} \quad (15)$$

C. Fast-fan Specific Work (Y) Estimate at 10,000 rpm

Eq. (2) was used to calculate the Specific Work for each rotor. Table II shows the calculation result.

D. Fast-fan Stage Loading (ψ) Estimate at 10,000 rpm

Eq. (7) was used to calculate the Stage Loading of each rotor. Table II shows the calculation result. The Forward rotor ($\psi = 0.3$) is underperforming, operating below the ($\psi = 0.4$-0.75) desired range, whereas the Aft rotor ($\psi = 0.53$) is within the desired range and performing relatively well.

E. Fast-fan Coefficient (ϕ) Estimate Estimate at 10,000 rpm

Eq. (8) was used to calculate the fan flow coefficient as follows

$$\phi = \frac{C_x}{U} = \frac{49.49}{73.3} = 0.675 \quad (16)$$

The high flow coefficient value ($\phi = 0.675$) demonstrates that the rim-driven fan design is very permeable to airflow and exceeds the normally expected value of flow co-efficient for high-performance axial flow fans and compressor designs which is $\phi = 0.5$

F. Motor Currents

One of the reasons attributed to the high motor efficiency indicated from the test results (approximately 93%) is the relatively low motor current requirements and the reduction of the resistive heating in the Fast-fan rim-drive configuration. The outer motor cages were barely warm to the touch when inspected after the test runs.

G. Motor Power Distribution

The testing showed that although both fan motors were rotating at the same speed, the aft motor was transferring energy to the airflow at a much greater rate than the forward motor. This was evident from the respective power consumptions of 3.55 kW for the forward motor and 6.22 kW for the aft motor (almost twice as much). This anomaly has been attributed to the aft motor somehow off-loading the forward motor. Therefore, future work is planned to investigate the benefits of modulating the rotor speeds to obtain optimum dual fan performance.

H. Noise and Vibration

The qualitative analysis of the Fast-fan testing can be assessed from a test video of the Fast-fan available via the internet [13]. From this, it was determined that the fan runs relatively quietly and smoothly. These benefits were mainly attributed to two design features: the distance between the rotors provided by the structural stator and the fixed shaft construction which avoids the “shaft wobble” problem inherent with rotating shafts.

IV. CONCLUSION

It was considered that the objectives of the testing conducted on the prototype Fast-fan have been successfully achieved. The concept has been successfully demonstrated to work and the testing has verified the feasibility of applying rim drive technology for high-speed flight.

The first objective was to prove the mechanical design of the Fast-fan device up to rotational speeds of 10,000 rpm. This was a very important milestone because, at the time of testing, this speed threshold had never been achieved before with an electrical rim driven fan arrangement. It was also considered important to prove the mechanical integrity of the Fast-fan design whilst operating at high speeds and to realise the extent to which its smooth operation is achievable owing to its stationary shafts and lightweight rotors. The second objective was to collect data relating to the fan’s aerodynamic performance and motor efficiency.

It is worth noting that this test also demonstrates that to obtain a high efflux velocity an element of the thrust must be sacrificed, or input power increased. This indicates how important it is to (1) minimise the drag characteristic of the fan, (2) maximise the rate of torque transmission to the airflow, and (3) achieve a high overall efficiency of the system. It is considered that the rim-driven Fast-fan design satisfies these parameters by having a relatively small intake area whilst still providing the capability to maximise the core airflow and torque per swept volume.

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