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Aerodynamic Evaluation of the Djebel Laassa UAV

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Abstract: Marqués P, Bachouche A and Maligno A. (2013). Aerodynamic evaluation of the Djebel Laassa UAV. *International Journal of Unmanned Systems Engineering*. ***1***(1): 9-15. Tunisia Aero Technologies Industries S.A. has recently launched an R&D program that includes several UAVs and has led to the development of the Djebel Laassa UAV (‘*mountain watch’* UAV). The current multi-disciplinary R&D program of Tunisia Aero Technologies Industries S.A. endeavors to further enhance the potentiality of the Djebel Laassa vehicle for a broad range of civil and military applications. In particular, a great effort is devoted to the improvement of the vehicle’s aerodynamics for enhanced performance and survivability in unsteady flight environments. This paper presents the aerodynamic R&D of the medium-size Djebel Laassa UAV prototype. Aerodynamic modifications are specified to enhance the maximum lift, flow control, stalling behaviour and flight stability characteristics of the air vehicle. Modifications include the use of an S1223 airfoil, vortex generators and a Gurney flap for the wing, a constant-section variable-thickness S1223 airfoil for the propeller, wing fence adjustments, and introduction of wing taper, dihedral and geometric twist. This aerodynamic evaluation is part of the current R&D programme of Tunisia Aero Technologies Industries S.A. that prioritises the development of advanced aerodynamic concepts and modifications to the air vehicle's engine and structural design for enhanced performance in medium/high altitude, long-endurance missions.

Keywords:
Aerodynamics
Djebel Laassa UAV
Flight stability
R&D programme
Unsteady flight environment

1. INTRODUCTION

The airframe of the Djebel Laassa UAV prototype developed by Tunisia Aero Technologies Industries S.A.[1] consists of a cantilever high-wing monoplane with a fuselage pod and twin tail booms (Fig. 1).

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The twin-boom arrangement allows the engine to be mounted as a pusher system that frees the front fuselage for the installation of payload and provides protection for and from the propeller[2]. The vehicle features swept-back fuselage pod sides and bulkheads for low signature radar. The UAV is constructed using a modular design, whereby the wing is divided spanwise into 3 pieces. The main spar is made of titanium and the wings are hollow to accommodate bladder-type auxiliary tanks. The central wing region is equipped

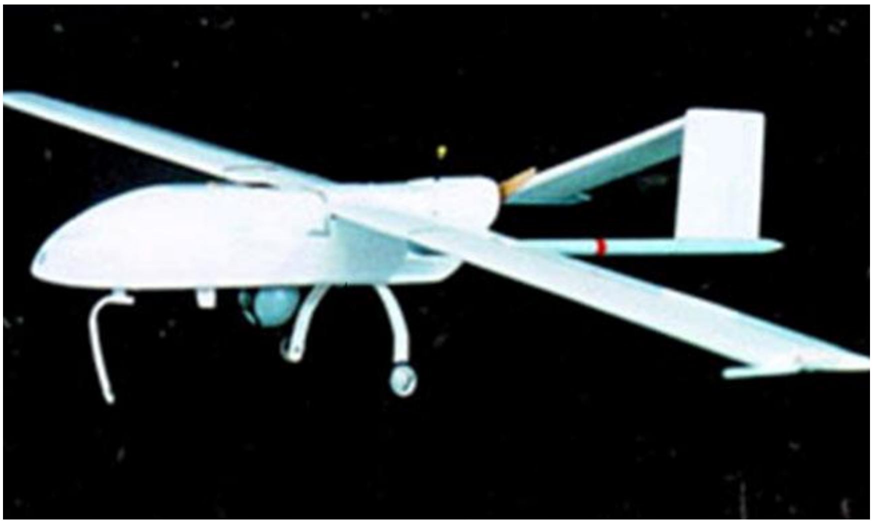

Fig. 1: The Djebel Laassa *'Mountain Watch'* UAV
(Photo: Tunisia Aero Technologies Industries S.A.)

with flaps and the outboard wing with ailerons[1].

This paper presents the aerodynamic R&D of the medium-size Djebel Laassa UAV prototype. Technical specifications and payload details are presented followed by an analysis of aerodynamic and flight stability characteristics of the air vehicle. Aerodynamic modifications are suggested for enhanced lift, aerodynamic efficiency, stall control and flight stability for operations in adverse atmospheric conditions. The aerodynamic improvements expand the UAVs flight envelope and versatility for diverse applications and missions that encompass city reconstruction mapping, remote sensing and mapping, land & maritime border patrol, sea and land search and rescue, long endurance military intelligence, reconnaissance, targeting, surveillance of oil and gas installations, inspection of natural disasters, precision agriculture, and fire fighting[1].

2. TECHNICAL SPECIFICATIONS

The shape of the fuselage is low radar detection. A 39 hp engine is mounted at the rear of the fuselage pod, driving a two blade fixed pitch wooden propeller of 75-79 cm in diameter[1]. The fuselage pod contains the main fuel tank. The airframe can be fitted with a rail or pod under each wing in line with the tail booms for carriage of external stores (e.g., chaff). Airframe construction is primarily of reinforced graphite, Kevlar and epoxy resin and is fully sealed for long life in hot or humid environments. Table 1 shows the dimensions, weight and performance features of the air vehicle[1].

3. PAYLOADS

The UAV prototype is equipped with a Cloud Cap TASE 200 Camera during flight testing[1]. The large fuselage volume can accommodate a wide variety of payloads, according to the requirements of the various missions: Electro optical and infrared cameras mounted on a turreted 360° gimballed "chin", gyro stabilized daylight and low light black and white or colour cameras, laser designator, range finder, miniature aperture radar for visibility in conditions of dense fog, radar altimeter, automatic video tracker, nuclear bio/chemical/multiple sensors, meteorological appliances, laser detector tracker pod, and wing-pod ejectable items (such as chaff, leaflets, flares, or communication jammers). Other payloads can be installed: Mine detection payloads, electronic warfare systems, SIGINT, and scientific sensors. Larger and more sophisticated payloads for maritime surveillance and search & rescue missions for day and night can be fitted to the UAV (e.g., FLIR systems, UK)[1].

Table 1: Technical specifications of the Djebel Laassa UAV[1]

Dimensions	**Performance**
Length: 3.75 m	Loiter speed: 130 km/h
Height: 1.25 m	Cruise speed: 140 km/h
Max. body diameter: 38 cm	Max speed: 170 km/h
Body fuselage pod length: 1.85 m	Max rate of climb: 300 m/min
Propeller diameter: 75-79 cm	Take off distance: 250 m (on asphalt)
	Take off distance: 10 m (launch option)
Weight	Flight range: 1,680 km
Empty weight: 110 kg	Operational radius: 200 km; extended to 800 km using ground or airborne relays on mountains.
Max. total weight (MTW): 200 kg	Typical command and control range: 150-200 km
Max. payload weight: 30 kg	Service ceiling: 4,575 m
	Endurance: 12 hrs with normal gasoline/oil mix; 24 hrs with heavy fuel (Jet A1).
	Fuel capacity: 53 ltrs (1 main tank and 2 auxiliary wing tanks)
	g limits: ± 6

4. AERODYNAMIC CHARACTERISTICS

4.1 Airfoil

There are several considerations when selecting an airfoil for a UAV. These include: a high maximum lift coefficient ($c_{l\ max}$), effectiveness at low Reynolds numbers (*Re*), high lift-to-drag ratio (c_l / c_d), low pitching moment coefficient ($c_{m,c/4}$) to minimize the load on the tail, gentle stall characteristics, insensitivity to surface roughness caused by rain or dust, good flap performance, and minimal airfoil complexity for ease of manufacture[2].

The airfoil used in the wing of the Djebel Laassa UAV prototype is a Wortmann FX61-147 (Fig. 2). This airfoil has a thickness ratio of 14.8% of the chord (*c*), camber of 3.18% *c* and a $c_{l\ max}$ of 1.5. At relatively low flight speeds (e.g., Re 1.4 x 10^6), this airfoil generates low drag due to extensive laminar flow on both the upper and lower surfaces[3]. Its thickness allows the low drag bucket to be maintained for a large range of lift coefficients, although the minimum drag coefficient is higher. At an angle of attack (α) of 1°, upper surface transition occurs at 0.45% *c* and at α = 8° transition moves forward to 0.25% *c*. Transition from a laminar to a turbulent boundary layer is caused by laminar separation bubbles. In the Wortmann FX61-147 airfoil, attention needs paying to movement of the transition point towards the leading edge (LE) and the extent of the laminar separation bubble at low *Re*s. Aerodynamic evaluation suggests that the Wortmann FX61-147 airfoil is suitable for the medium-size Djebel Laassa UAV (*c* = 55 cm, MTW = 200 kg). Specifically, the Wortmann FX61-147 shows good performance in climb conditions, progressive stall, $c_{l\ max}$ insensitivity to dust or rain contamination, and a small $c_{m,c/4}$ that reduces the drag penalty associated with balancing the aircraft. In the Djebel Laassa UAV, a Fowler flap with a maximum downward deflection angle of 30° augments lift during takeoff and landing. Aerodynamic characteristics of the vehicle are summarized in Table 2.

The S1223 is a high-lift airfoil often used in UAVs[4] that may be considered for the Djebel Laassa UAV, Fig. 2. Other suggested aerodynamic modifications to the Djebel Laassa UAV prototype appear in Table 2. The S1223 follows a high-lift design philosophy characterised by concave pressure recovery with aft loading. At the low *Re* of 2 x 10^5, the airfoil achieves a $c_{l\ max}$ of 2.2, high c_l / c_d, and acceptable stall characteristics[5].

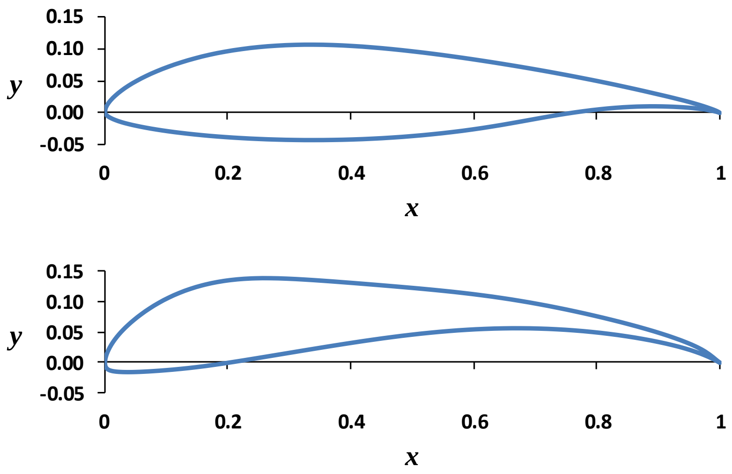

Fig. 2: Coordinates (x, y) of the Wortmann FX61-147 (top) and S1223 (bottom) airfoils

The $c_{l\ max}$ increases to 2.3 with either the installation of vortex generators (VGs) placed at 17% *c* or with the use of a 1% *c* Gurney flap[5]. Because of its effective high-lift characteristics alongside its simplicity as a mechanical device, the use of a Gurney flap for the UAV is advocated[6,7]. The airfoil's nose-down $c_{m,c/4}$ of – 0.29 requires balancing with the aircraft tail and it is recommended that the tail stabiliser is set at an angle of incidence (δ) of -1° to provide downforce at the tail. From the LE to 0.2 *c*, the boundary layer is prescribed to be close to laminar separation, a laminar analogy to the turbulent Stratford pressure recovery, and at 0.2 *c* a short bubble ramp is employed[5]. The S1223 performs well in small- and medium-size UAVs (e.g., Tunisian Spring UAV and Djebel Laassa UAV, respectively), allows heavier payloads, shortens the takeoff and landing distances, attenuates aircraft noise, and reduces the stall speed. Its moderate stall characteristics are suitable for the UAV to operate with the wing near $c_{l\ max}$ at low speed regimes. However, the complex geometry and camber of the S1223 airfoil makes the wing of the vehicle - span (*b*) of 6.5 m, aspect ratio (*AR*) of 10 and surface area (*S*) of 3 m^2 - more difficult to manufacture.

At low *Re*, common airfoils show a rapidly decreasing $c_{l\ max}$ as the *Re* drops, and separation bubbles that augment drag. Nonetheless, the high-lift S1223 and the optimised S1223 OPT2 airfoils exhibit high c_l / c_d and good stall characteristics at low *Re*s and these two airfoils are therefore appropriate for the design of a high-efficiency constant-section propeller[4,8]. The optimised S1223 OPT2 was the result of hierarchical multi-objective optimization carried out by Ma *et al.* (2010)[8]. Compared to the S1223, the optimised S1223 OPT2 achieves an increase in $c_{l\ max}$ from 2.14 to 2.17 (1.4% increase), a reduction in drag coefficient from 0.034 to 0.033 (3%), an improvement in c_l / c_d from 63.1 to 64.8 (3%), and a wider range of low drag; based on α = 10° and *Re* = 0.5 × 10^6. The simulation of airfoil thickness conducted by Ma and Liu (2009)[4] reveals that an airfoil thickness of 20% - 25% is detrimental to c_l / c_d and propeller efficiency. In fact, the best propeller performance is achieved using 5% and 12% thickness. Consequently, an optimised propeller for the Djebel Laassa UAV can be constructed using an S1223 OPT2 airfoil of thickness ratio of 12% *c* at the blade root and 5% *c* at the blade tip.

4.2 Wing and tail design

The wing's central section of *b* = 1.62 m is sweptback by 6° (*c* = from 64 to 55 cm) and the two outboard wing modules are rectangular (constant *c* = 55 cm). The wing is rigged at δ = 1.5°, it is untwisted and has no dihedral. Proposed modifications to the Djebel Laassa vehicle prototype include introduction of geometric twist to promote a gentle stall that initiates at the wing root region[9,10].

Table 2: Aerodynamic characteristics of the Djebel Laassa UAV prototype and suggested modifications

AERODYNAMIC CHARACTERISTICS		SUGGESTED MODIFICATIONS	
Airfoil		**Airfoil**	
Type:	Wortmann FX61-147	Type:	S1223
Thickness (% c):	14.8	$c_{l\,\max}$:	2.2 at $Re = 2.0 \times 10^6$
Camber (% c):	3.18		2.3 with VGs
$c_{l\,\max}$:	1.5 at $Re = 1.4 \times 10^6$		or Gurney flap
c root (cm):	64	$c_{m,c/4}$:	-0.29
c outboard modules (cm):	55	VGs:	Positioned at 17% c
		Gurney flap:	Height of 1% c
Wing			
δ (°):	1.5	**Wing**	
b (m):	6.5	Flow control:	Wing fences around LE,
AR:	10		up to 1/3 c
S (m^2):	3	Flight stability:	5° dihedral
Flow control:	Wing fences	Stall control:	5° geometric twist
Flap:	Fowler	Taper:	5°
Max. flap defelection (°):	30		
Tip device:	Hoerner tip	**Tail**	
		δ (°):	-1
Tail			
Airfoil type:	NACA 009	**Propeller**	
c (cm):	48	Airfoil type:	S1223 OPT2
δ (°):	0	Thickness (% c):	12 at blade root,
b (m):	1.5		5 at blade tip
S (m^2):	0.72		

The tail of the Djebel Laassa vehicle is of inverted V-shape and sweptback configuration, with two fins and two elevators. Double servos and double rudder provide redundancy and enhance flight safety. A symmetric NACA 009 airfoil of c = 48 cm set at δ = 0° is used in the aircraft tail; where the tail span is b = 1.5 m and S = 0.72 m^2.

4.3 Analysis of flight stability and control

An aerodynamic advantage gained with the pusher propeller configuration of the Djebel Laassa UAV includes the engine positioned closely behind the aircraft's centre of mass, which reduces the inertia of the vehicle in pitch and yaw. Also, the proximity of the propeller to the empennage enhances control power due to the slipstream passing over the elevators and rudders and, together with the lower inertia, makes the aircraft more responsive to pitch and yaw control. These qualities account for the popularity of the pusher propeller configuration in medium-size UAVs[2].

Although the main spar is made of titanium for enhanced wing structural rigidity, a certain amount of aeroelastic behaviour is suspected in the Djebel Laassa UAV. It is possible for the wing to twist under aerodynamic load during flight. This may change the angle of attack near the wing tip, particularly in turbulent flight conditions, and trigger an early stall in the tip region. Aeroelasticity may also affect aileron control response[14,15] which may be assessed during flight testing.

Stability in roll of the aircraft in rough weather conditions can be enhanced by applying 5° of dihedral[12,16]. Roll control may be improved using 5° of geometric wing twist to reduce the aeroelastic load near the wing tips and provide enhanced aileron performance[11,14].

4.4 Response to air turbulence

In severe weather and harsh flight environments, it is highly desirable to reduce the response of the UAV to turbulence to maintain payload sensors on the target. Maintaining a pre-specified course may also be difficult in extreme turbulence. Strong inherent aerodynamic stability, large surface areas and high *AR* in relation to the vehicle's mass cause UAVs to exhibit high response to atmospheric turbulence[2]. The Djebel Laassa aircraft's *S* of 3 m^2, *AR* of 10 and MTW of 200 kg (Table 1) provides moderate surface area to mass ratio and therefore reasonable responsiveness to gusts. The wing surface of the vehicle represents a good compromise between gust reduction and low-speed performance required for take-off and landing[10,13]. To achieve stability in adverse flight conditions, it is preferable to design the aircraft with near neutral aerodynamic stability to ensure minimum disturbance from air turbulence. However, a control system is often required to ensure that the vehicle has positive spatial stability to prevent the aircraft wandering off course. This control system requires sensors for the measurement of aircraft attitude and height integrated into an automatic flight control and stability system (AFCS).

4.5 R&D programme and impending innovations

The current R&D programme of Tunisia Aero Technologies Industries S.A.[1] prioritises engine, airframe material and structural development, and enhanced aerodynamics to maximize the performance of the future Djebel Laassa UAV. The R&D programme includes the following:

Engine, Airframe Materials and Structures

- Development of a new Italian-made 4-stroke twin-opposed cylinder engine that extends flight endurance to 24 hours.
- Implementation of an integrated approach to enhanced vehicle configuration and structural design using numerical analysis for the aeroelastic tailoring of composite structures of the vehicle. The new structural design increases the vehicle's aerodynamic performance during medium/high altitude, long-endurance missions.

Aerodynamics

- Boundary-layer research focuses on (1) transition prediction according to the three-dimensional pressure gradients, Reynolds numbers and Mach numbers typical of the UAV flight regimes and (2) flow modelling to explore the benefits of natural laminar flow.
- Application of real-time flow sensing and actuation techniques.
- Use of design architectures for complex multidisciplinary problems that include highly integrated systems.
- Aeroelastic analysis and design of a flexible, adaptive wing.
- Incorporation of novel vehicle flight control concepts based on flow control.
- Modelling and exploitation of unsteady, nonlinear, three-dimensional aerodynamics.

5. CONCLUSION

Aerodynamic modifications are proposed that enhance the maximum lift, flow control, stalling behaviour and flight stability characteristics of the air vehicle prototype. The main modifications include the use of an S1223 airfoil, VGs and a Gurney flap for the wing, a constant-section variable-thickness S1223 airfoil for the propeller, wing fence adjustments, and introduction of wing taper, dihedral and geometric twist. The current R&D programme of Tunisia Aero Technologies Industries S.A.[1] prioritises modifications to the air vehicle's engine and structural design and the introduction of advanced aerodynamics concepts that enhance the vehicle's performance in medium/high altitude, long-endurance missions.

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National de la Propriété Industrielle, Tunis, under Patent No. 17870. Title: Endurence Unmanned Airplane System for Multiple Application. Patent holder: Mr Azouz Bachouche.

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7. NOTATION

AFCS	automatic flight control and stability system
AR	aspect ratio
b	spam (m)
c	chord length (cm)
c_l / c_d	lift-to-drag ratio
$c_{l\,max}$	maximum lift coefficient
$c_{m,c/4}$	moment coefficient
g	*g*-force (units of standard gravity)
LE	leading edge
MTW	maximum total weight (kg)
Re	Reynolds number
S	surface area (m^2)
VG	vortex generators
x, *y*	Cartesian coordinates
α	angle of attack (°)
δ	angle of incidence (°)