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Aerodynamics and Stealth of the Low-observability RQ-3 DarkStar

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Abstract: Marqués P. (2013). Aerodynamics and stealth of the low-observability DarkStar. *International Journal of Unmanned Systems Engineering*. ***1***(S3): 1-5. The RQ-3 DarkStar high-altitude endurance UAV has an unusual shape that represents a compromise between aerodynamic efficiency and stealth constraints for low detectability in heavily guarded airspace. This technical note examines the aerodynamic and stealth characteristics of the rare RQ-3 DarkStar configuration. The distinctive flying-saucer fuselage and slightly-forward-swept rectangular wings present a challenge in aerodynamic design. The vehicle's lifting body sheds a leading edge vortex that triggers flow separation in the wing root region at high angles of attack. Also, the disk-shaped body generates upwash in the inboard wing area, increasing the angle of attack and the likelihood of flow separation. CFD played an integral role in the rapid prototyping environment in which the DarkStar was designed, built, and fight-tested. A wing root insert was devised using CFD that decreased the lift generated by the body, and attenuated the strength of the leading edge vortex and flow separation. Therefore, CFD was essential in diagnosing the complex aerodynamics and preventing the pitch up tendency of the initial DarkStar prototype. The turbo engine is mounted above the fuselage to shield the compressor and exhaust noise and heat signatures. The small size and low-profile airframe of the DarkStar is the result of shaping for radar concealment at the expense of downgraded aerodynamic performance.

Keywords:
Anti-radar stealth
Flying-saucer lifting body
Low observability
Radar signature
RQ-3 DarkStar
Ruddervons

1. INTRODUCTION

The RQ-3 DarkStar low-observability high-altitude endurance (LO HAE) UAV, known as Tier III minus, incorporated stealth technology for low detectability in heavily defended airspace.[1]

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The first flight of the RQ-3 DarkStar was on March 29, 1996. The RQ-3 was capable of autonomous takeoff, flight and recovery, and carried either an electro-optical (EO) sensor or synthetic aperture radar (SAR), and could relay digital information via satellite.[2] The designation RQ-3 stands for reconnaissance (R), unmanned aircraft system (Q), and third in the series (3) of the unmanned reconnaissance aircraft systems built by the U.S. Department of Defense.

The prime contractor of the DarkStar was the Lockheed Martin/Boeing team, overseen by the Defence Advanced Research Projects Agency (DARPA) under their policy of developing Advanced Concept Technology Demonstration (ACTD) aircraft. The DarkStar trades aerodynamic performance and payload capacity for survivability.[2] On its second flight, due to a software fault in the flight control system the aircraft's porpoising oscillations increased to a nose-high stall as it left the ground and the vehicle crashed.[3] Although the modified RQ-3A design was aerodynamically more stable, the Department of Defense determined that the aircraft lacked aerodynamically stability and terminated the DarkStar programme in 1999, due also to budget cuts. The DarkStar is a tailless vehicle with an unusual shape consisting of a rectangular wing and disk-shaped fuselage that represents a compromise between aerodynamic efficiency and stealth requirements (Fig. 1).

Fig. 1: RQ-3A DarkStar at the National Museum of the United States Air Force. (Photo: U.S Air Force).

The RQ-3A is a flying-wing configuration with very slight forward sweep and a flying-saucer fuselage section.[2] The DarkStar presented complex challenges in aerodynamic design. Aerodynamic efficiency and low-observability are in conflict.[4] The disk-shaped lifting body generates a leading–edge vortex that interferes with the wing flowfield.[1] The laminar-flow high-aspect ratio wings fulfil the long endurance requirement of the vehicle. However, the flow tends to separate at high angles of attack (α). The desire to reduce an aircraft's radar signature is as old as the emergence of the Radar system itself.[5] The Gotha/Horten 229 was the first aircraft that incorporated stealth characteristics and parallel advanced aerodynamic solutions consisted of a blended wing-body configuration and drag rudders to minimize the cross-section presented to the radar detector on the ground.[6] Anti-radar stealth principles in the Gotha/Horten 229 included surface blending, flying wing design, masked air intakes and jet exhausts, and the absence of a vertical stabilizer. Similarly, the DarkStar has a stealthy configuration and relies on large split elevons and ruddervons on the wing for flight control (Fig. 1). The short length of the vehicle (4.6 m) gives the aircraft a small moment arm for stability in pitch.[4] This technical note examines the complex aerodynamics and stealth characteristics of the rare RQ-3 DarkStar configuration.

2. DarkStar SPECIFICATIONS

The DarkStar was designed for high altitude surveillance and reconnaissance missions, and was capable of operation at above 45,000 ft and 500 nm from its base. The vehicle's endurance was 8 hrs. The wingspan is 21.3 m and the aspect ratio is approximately 15.[1,2] The aircraft is made of graphite composite for low weight and is powered by a single Williams-Rolls FJ44-1A turbofan engine with which the DarkStar achieved speeds above 250 kts. Specifications of the air vehicle are shown in Table 1.

3. DarkStar AERODYNAMICS

Warfield *et al*.[1] evaluated the aerodynamics of the DarkStar using Navier-Stokes CFD. The use of CFD proved essential in the rapid prototyping environment in which the DarkStar was designed, built, and fight-tested (Fig. 2). The study examined cruise, takeoff, gear/bay, deflected control surface, and propulsion integration configurations, and used nonlinear numerical models to examine wing laminar flow, wing-body vortex-induced flow separation, and vehicle performance in ground effect. The wing center section is assumed to maintain laminar flow for 40% of the chord on the upper wing surface and for 60% on the lower surface.

Table 1: RQ-3 DarkStar specifications.[2]

SPECIFICATIONS			
Dimensions & Weight		**Performance**	
Length (m)	4.6	Cruise speed (km/h)	464
Wingspan (m)	21.3	Range (km)	925
Height (m)	1.1	Service ceiling (m)	13,500
Empty weight (kg)	1,980		
Loaded weight (kg)	3,860		

The UAV's lifting body sheds a leading edge vortex that causes separation of the boundary layer on the root region of the wing. The body also generates upwash on the wing root, increasing the angle of attack and the likelihood of flow separation. Flow separation initiates at α = 4°, and grows rapidly at higher α. At α = 7°, the flow separation zone extends to one third of the wing span and the separated flow reaches several inches of thickness in the wing upper surface. The high aft body closure angle is another potential source of flow separation. CFD analysis was used to guide the design of a wing root insert that reduced the adverse effects of vortex-induced separation in the wing-body region.

Fig. 2: The DarkStar executing a fully autonomous flight in 1998 using the differential Global Positioning System. (Photo: Carla Thomas).

Rapid prototyping and constraints in programme costs allowed modifications to the wing root only. A wing root insert was devised that increased α at the wing root by 2° This new arrangement decreased the lift generated by the body, and reduced the strength of the body leading edge vortex and the size of the flow separation zone.[1] During taxing, the lift coefficient (C_L) decreased for α < 2.5°, however at larger α the C_L increased due to ground effect. The CFD grid setup also allowed rapid analysis of the vehicle's landing gear components, ground heights, and control surface deflections at different Reynolds numbers.[1] CFD played an integral role in diagnosing the complex flow separation and preventing the pitch up tendency of the initial DarkStar prototype.

4. DarkStar STEALTH CRITERIA

The main means for detecting a UAV are through its acoustic and electromagnetic (optical, infrared, and radar) signatures, which are related to the operating height of the vehicle.[5-7] An unmanned vehicle is superior in achieving low detectability compared to a manned aircraft. Without the need to accommodate air crew, a UAV is smaller and lighter, and the shape is more aerodynamic, in a compromise between aerodynamic efficiency and signature reduction. A source of aerodynamic noise in the DarkStar is the wingtip vortices, which increase with span loading. Noise originating from the powerplant is of greater concern, However, engine noise is minimised by keeping aircraft mass and drag to a minimum. Although noise from HAE vehicles is considerably attenuated by the time the sound waves reach the ground, the turbo engine of the DarkStar is mounted above the fuselage to shield the compressor and efflux noise and heat.[5,6] In the DarkStar, the exhaust heat is screened by the airframe. Heat radiation from the aircraft to the ground is prevented by containing the heat within the aircraft and emitting it skywards away from ground-based detectors.[6] Visual signature is a function of size and shape of the vehicle, contrast against the background, movement of the vehicle, exposure time, and atmosphere and glint effects.[7] The small size and low-profile shape of the DarkStar (Fig. 3) implies less reflective area that minimises the reflection of pulses back to a radar receptor on the ground. An effective way to reduce radar signature is by shaping the UAV externally to reflect radar pulses away from the transmitter.[5,6] No surface area of the aircraft should present at or near right angles to the radiation. The radiation is typically received at a small angle to the horizontal. Consequently, vertical surfaces, in particular fins, are not present in the DarkStar. Aircraft surface junctions at 90° should also be averted as these act as corner reflectors that give strong radar returns. Mounting of the intake and exhaust above the fuselage ensures that there are no apertures on the lower surface of the airframe and helps suppress radar returns. The airframe of the DarkStar is the result of shaping for radar concealment and a critical compromise between aerodynamic requirements and radar signature criteria.

Fig. 3: The second Tier III Minus DarkStar LO HAE UAV flying over the NASA Dryden Flight Research Center in 1998. (Photo: Carla Thomas).

5. CONCLUSION

The unusual DarkStar LO HAE vehicle is a flying-wing design with a flying-saucer fuselage in which aerodynamic efficiency and stealth requirements are in conflict. The low-profile stealth configuration dictated a tailless craft that uses large split elevons and ruddervons for flight control. The complex aerodynamics of the DarkStar presented challenges in design. A leading–edge vortex emanated from the disk-shaped lifting body which interfered with the wing flowfield and caused large regions of separated flow. CFD was crucial in the rapid prototyping climate in which the Darkstar was developed. CFD guided the design of a wing root insert that attenuated the vortex-induced separation in the wing inboard region. The role of the DarkStar to infiltrate and survive in areas of denied airspace was conceived to complement the surveillance and reconnaissance capabilities of the air-superiority Global Hawk; a vehicle with greater range, endurance and multi-sensor payload.

6. REFERENCES

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7. NOTATION

ACTD	Advanced Concept Technology Demonstration
CFD	Computational Fluid Dynamics
C_L	Lift coefficient
DARPA	Defence Advanced Research Projects Agency
EO	Electro-optical sensor
HAE	High-altitude endurance
LO	Low observability
SAR	Synthetic aperture radar sensor
α	Angle of attack