same manner as the small models, described in this study, flew at a stable angle of attack of 0 deg in the wind tunnel and behaved in all respects like a large ribbon parachute. Since the slot size is larger in large parachutes, it was hypothesized that slot geometry or size somehow affects parachute performance, perhaps by reducing the effective porosity of the models if the slot is too small. A slot Reynolds number was defined and the trim angle $dC_M/d\alpha$, and tangent force coefficients were determined as a function of this Reynolds number.[4] For a slot Reynolds number greater than 10^4, the stability characteristics of the model ribbon parachutes approximated those of full-size parachutes.[4] These results are still tentative, however, and more study is required before definitive statements about the effect of the slot Reynolds number on stability can be justified.

Conclusions

Several important model design parameters emerged from this study. It was found that the number of gores was a dominant factor influencing inflated canopy shape. The stiffness of the parachute did not strongly influence stability characteristics, and, in fact, stiffer models appeared to perform more like full-size parachutes than did more flexible models. Finally, the Reynolds number obtained by using slot height as the characteristic length appears to affect the stability characteristics of the models. This may be due to a reduction in the effective porosity of the parachute, and further studies should be focused on slot Reynolds number effects.

Acknowledgment

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References

[1] Heinrich, H.G. and Schmitt, J.C., "Aerodynamic Coefficients of a Twin Parachute Cluster," *Proceedings of the AIAA 6th Aerodynamic Decelerator and Balloon Technology Conference*, Houston, Tex., March 1979, pp. 356-362.

[2] Weber, T. and Garrard, W.L., "Aerodynamic Coefficients of 20% Geometric Porosity Ribbon Parachutes," Sandia Laboratory Contract 07-4328 Technical Report, Department of Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, Minn., July 31, 1979.

[3] "Performance of and Design Criteria for Deployable Aerodynamic Decelerators," AFFDL-TR-61-579, Dec. 1963.

[4] Weber, T. and Garrard, W.L., "The Effects of Flexibility on the Steady State Performance of Small Ribbon Parachute Models," AIAA Paper 81-1923, Oct. 1981.

[5] Heinrich, H.G. and Hektner, T.T., "Flexibility as a Model Parachute Performance Parameter," *Journal of Aircraft*, Vol. 8, Sept. 1971, pp. 704-709.

AIAA 81-2657R

U.S. Marine Corps AV-8A Maintenance Experience

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Introduction

THE Hawker Siddley Harrier, AV-8A, is the free world's only operational V/STOL (vertical short takeoff and landing) jet aircraft. The rigorous operational demands imposed by V/STOL operation, especially with a payload greater than the empty weight, would lead one to expect an airframe requiring excessive maintenance downtime and massive expenditures to maintain its structural integrity and flight worthiness, but this is not the case. Maintenance data show that this aircraft is as good as most Naval aircraft. Although it is as reliable as other aircraft, the lightweight design of the aircraft along with its operational and maintenance idiosyncrasies have created some airframe problems.

The AV-8A

The AV-8A (Fig. 1) is a single-fanjet engine, single-seat, high-wing monoplane with conventional monocoque fuselage and built-up empennage, all of 2000 series ALCLAD aluminum. Both wing and stabilator have anhedral with the wing tips having support ribs for outrigger landing gear. The fuselage has retractable bicycle-style landing gear with brakes on only the dual wheel main landing gear. The fanjet engine has a bifurcated inlet with peripheral, airload operated, auxiliary air doors and four rotatable exhaust nozzles. The two forward (cold) nozzles located just under and forward of the wing, on either side of the fuselage, exhaust over 60% of total engine airflow (430 lb/s in V/STOL). The remaining fan air, after passing through the turbine, is exhausted through the aircraft's two rotatable (hot) nozzles located again on either side of the fuselage below and slightly forward of the wing rear spar. All four nozzles are mechanically connected, synchronized, and driven by a dual air motor through torque shafts, gear boxes, and chains, from a full aft (0 deg) position to a maximum forward (98 deg) position called "braking stop." This system, although it weighs only 120 lb, can rotate the nozzles through their full travel in under 1 s and do this while the aircraft is in flight at up to 450 knots airspeed. As the nozzles go past the 16-deg position, a valve begins opening to pressurize the reaction control system (RCS) with eighth-stage compressor bleed air which permits nonaerodynamic aircraft attitude control via the reaction control valves (RCVs), which are mechanically connected to the normal flight control system. With a weight of only 200 lb, this system transmits and controls up to 10% of engine airflow, which in the form of hot compressor air approximates 3000 hp over distances of 20 ft.

Maintenance

The Navy has three levels of aircraft maintenance: organizational (O), intermediate (I), and depot (D). O-level maintenance is performed by the aircraft user and, aside from servicing and flying the aircraft, consists of aircraft and engine inspection and maintenance. This includes the removal and replacement (R&R) of various bolted components including both wing and engine. It should be noted that the O level performs the majority of high power runups which are

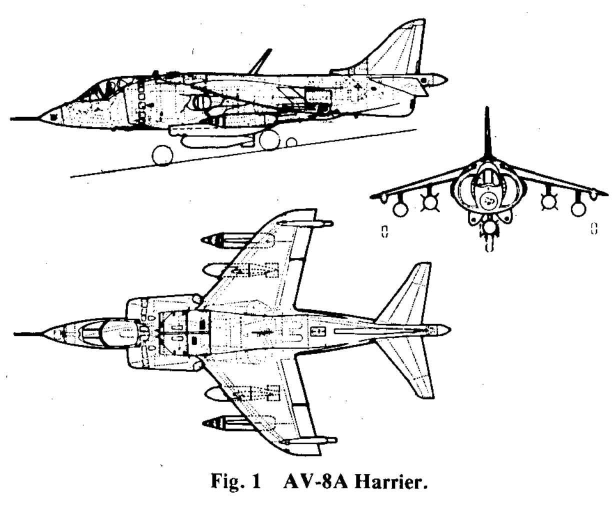

Fig. 1 AV-8A Harrier.

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required whenever certain work is performed on the engine, fuel control, water injection system, or reaction control system. Presently, engine runup requirements occur on an average of every 125 flight hours.

The I level supports the O level by rebuilding many of these removed components, if possible, and returning them to the O level for installation. In addition, corrosion control, sheet metal repair, and flight control system rework are performed on all Navy aircraft. This accounts for about 10% of the maintenance manhours that the O level expends in supporting the aircraft.

The depot maintenance activities repair, refurbish, and test the aircraft, engine, and components on both an as-needed and life cycle basis. Scheduled depot visits for the Harrier are at 1000, 1800, and 2400 h of a 3000 flight hour airframe life.

The O and I levels submit documentation forms which are computerized for data usage. The D level as of now is not computerized but is tabulated into hourly "norms" for planning purposes.

Table 1 shows the maintenance data summaries for several Naval aircraft. The Harrier, as the 7.2 flight hours per maintenance action indicates, is the worst or most unreliable of the group; however, the typical sortie is of a shorter, much more demanding nature than most Naval aircraft.

The third column of figures, with its 8.9 figure, indicates that once the defect is found it is relatively simple to fix when compared to other Naval aircraft. The next column contains numbers that really show, from a maintenance manhour (MMH) standpoint, how good or bad a weapon system is. The AV-8A's MMH per flight hour is comparable to the A-4E and A-7E and worse than the A-4 community taken as a whole. It is interesting to note that the fourth column of figures indicates that the A-4E and A-4 (all) require more I-level support than does the AV-8A. When sorties per maintenance action are considered, the AV-8 demonstrates a high level of aircraft availability.

Depot Data

At the depot level, the aircraft are taken apart and inspected to the maximum extent required to determine extent of damage. They are then repaired and reassembled. The italic numbers in Table 2 indicate the complexity of the aircraft's structure and flight controls and also the amount of time required to replace or repair discrepant structure and flight control system components.

The Harrier, unlike conventional aircraft, is capable of maneuvering in all three axes during hover. This is accomplished by rotating the four engine nozzles down to the hover position. The pilot then maintains the aircraft attitude by means of reaction control valves mechanically attached to the existing flight controls and located at the fuselage and wing extremities. The pilot, using the control stick, controls the bleed air efflux from the valve and therefore controls the aircraft attitude.

These RCVs along with the associated control system linkages and high pressure piping must be disassembled, inspected, installed, rigged, and tested. The 1855-h rework time includes the nozzle drive and RCV along with other aircraft systems required for hover capability that, if deleted from the norm, would show the Harrier rework hours to be almost the same as the A-4.

Structure

Most aircraft inducted for their first depot maintenance (1000 h of a 3000-h life) show signs of fatigue damage in the engine inlet ring, ventral fin, main landing gear door, and stabilator. All the deficiencies are in the secondary structure and are attributed to the engine or its efflux. The engine inlet ring, a titanium structure, was experiencing skin cracks which have been corrected by "painting" the skin with a silicone rubber layer to reduce sonic vibrations. The ventral fin, MLG door structure, and stabilator have had the degree and frequency of their damage lessened by changing the engine nozzle's position during high power runups to a minimum 10-deg (down from straight aft) position to reduce the impingement effect of the engine efflux on the airframe. Ad-

Table 2 Navy depot level rework

	AV-8	A-7E	A-4M	F-4
Aircraft induction	204	279	206	39
Strip and corrosion control	118	185	198	325
Disassembly, structural repair, and assembly	*1855*	*2512*	*1315*	*5089*
Ground/flight check	313	259	210	611
Final finish	181	113	182	330

Table 1 Summary of Naval aircraft structure and flight control maintenance for CY-80

T/M/S	Flight hours per maint. action	Maint. manhours per maint. action	Maint. manhours per flight hour	Intermediate maint. manhours
AV-8	7.2	8.9	2.67	>10%
A-4E	11.0	11.9	2.45	<10%
A-4 (all)	12.4	8.8	1.50	<10%
A-6E	9.5	14.9	3.82	>10%
A-6 (all)	9.5	14.9	3.82	>10%
A-7E	14.6	14.1	2.45	≥10%
F-4J	7.3	14.9	4.04	>10%
F-14	8.2	19.8	5.44	<10%

Summary of Naval aircraft sorties for CY-80

T/M/S	Flight hours/ sortie	Sortie/ maint. actions
AV-8	1.13	6.34
A-4E	1.44	7.60
A-4 (all)	N.A.	N.A.
A-6E	1.97	4.82
A-6 (all)	1.97	4.82
A-7E	1.74	8.36
F-4J	1.45	5.03
F-14	1.67	4.90

ditionally, those persons in charge of high power runups with the aircraft in a restrained position were advised to minimize high power engine runtime. By doing this, the impact on the structure has abated, with the exception of the ventral fins, which are being rebuilt, including new skins, and are being assembled with solid universal head aluminum rivets, in lieu of flush blind rivets.

On those aircraft being inducted for their second depot visit (1800 h of a 3000-h life), fatigue damage to the empennage primary structure exists. This includes fuselage skin cracks, stabilator structure cracking, loose/missing rivets in the fuselage skins, and fuselage frame cracking. Fortunately, these defects were not totally unanticipated since RAF aircraft, operating in a more turbulent low-altitude flight mode, have experienced similar problems earlier in their life cycle. Repairs for most of these defects have been designed and tested. Two aircraft recently inducted with the rebuilt ventral fin using new skins and solid universal head rivets exhibited no structural cracks or loose fasteners. Much of the original damage was to the aluminum sheet metal structure and not to support fittings or other machined-type parts, as their use is extremely limited on the Harrier.

AV-8 V/STOL Peculiar Systems

Engine Nozzles

The engine exhaust nozzles are the main reason for the success of the Harrier. By directing the engine fan and turbine exhaust efflux, the required thrust is vectored for vertical, horizontal, or transition flight. This system consists of a pneumatic motor drive unit with gear boxes, shafting, and chains to drive the four nozzles in unison. The nozzles and drive system are so strong and reliable that vectoring in forward flight has been used in air combat maneuvering. The system is designed to rotate the nozzles through their 98 deg of travel in less than 1 s. Additionally, the system is designed to have the nozzles synchronized and locked if a malfunction or binding should occur. Only one in-flight failure of a drive system component has occurred.

Reaction Control System

As the aircraft becomes jetborne, the reaction control system (RCS) allows the pilot full control authority at airspeeds below conventional aerodynamic control effectiveness. Made up of a butterfly valve, thin wall tubing, and reaction control valves, the system is simple, reliable, and contributes only 200 lb to total aircraft weight. The main problems have been maintenance induced damage (bends, dents, gouges) to the pipes, and bearing failures (corrosion, seizing, roughness) created by the high temperature operational requirements of the butterfly and reaction control valves. The ducts have had a very commendable performance record with only one catastrophic failure in the life of the weapon system. At the depot level, significant work has been expended to rework and repair people-induced damage to the ducting. This damage is a result of the thin wall ducting being located in the highly vulnerable lower section of the engine bay, where dropped tools tend to accumulate, and where improperly placed feet can cause duct damage (collapsing).

The reaction control valve bearings and the rod end bearings that operate the valve have been a nagging problem. Because of the operating temperature of the air (750°F) no lubrication is used since it can result in unacceptable binding or premature bearing failure due to corrosion or seizure. At present, the latest type valve bearings are doing quite well, experiencing only minor surface corrosion. The rod end bearings, especially the two rods that connect each wing tip roll RCV to its corresponding aileron, still wear out at an unacceptable rate. Changes are being effected which hopefully will correct this problem.

Water Injection System

The water injection system provides reduced turbine entry gas temperature, thereby increasing takeoff thrust at high ambient temperature conditions. The system comprises a 59.5-gal tank, a gravity fed water pump driven by engine bleed air, combined filter, pressure switch/drain valve assembly, injection nozzles, and associated plumbing and electrical/indicating interface. A flow rate of approximately 40 gal/min is provided automatically at the annular combustion chamber through 23 spray nozzles when the system is preselected and the throttle is advanced past the 92% LP compressor speed position.

Overall system reliability is not up to desirable standards primarily because of the design and maintenance induced errors in the quantity indicating system. Significant numbers of pumps fail annually owing to inadvertent operation without water. Bearings, relying on water for lubrication and heat dissipation, cannot operate dry for more than 1 s. Bearing refurbishment generally requires a complete overhaul.

The requirement for the water injection function is seasonal; therefore it is not unexpected that calendar related defects are observed. During the 4- to 5-month annual operating period, demineralized water generally precludes corrosion problems. Corrosion does tend to originate and progress during the longer nonoperating period. A new corrosion resistant coating now being applied to sensitive areas should reduce maintenance requirements.

Wing/Engine Replacement

The engine is too large to remove in the aft direction, and impractical to remove in the forward direction; the vertical direction is the only practical alternative. Removing the engine from above requires that the aircraft be jacked and leveled, and that all engine-to-airframe interfaces be disconnected. The engine is hoisted from the fuselage after removing the wing. The same heavy wing fittings are used for both wing attachment and engine access. The only systems affected in addition to the normal engine related systems are the flight control system, wing reaction control system connection, and some avionic systems.

The wing is bolted to six wing attach fittings, three each along the upper sill longeron, with a removable aerodynamic fairing along the fuselage covering the fittings. The fuel system and hydraulic system have quick disconnects and the electrical systems have conventional plug-in connectors which allow a fairly rapid wing removal or installation.

The wing, because of its inherent interchangeability, has proven to be beneficial from a squadron aircraft readiness standpoint. On occasion the squadrons interchange wings to maximize operational aircraft availability. This has worked very effectively on aircraft experiencing minor crash damage.

Conclusions

The basic structure of the Harrier has been and continues to be a very reliable and forgiving structure. The use of 2014T6 Al alloy with an epoxy primer and polyurethane paint system applied 5 mils thick has effectively precluded airframe corrosion and eliminated the need for extensive corrosion control with its attendant structural repair and replacement.

Minimizing high power runup has significantly reduced structural damage to the AV-8 airframe and to the empennage in particular. The reduction in time at high power, coupled with rebuilding the ventral fin with solid rivets, should eliminate much of the empennage structural rework.

The AV-8 aircraft and its V/STOL peculiar systems have proved in over 125,000 flight hours to be of a simple and reliable design which is capable of meeting the requirements of V/STOL operation.