SUMMARY OF THE 1991-1992 AERONAUTICS DESIGN PROJECTS

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Abstract

The Auburn University design groups have completed a study of regional transport aircraft culminating in two approaches for the design of a regional transport aircraft. Under the sponsorship of the NASA/USRA Advanced Design Program, the design project was suggested by S. J. Morris, center mentor at Langley Research Center, and implemented in the senior-level design courses at Auburn University. The first design (the DART-75) is based on a 75-passenger turbofan-powered regional aircraft, and the second design (the Eagle RTS) on a 66-passenger twin-turboprop powered regional aircraft design. The DART utilizes a three lifting surface configuration with aft-mounted turbofans and advanced aircraft components, and has a range of 1050 nautical miles. General descriptions of the structures, weight and balance, stability and control, performance, and engine design are included. The Eagle RTS has a similar layout to the DART, with aft-mounted pusher-props, and a range of 836 nautical miles. A study of the narrow-body aerodynamics, performance, stability and control, structures and materials, propulsion, and cost analysis is included. Both aircraft are designed for regional use and should breathe new life into the 50-100 passenger aircraft market.

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DESIGN OF THE ADVANCED REGIONAL AIRCRAFT, THE DART-75

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Introduction

The need for regional aircraft stems from the problem of hub airport congestion. Regional travel will allow a passenger to commute from one spoke city to another spoke city without entering the congested hub airport. In addition, those people traveling longer routes may begin the flight at home instead of traveling to the hub airport.

At this time, there is no American aerospace company that produces a regional transport for under 100 passengers. The intention of the Developmental Advanced Regional Transport (DART-75) is to fill this void with a modern, efficient regional aircraft. This design achieves the efficiency through a number of advanced features including three lifting surfaces, partial composite construction, and an advanced engine design.

Efficiency is not the only consideration. Structural integrity, fatigue life, ease of maintenance, passenger comfort and convenience, and environmental aspects must all be considered. These factors force the design team to face many tradeoffs that are studied to find the best solution. The final consideration that cannot be overlooked is that of cost.

The DART-75 is a 75-passenger medium-range regional transport intended for spoke-to-spoke, spoke-to-hub, and some hub-to-hub operations. Included are the general descriptions of the structures, weight and balance, stability and control, performance, and engine design.

General Design

The configuration, as seen in Figure 1, has three lifting surfaces, which enable the airplane to be trimmed without using negative lift. Three lifting surfaces also provide a more efficient takeoff and landing. The lifting surfaces include the canard, uniquely shaped wing, and a lifting horizontal tail. Table 1 gives some basic design and geometrical parameters of the aircraft.

The semi-diamond shaped wings are designed to provide efficient fuel placements. The large inner portion of the wing, where structural integrity is most easily maintained, is used to hold most of the fuel. Therefore the outer portion can be made lighter, thus decreasing overall weight of the aircraft. The inner portion of the diamond also provides for around half of the lift of the airplane, therefore maximizing efficiency though structural soundness. To eliminate the cost involved in the development of a new airfoil design, the NACA 2412 standard airfoil was adopted for the DART 75. This airfoil provides the lift and drag characteristics necessary for this design. By choosing an existing airfoil, more time was given to determine the actual flight characteristics of the uniquely designed wing.

Table 1 Basic design parameters

Number of Seats	75
Number of Crew	5
Range (n mi)	1050
Cruise Mach	0.7
Wing Area (sq ft)	615
Wing Span (ft)	75
Aspect Ratio	9.14
M. A. C. (ft)	10
Fuselage Diameter (ft)	11
Fuselage Length (ft)	95
Tail Span (ft)	26
Canard Span (ft)	26
Takeoff Thrust (lb)	35,000
Cost Range (millions)	$ 18-28

With a span of 75 feet, the semi-diamond shaped wing has an aspect ratio of 9.14. The canards and the tail both span 26 feet. The tail, while providing a marginal lift increase, is mainly used as a control surface and as a stability measure.

The canard is placed forward and low on the fuselage to decrease interference on the engine inlets at various angles of attack. The semi-diamond wing is placed higher than the canard, at mid-length of the body. The engines are located behind and slightly above the wing. This stacking effect will help eliminate the possibility of canard vortices entering the engine.

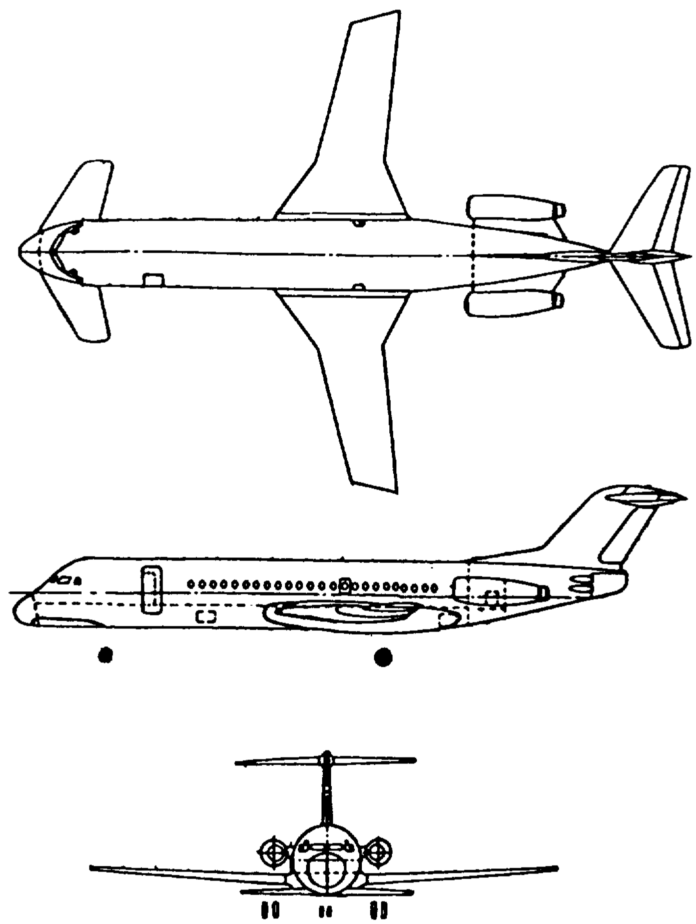

Fig 1 Three-view of the DART-75

The body of the DART has a diameter of 11 feet. The basic interior configuration consists of the flight deck, followed by the stewards' area, galley, and lavatory. Next is the passenger compartment containing five abreast coach seating with an overhead storage compartment on each side. The rear stewards' section consists of an additional lavatory and possible galley. There are three stewards to accommodate the 75 passengers.

The aircraft has a two-person flight crew assisted by an advanced technology glass cockpit. A digital fly-by-wire flight control system will be utilized for the aircraft.

The preliminary cost estimate of the DART-75 was slightly over 30 million dollars per plane. This cost seemed rather high to be competitive, but research into the cost of aircraft in this class resulted in a change of this impression. The new Canada Air Regional Jet costs about $18 million per plane, and only carries 50 passengers. In light of these estimations, the cost of the DART was expensive, but not unreasonable.

The cost of the DART-75 was estimated using the DAPCA IV model of aircraft cost. In this method, a factor representing the amount of composite materials used has to be chosen. A slight reduction in this number results in a considerable decrease in cost. By using slightly fewer composite materials, the cost of the DART-75 can be reduced to about 28 million at 100 units. The overall weight of the aircraft will not be greatly affected since only slight modifications in the amount of composite materials were made. The final cost per aircraft will range from about 18 million to 28 million dollars, depending on the number of aircraft produced.

Structures

One of the most important aspects of any aircraft design is the structural integrity of the craft. To determine the integrity of the plane, the loads must be identified and calculated. From the loads, the shear forces and moments can be determined, and then finally the levels of stress can be calculated. These steps must be taken for the wing, canard, tail, and fuselage.

The construction of the DART-75 will not vary much from conventional designs. The actual material make-up of the DART will consist mainly of an aluminum alloy. However, some composites will be used to construct the top of the wings, horizontal tail, canard, and parts of the fuselage. The determination of the type of composite used, whether graphite epoxy or fiberglass, will require time for further investigative analysis.

The structures will consist of a relatively thin skin along with stringers to handle most of the bending stress. This construction is approximated by a stiffened beam of skin and stringers, where the skin does not handle any normal stress. The stringers that are used to calculate the stresses were assumed to be rectangular. The stiffened beam approximation and the rectangular stringers tend to make these estimates conservative.

Using these estimations, the stress levels in the stringers are calculated. The material used for the structural members was 6061-T6 wrought aluminum. This material is very widely used in the aircraft industry, and is known to have yield strength of 35,000 psi and an endurance limit of 13,500 psi. The endurance limit is the amount of stress that can be applied to the specimen an indefinite number of times without the specimen breaking. Some of the structural members are designed to have maximum stress levels under the endurance limit. Although this makes for a slightly heavier aircraft, it extends the life of the structural members to infinity, at least in theory. However, the members that are most important are those which endure the maximum levels of stress.

In the wing the maximum stress occurs where the large diamond-shaped portion ends. This stress was determined to be about 16,100 psi. This value gives the vital members a safety factor of 2.19. In both the canard and tail the maximum stress occurs at the root of the structure. The maximum stress in the canard is 11,400 psi and 13,300 psi in the tail. These values correspond to safety factors of 3.07 and 2.63, respectively. The maximum stress in the fuselage occurs near the center of gravity of the craft, and has a value of 7600 psi. This level of stress translates into a safety factor of 4.6. These values for stress are only approximations used in the calculations, but are acceptable values for this preliminary design project.

Weight and Balance

In estimating weight, a combination of formulas was used from two sources, Torenbeek and Nicolai. The two sources allowed tailoring of the weight calculations to our specific design and gave a good approximation to the weight that is appropriate in this stage of the design.

The weight is divided into major structural groups and individual groups of components within the major groups (see Table 2). The balance analysis was done with reference to Torenbeek's book. The calculation was done by breaking down the aircraft into major components and subcomponents with a simple center of mass technique. The forward tip of the fuselage was used for the reference datum line, while the center of gravity was calculated along the length of the aircraft.

Table 2 Weight and balance calculations

Component	Weight (lb)	CG Loc. (ft)	Total CG Loc. (ft)
Fuselage	13325	38	
Wing	4590	55	
Tail	1054	94	
Canard	659	8	
Engines	4500	75	
Main gear	1624	53	
Nose gear	541	15	
Avionics	200	15	
Fuel	22100	45	
Passengers	13825	43	
Furnishings	4712	40	
Baggage	3750	35	
Eng. acc.	1972	72	
Surface cont	1426	53	
Reserve fuel	1625	40	
Misc.	7386		
MZFW	63000		
MTOW	80000		
W empty	40870		
MTRW	80545		
Total no pass., full fuel			46.03
Total reserve fuel, pass.			44.06
Total no pass., res. fuel			45.20
Total full fuel, pass.			45.00

Different loading configurations were examined in order to represent all of the extremes encountered in flight. This gives a defined set of center of gravity positions, two of which are the most fore and aft center of gravity locations. The difference in the two positions gives the center of gravity travel that can occur in flight. The four payload-type configurations are: full load (all passengers and full fuel), full fuel and no passengers (and no baggage), reserve fuel and all passengers, and reserve fuel only. Table 2 shows the figures calculated for each of the configurations. The centers of gravity for the fuel, baggage, avionics and other accessories were placed to satisfy stability requirements.

Stability and Control

The subjects of stability and control deal with how well an aircraft flies and how easily it can be controlled. These factors are especially important for a commercial transport because of the passenger comfort requirements. A passenger aircraft must adjust quickly and smoothly to perturbations in the atmosphere and changes in flight conditions.

There are many criteria that must be satisfied before an aircraft is considered statically stable. Many stability parameters were determined by using one of the Army's Missile Aerodynamic Design Programs written by William David Washington in 1980 and modified by Dr. John E. Burkhalter of Auburn University in 1990. One criterion for the DART to be stable is that the moment curve slope must be negative. The moment curve slope for the DART is approximately -4.304 per radian. The numbers obtained from the program are approximate since modifications were made to the program for a cranked wing configuration.

A stable aircraft must also be able to be trimmed. The Y-axis intercept of the pitching moment curve must be positive and was determined to be 0.152 for the DART. Another important stability parameter is the stick-fixed static margin. The static margin must be positive for a stable aircraft, and the static margin for the DART at cruise was found to be 2.73 ft, or 34% of the mean aerodynamic chord. Acceptable values for the static margin for commercial transports range from 25 to 50% of the mean aerodynamic chord. This means that the center of pressure is 2.73 ft behind the center of gravity and that, therefore, the DART is statically stable.

The maneuver margin is another important stability parameter. The maneuver point should be behind the center of gravity. The maneuver margin was determined to be 10.2 ft. Therefore, the maneuver point at cruise for the DART is 10.2 ft behind the center of gravity.

The stability characteristics of the yaw and roll planes are closely coupled. The upward sweep of the wings generates a dihedral effect that produces restoring forces and moments in the yaw and roll directions. A dihedral angle of about 8° is necessary in order to reduce the body interference factor on the dihedral effect.

The DART-75 will use three control surfaces. Elevators will be used on the tail to control pitch and atitude changes. Due to the close coupling of the yaw and roll controls, the rudder mounted on the vertical tail plane and the ailerons on the wing are interdependent. These surfaces will give adequate response to perturbations and sideslip forces. These controls are conventional in design and should give the DART-75 handling qualities similar to other regional jets. Dynamic analysis of the aircraft was omitted due to time and resource constraints. However, when a model is produced, further analysis may be done.

Performance

The DART's performance data was obtained through the use of two main sources, Shevell's book and USAir Operations Chief Engineer Mike Pulaski. The drag polar was calculated by using Roskam's methods.[6] This method shows the drag polar to be:

$$C_D = 0.02167 + 0.0301\, C_L{}^2$$

for the clean configuration and

$$C_D = 0.065341 + 0.0309\, C_L{}^2$$

for the dirty configuration.

The dirty drag polar was obtained from several figures and charts providing data for several different aircraft. The coefficient of lift is assumed to have a maximum value of 1.75 for the clean configuration and 2.2 for the dirty configuration. The coefficient of lift for maximum lift over drag, incorporating the calculated drag polar, is 0.75.

The next calculation involved the determination of the flight speed. The maximum cruise speed of the DART is Mach 0.7 at 30,000 feet with takeoff speed at 140 knots and landing at 120 knots. The DART has a range of 1050 nautical miles. Knowing the engine's specific fuel consumption and the weight of the fuel showed the endurance of the flight to be around five and a half hours. If operating at full power, the maximum aircraft endurance is calculated to be around five hours.

The DART will climb from sea level to around 75 % of cruise altitude in approximately 10 minutes. This will be at an initial climb angle of between 8 and 14° at a climb rate of between 3400 to 5500 ft per minute. After reaching the 22,500 ft level, the DART will begin to level off to a more relaxed climb angle ranging from 2 to 5°. The climb rate will then be 1000 to 3000 ft per minute. Another five minutes and the aircraft will be at a cruise altitude of 30,000 ft.

The DART's performance proves to fit well with the mission profile. Comparing the calculated values with those values that are known for today's aircraft achieved reasonable results. The landing and takeoff field lengths are respectable and compare well with any regional aircraft in existence today. The range and endurance meet the need for a medium range, very fast aircraft.

Propulsion

Due to the multi-faceted role of the regional aircraft, a propulsion system designed for this aircraft must be able to handle many different flight conditions. The engines will not be the best design for any one situation, but they should be a good compromise for the situations in which the airplane is to be used.

To achieve this goal the turbofan engine has been selected for consideration primarily due to its proven technology. Each engine will produce 12,500 lbs of static thrust, be able to provide reverse thrust, and will comply with the latest aircraft noise regulations. Since there have been so many aircraft designed for turbofan engines, there is an abundance of research that has already been conducted in this field. Trends in turbofan engine design tend to increase the engines bypass ratio rather than improve the engines core design. The increase in bypass ratio allows the engine to produce the same thrust with a smaller TSFC and with less noise.

The engine used on the DART will be rated for a static thrust of 12,500 lbs and will produce 2500 lbs of thrust at

30,000 ft and a Mach of 0.7. The TSFC of the engine is approximately 0.6293 lbs of fuel per hour per lb of thrust, which was calculated using a computer program discussed later. To achieve such a low TSFC an engine needs a bypass ratio of between 7 and 10. The weight of the engine is about 1800 lbs with a length of 7.3 ft and a diameter of 5 ft.

Most engines that are put on higher performance aircraft are d-rated. In other words the engines can produce greater power when needed than the actual design power required for any flight situation. Hence, the actual engine on the DART-75 will be *capable* of producing from 1000 to 5000 lbs more static thrust than the rated power. This increase of power would allow for greater single engine takeoff and climb performance and would also allow the airplane to climb to a higher altitude in case it needed to avoid disturbances. The increase in thrust to 17,500 lbs would require an engine that weighs 2535 lbs, is 8.32 ft long, and is 6.36 ft in diameter. The added increase in weight would only change the total aircraft weight by 1570 lbs, which would be an increase of only 2.0%. However, the increase in static thrust would change the single engine thrust to weight ratio on takeoff from 0.156 to 0.22.

The calculation of this engine was done using the ONX engine analysis program. This program was derived from the book *Aircraft Engine Design* by J.D. Mattingly, W.H. Heiser, and D.H. Daley. The program allows the engineer to input Mach number, altitude, atmospheric conditions, bypass ratio, burner can temperatures, and component efficiencies. The program then calculates the engine's mass flow rate, thrust, and thrust specific fuel consumption (TSFC). The burner can temperature was estimated at 3000° R. The fan pressure ratio is 1.4 and the compressor pressure ratio is 39.0. These values were derived by iterations done with the ONX program. A total number of over 200 iterations using different bypass ratios and fan and compressor ratios was used in the program before an optimal engine based on the lowest TSFC was found. The engine is also based on the two nozzle non-mixing design.

A bypass ratio of 9.6 was chosen because it proves to be the highest bypass ratio that can be obtained using a standard fan and keeping the engine flow stable. A higher bypass ratio can be obtained; however, to keep the engine flow stable, a fan cascade with variable pitch fan blades would be required. This design would require a significant increase in engine weight and would decrease the reliability of the engine. Therefore, it was determined that, the simpler design would satisfy the airplane operator's needs better than the variable pitch blade design.

The engine will reverse thrust using ballistic reversers. The failure of ballistic reversers is known to be very unlikely. In fact, there has never been a recorded failure of the clamshell type reverser. The only other option for thrust reversing is available through a variable pitch fan design of a turbofan engine. This option is to deflect the blades in such a way as to give them a negative angle of attack. Reversing thrust in this manner is more efficient than in the ballistic way but it would once again add unwanted weight and complexity to the engine design.

Conclusions

The regional aircraft currently available are old and inefficient. A new regional transport could well take over the regional market. The DART-75 is the proposed new regional transport with single class accommodations for 75 passengers and a crew of five. This aircraft will achieve success through its efficiency, excellent multi-role capability, advanced general design, and competitive cost.

The DART-75 will be capable of point-to-point, hub-feeder, as well as shuttle-type services. The wing shape, decreased weight, and efficient engines combine to yield good short field performance, excellent range, and competitive cruise speed. These factors make the DART-75 a very versatile craft that will appeal to many airlines for different types of missions.

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Eagle RTS: A Design of A Regional Transport

Paul Bryer, Jon Buckles, Paul Lemke, Kirk Peake

Introduction

The Eagle RTS (Regional Transport System) is a 66-passenger aircraft designed to satisfy the need for accessible and economical regional travel. The first design objective for the Eagle RTS is safety. Safety results primarily from avoidance of the hub airport air traffic, implementation of anti-stall characteristics by tailoring the canard, and proper positioning of the engines for blade shedding. To provide the most economical aircraft, the Eagle RTS will use existing technology to lower production and maintenance costs by decreasing the amount of new training required.

In selecting the propulsion system, the effects on the environment were a main consideration. Two advantages of turbo-prop engines are the high fuel efficiency and low noise levels produced by this type of engine. This ensures the aircraft's usage during times of rising fuel costs and growing aircraft noise restrictions.

The design of the Eagle RTS is for spoke-to-spoke transportation. It must be capable of landing on shorter runways and have speeds comparable to that of the larger aircraft to make its service beneficial to the airlines. With the use of turbo-prop engines and high lift devices, the Eagle RTS is highly adaptable to regional airports. The design topics discussed include: aerodynamics, stability, structures and materials, propulsion, and cost.

Aerodynamics

The fuselage of the Eagle RTS resembles an elongated "teardrop" shape with pusher-prop engines located behind the swept-back wings. This configuration will allow for minimum body drag while allowing for maximum flexibility in designing the interior arrangement. Figure 2 provides a three-view of the Eagle RTS.