X-22A Design Development

Vincent B. Paxhia* and Edward Y. Sing†
Bell Aerosystems Company, Buffalo, N.Y.

The X-22A is a dual-tandem, ducted propeller triservice VTOL research aircraft. The configuration provides for high control and trim forces in all three axes and for a high useful load. The ducts increase the thrust of the propeller in takeoff, thereby allowing use of a small and light propeller, and then serve as lifting surfaces in conventional flight. Design considerations and the over-all results of the test programs in exploring the full handling qualities spectrum of the X-22A aircraft are discussed. The high control power and high thrust-to-weight ratio, in conjunction with the three-axis variable stability system, afford the capability of performing similar research on other types of VTOL aircraft by simulation of their stability and control characteristics.

Introduction

IN Ref. 3, the evaluation of a dual tandem configuration was described briefly and the advantages were reviewed. Also discussed in the paper were the configuration selection and the tradeoff studies conducted with regard to propulsion system arrangements, duct and propeller design, aerodynamic design, control in hovering and transition, thrust to weight, endurance, and other design parameters. In addition, the wind tunnel, propulsion, flutter, and structural test programs were reviewed and the research mission capabilities of the X-22A were described.

At the time the paper was presented, the X-22A program had been under contract for two months. Detail planning of the test programs was well underway and the preliminary design was being finalized in preparation for the next step, the detail design phase. The purpose of the present paper is to report on the progress made during the first 18 months of the X-22A development program. In addition, some of the more important design considerations and test program results will be described.

Before reviewing the current design status, it would be of value to review the fundamental characteristics of the dual tandem ducted propeller aircraft. The factors of major importance are as follows.

1) The dual tandem arrangement of the propellers in conjunction with interconnecting shafting provides high pitch and roll control (and trim) forces in hover and transition with little or no loss in thrust by increasing the blade angle on one set of propellers while decreasing the blade angle on the other. For rather large changes in loading, the decrease in thrust per horsepower for the more heavily loaded set of propellers is balanced by the increased thrust per horsepower for the more lightly loaded set of propellers, thereby maintaining the total thrust.

2) The ducts serve as lifting surfaces in level flight and increase the static thrust of the propellers making it possible to use a much smaller and lighter propeller to obtain a specific thrust than would be feasible with a bare propeller. In turn, the smaller propeller can be operated at higher revolutions per minute which results in a saving in gear reduction ratio and thus gearbox and shafting weight because of the lower torque transmitted.

3) The ducts provide a convenient source of high-energy air and permit the use of effective aerodynamic surfaces in the duct slipstream resulting in powerful yaw control in hover and transition. In general, adequate yaw control and trim forces are difficult to obtain with other types of VTOL vehicles. With the X-22A, the standard plain elevons provide a level of yaw control power which meets the requirements of MIL-H-8501A and, for special research, an auxiliary set of elevons which provides approximately 3 times this control power may be used.

4) The arrangement in combination with the small size of the propellers results in a compact configuration, which minimizes or eliminates site preparation. The net effect of the dual use of components and lack of auxiliary control components are substantial weight savings resulting in a high useful load capability and a maximum VTOL operational capability. Transition from hover to level flight and return has been shown by analyses, wind-tunnel tests, and simulator studies, to be a straightforward flight maneuver because of the powerful control available and the absence of stalled or blanketed aerodynamic surfaces. The high control power in all axes makes the X-22A easy to fly and maneuver in strong winds. For example, hovering turns in 35-knot winds can be made with control forces exceeding the required trim force by 100% or more.

Configuration

Current pictures of the X-22A aircraft illustrate the change in appearance that has taken place since the inception of the design. Most significant is the change in body shape. Less evident are the changes in wing planform and fin and stabilizer sizes, as a result of the evolution from preliminary design through detail design, as supported by wind-tunnel testing.

The original configuration is shown in Fig. 1. Power was transmitted to the forward propellers via fore and aft interconnect shafts. This shafting was on the right-hand side o

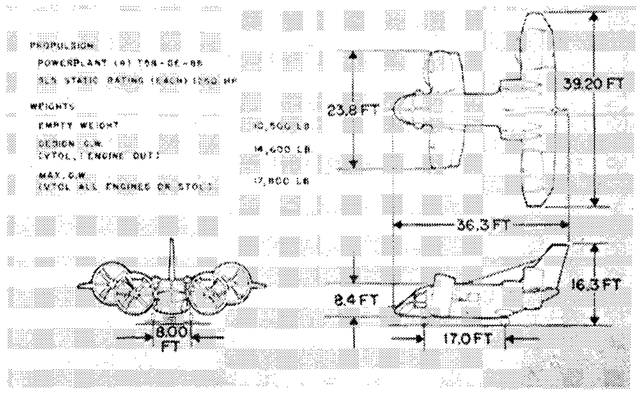

Fig. 1 Original X-22A general arrangement.

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* Assistant Chief Engineer, Technical Director. Associate Fellow Member AIAA.

† Assistant Technical Director. Associate Fellow Member AIAA.

the fuselage frames. Because of the small size of the X-22A, this arrangement posed some very difficult design problems in the region of the forward ducts. Providing an adequate duct support structure and locating the duct rotation mechanism and the "tee" gearbox (which transmitted power from the fore and aft interconnect shaft to the forward propellers) in a small space appeared undesirable.

The best solution was to locate the fore and aft shafting on the airplane centerline. But as brought out in the previous paper, it appeared highly advantageous, from a directional stability viewpoint, to locate the front ducts below the aft ducts. These requirements meant that deep supports would be required to support the shafting from thef uselage frames, and in any event the space above the fore and aft shaft was largely useless. For these reasons, the upper contour line of the fuselage was sloped to conform to the fore and aft shaft and thus provide an improved structural configuration. This revision in body shape is shown in Fig. 2. Shown also in Figs. 1 and 2 are the current design and maximum gross weights and the empty weight not including the variable stability system installation.

Propulsion System

The heart of the X-22A airplane is its propulsion system. Four T58 engines with speed controls or power controls drive the four 7-ft-diam propellers through a power transmission system as shown in Fig. 3. With these controls, the aircraft can be operated in a conventional mode, with propeller governing, or as a helicopter, with pitch control directly on the propellers and speed governing on the engines.

The four engines drive through overrunning clutches and speed is reduced in the engine tee boxes from 19,500 to 7100 rpm. The propeller gearboxes reduce the revolutions per minute to 2590 at takeoff. Hamilton Standard Division propellers, using a steel spar with Fiberglas covering, are used. The fuselage and engine gearboxes are being supplied by Steel Products Engineering Company.

This propulsion system represents the present state of the art with regard to shaft speeds and gear and bearing design. Conservative criteria for design of shafts, gearboxes, and propellers has been selected to assure that a rugged trouble-free propulsion system will be delivered with the aircraft. A minimum B_{10} (90% undamaged) life rating of 2000 hr at normal rated power has been specified for all bearings, and a fatigue life of at least 10,000 hr required for all gears, shafts, and housings. Clutches have been designed with a 50% margin over expected maximum loads. A comprehensive test program is planned to qualify the system. This will consist of a 125-hr run on a propulsion system test stand followed by 125 hr on aircraft tie-down tests. All of the dynamic components of the transmission, associated subsystems, and engines will be operated on the test stand. The fabrication of the propul-

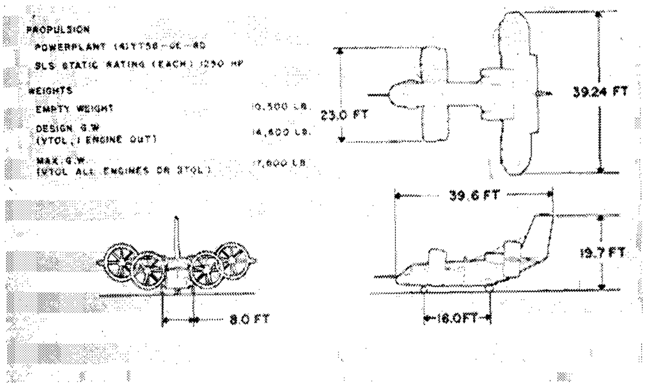

Fig. 2 Current X-22A general arrangement.

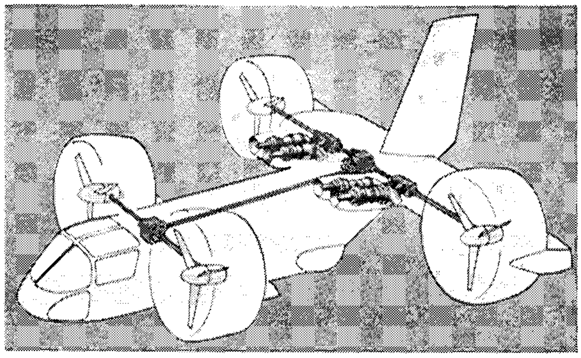

Fig. 3 Propulsion system.

sion system test stand is well advanced as shown in Fig. 4, and testing is scheduled to begin in the near future.

Propeller System Status

The first set of X-22A integral propeller gearboxes is in the final stages of acceptance testing following successful completion of the 50-hr propeller development testing on the T58 powered propeller test stand, and the 100-hr whirl stand test of the propeller blade retention and blade pitch change systems. The formal 50-hr propeller system preliminary flight rating test (PFRT) will be completed before initiation of the 125-hr test on the Bell Aerosystems Company (BAC) propulsion system test stand.

Transmission System Status

All of the qualification tests of the transmission system components have been completed by the subcontractor and the first set of the engine reduction gearboxes and shafts have been acceptance tested and delivered. These components are being installed in the propulsion test stand for complete system tests and the 125-hr endurance tests. Acceptance testing of the first set of fuselage gearboxes and shafting is in the final stages of completion.

Flight Control System

Primary Control System

The flight control system utilizes elevons in all four ducts and propeller blade pitch change to provide control in hovering, transition, and conventional flight. Height control is provided by either of the two systems described previously. One system uses basic engine power lever (throttle) with a selector for propeller governor revolutions per minute. As the power is increased or decreased, blade angle is adjusted to maintain revolutions per minute. This is the conventional mode for fixed-wing aircraft and the system has the advantage of requiring minimum pilot attention. In the other mode, propeller blade angle is controlled directly and revolutions per minute are governed by the engine speed control.

This is a helicopter mode, and it is evident that the thrust response to pilot input will be faster. However, maximum

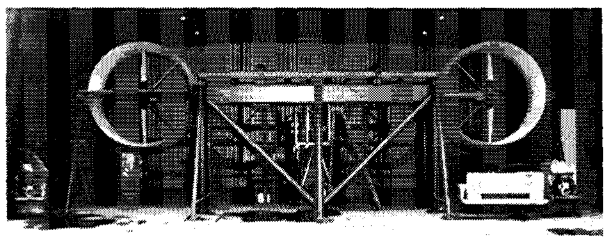

Fig. 4 Propulsion system test stand.

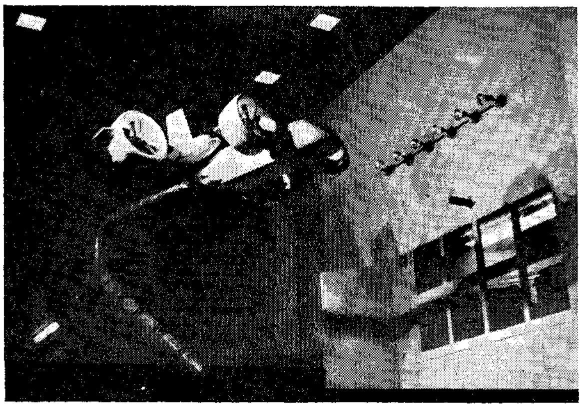

Fig. 5 One-fifth-scale powered airplane model.

pilot attention is required as speed increases since the blade angle range from zero thrust to maximum torque becomes very small.

The propeller pitch and elevon controls are operated by dual hydraulic systems, with the pilot's controls consisting of a conventional stick and rudder pedals. During transition, as the ducts are being rotated from vertical to horizontal, a variable ratio bellcrank system (phased by duct position) mixes the pilot's inputs so as to produce uncoupled, or pure pitch, roll, and yaw moments.

In addition to the primary mechanical hydraulic system, the flight control system incorporates a conventional dual stability augmentation system, an electrical-hydraulic trim and feel system, and a versatile variable stability system.

The electrical-hydraulic trim and feel system evolved as the best solution to the wide range of feel forces required in hovering and in level flight. The usual spring and q bellows arrangement proved unwieldy due to both the wide range of force required and also because of the difficulty in accomplishing the proper phasing with duct position.

Variable Stability System

An extremely versatile variable stability system (VSS) is an important feature of the X-22A aircraft. The purpose of this system, which is being developed for Bell by Cornell Aeronautical Laboratory, is to provide a means for conducting flight research on handling qualities for this type of VTOL, as well as to investigate handling qualities characteristics that would be generally applicable to all other VTOL types. The objective of the X-22A variable stability flight research would be to establish stability and control criteria that provide minimum-acceptable as well as optimum handling qualities of VTOL aircraft in the terms described in the following sections.

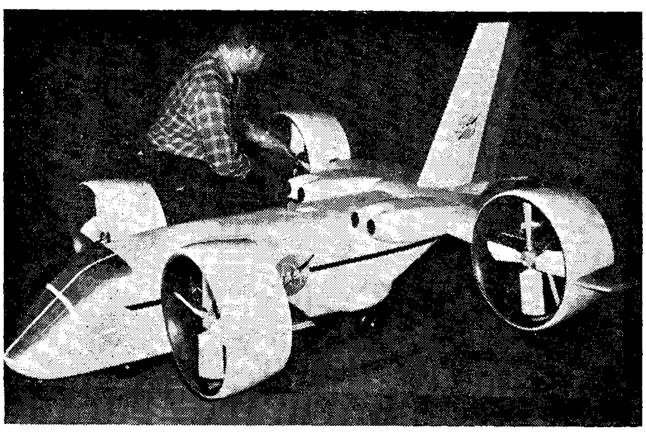

Fig. 6 NASA free flight model.

Dynamic response characteristics

Dynamic response characteristics are of importance particularly in the flight regimes peculiar to VTOL aircraft, i.e., hover and transition. Fairly extensive flight research has been conducted on conventional aircraft and helicopters to determine levels of dynamic response that provide acceptable handling qualities. The dynamic characteristics of VTOL aircraft, however, can be quite different from those of conventional aircraft or helicopters, particularly in transition flight, and very little flight research has been conducted on this type of aircraft.

The basic aerodynamic and control parameters that have a dominant effect on dynamic response in transition are different in many cases from those of conventional flight, and are known to change quite drastically with changes in speed, thrust, and conversion angle. In order to provide a capability in the X-22A to conduct in-flight research on dynamic response characteristics of VTOL aircraft related to handling qualities, the X-22A design specification requires that the VSS provide the following: 1) variations in the modes of the vehicle's motions (period and damping of oscillatory modes, time constants of the aperiodic modes, and amplitude ratios of the various modes); 2) variable damping of the angular motions; 3) variable height damping; 4) variable attitude stabilization; and 5) variations in the way vertical forces change with appropriate parameters such as speed.

It is felt that the range of these variations will encompass future design and weight variations of dual tandem ducted VTOL aircraft as well as characteristics of other VTOL types.

Control characteristics

Past flight research on helicopters has isolated several control system design parameters that have a most significant effect on handling qualities. These include such items as total control power, control power gradients, feel force gradients, breakout force, etc. Certain other control parameters have been shown to be most significant in conventional flight, e.g., stick force per maneuvering "g."

A comprehensive flight research program to investigate the significant control parameters and desired ranges for VTOL aircraft has not been undertaken (although a limited program is underway on the X-14). The variable stability system in the X-22A will provide the capability to vary all

Table 1 Aerodynamic test program

Model	Purpose	Status
$\frac{1}{6}$-scale model	Aerodynamic data	Completed
$\frac{1}{5}$-scale model	Performance and stability and control data	Completed
0.032-scale ground effect model	Hover characteristics	Completed
Elevon effectiveness model	Elevon performance data	Completed
$\frac{1}{20}$-scale spin model NASA Langley	Spin characteristics	Completed, July 1, 1964
0.018-scale free flight NASA Langley	Transition characteristics	Starting, July 1964
$\frac{1}{3}$-scale powered duct model	Ducted propeller performance verification	In progress
Full-scale powered duct model	Ducted propeller performance data	Starting, July 1964

of the significant control system parameters. These are 1) variations in total control power; 2) variation in control power sensitivity (including nonlinear gearing); 3) variations in control feel forces; 4) variations in control friction forces; and 5) variations in control coupling.

The left-seat pilot will serve as the variable stability pilot, and the right-seat pilot will be the safety pilot. The safety pilot's cockpit controls always stay connected to the primary controls of the airplane. Therefore, his controls may show odd motions during variable stability operations, as the control surfaces are moved by the variable stability system servos. Shutoff switches are provided on the control sticks of both pilots to turn off the VSS system. Operation of the shutoff switch immediately restores the airplane to its normal stability and control condition and the safety pilot assumes control of the airplane. It is this immediate restoration of normal handling qualities which makes the variable stability airplane a safe device for investigating handling qualities which are nearly unflyable or which are unknown.

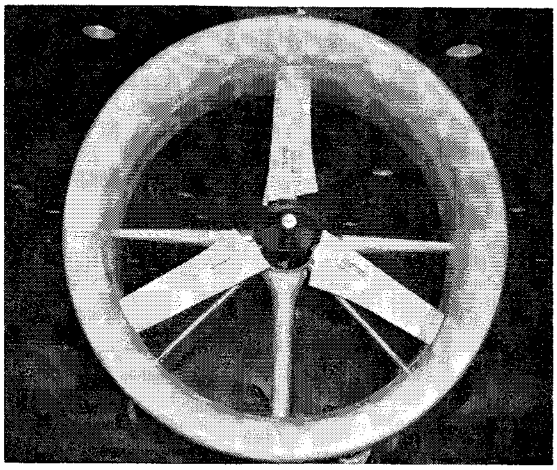

Fig. 8 Full-scale ducted propeller model.

Development Status

Design of the flight control system is complete and parts are being fabricated for the two aircraft and the flight control test stand. This stand will mount all elements of the mechanical and hydraulic components of the flight control system. Included also will be the stability augmentation system, the trim and feel system, and the variable stability system.

The basic aeronautical engineering effort is essentially complete for the variable stability system in the area of electronic hardware, and the circuit and printed circuit board designs have been completed for all basic required circuit modules, including function generators. Prototype modules have been constructed and tested throughout the required operating temperature, vibration, and acoustic ranges. In addition, the design approval tests of these modules have been completed.

Detail electrical and mechanical design is complete for a low-range airspeed system and preliminary tests have been conducted.

X-22A Aerodynamic Development

The aerodynamic development testing of the X-22A aircraft has provided design data for finalization of the configuration and system design. The basic objective is to satisfy or exceed the requirements delineated by the aircraft specifications which define the operating characteristics of the X-22A.

An aerodynamic test program consisting of eight separate models is being conducted to obtain the required design information. The models and pertinent information are listed in Table 1.

As evidenced previously, all the tests which supply design data toward the establishment of the aircraft configuration have been completed and the results incorporated into the detail design.

Models of primary interest in the program are the $\frac{1}{5}$-scale powered aircraft model (Fig. 5) that furnished the bulk of the performance and stability and control data, the NASA 0.018 scale free flight model (Fig. 6) that will be used to evaluate the dynamic characteristics of the X-22A in hover and transition, the David Taylor model basin (DTMB) $\frac{1}{3}$-scale powered duct model (Fig. 7) that is being used to investigate ducted propeller characteristics through the full X-22A flight spectrum, and the full-scale ducted propeller model (Fig. 8) being tested at NASA to verify the performance of the unit and to obtain propeller blade stress data at all flight conditions that will occur during the transition and conventional flight regimes.

The data obtained from the model programs has been used in combination with various analytical methods including dynamic computer studies to establish the design of the airframe components, control system elements, and the control phase relationships during transition.

A six-degree-of-freedom X-22A analog simulator for V/STOL and conventional flight operation has been constructed to perform piloted evaluation of the handling characteristics of the aircraft. A view of the simulator is shown in Fig. 9. Areas being studied include control in the stability

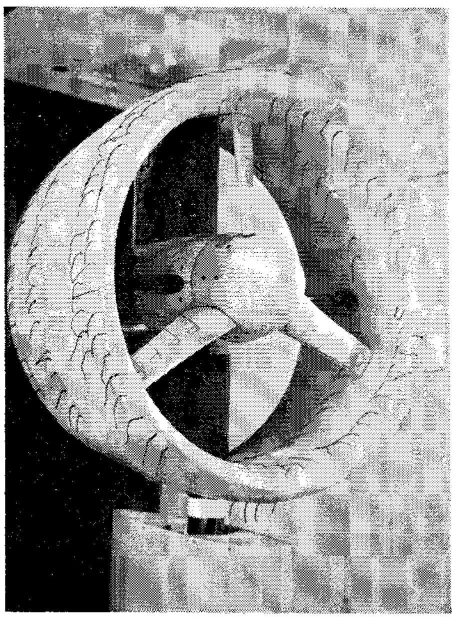

Fig. 7 DTMB $\frac{1}{3}$-scale powered duct model.

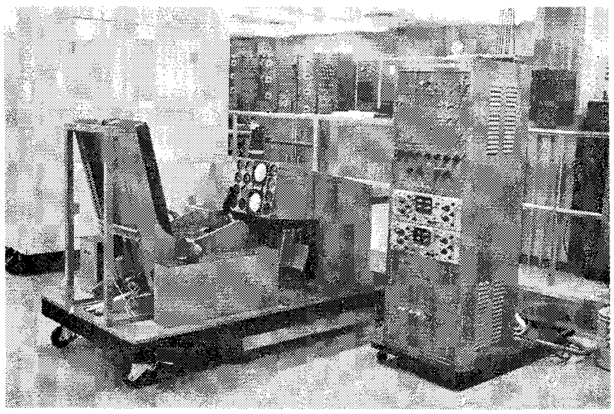

Fig. 9 X-22A analog flight simulator.

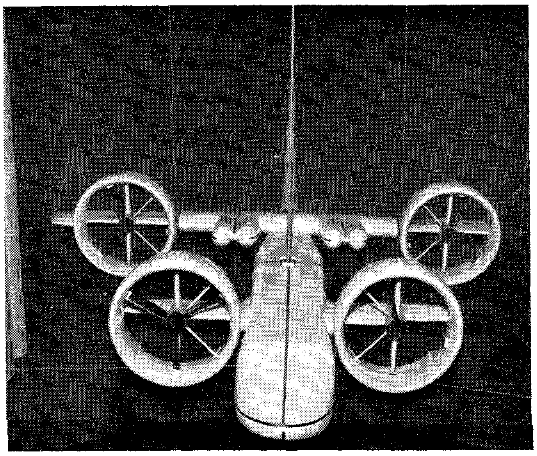

Fig. 10 One-seventh-scale aircraft flutter model.

augmentation mode, primary flight control and height control, duct rotation control and handling qualities in variable stability control, flight envelope limits, and emergency conditions. Verification of the basic design characteristics and establishment of pilot technique in operation of the X-22A will be accomplished on the simulator.

X-22A Structural Development

Airframe Description

The X-22A airframe consists, generally, of conventional sheet metal construction with extruded and machined caps on heavily loaded members and machined fittings at load concentration points. Outer coverings are cladded to provide resistance against corrosion, whereas the internal parts are made from bare sheet stock with alodine corrosion preventative treatment. Conventional sheet metal construction is used in all cases in the interest of minimizing fabrication cost and time.

Loadings are generally light and the vehicle life requirement is short; consequently, the choice of construction is based primarily on static strength. In many cases, this involves skin buckling below limit load, which might be a fatigue problem in longer life aircraft. The use of integrally stiffened machined parts is utilized where possible without weight penalty, particularly at heavy loaded points. This method of manufacture is more fatigue resistant than built-up subassemblies.

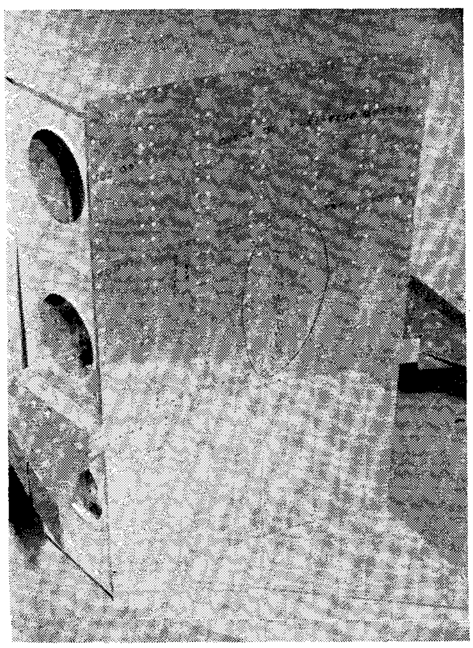

Fig. 11 Duct acoustic specimen.

As far as it is possible, fail-safe structure has been built into the design by minimizing single load path connections. Potential fatigue areas are likely to be the duct and landing gear attachments and the noise effects from the ducted propellers. Fatigue tests, however, are planned for the important areas. As described later, the acoustic tests of the duct have been completed and a satisfactory structure has been developed. Weight penalties to achieve a high fatigue life have been minimized because the aircraft is of an experimental research type with a low-life requirement of 1000 flight hours and 5000 landings.

The materials used are the conventional high-strength aircraft-grade aluminum, titanium, and steel alloys. For the design of high-strength shell elements, 7075-T6 sheet and extrusions are used. The moderate-strength shell elements utilize 2024-T3 and T4 sheet because this alloy is easier to form and dimple. The machined parts are made from forgings, bar, or extrusions of 7079-T651 aluminum alloy and 18% nickel maraging, 4330 modified, H-11, and 4340 steel alloys. For the structure in the vicinity of the engine compartment, such as the engine support beam, titanium alloys are used because temperatures are high and firewall protection is required. Built-up sections of formed sheet metal parts are made from 5AL-2.5Sn titanium, whereas fittings machined from forging or bar stock are made from 6AL-4V titanium alloy. Built-up structure of 5AL-2.5Sn is selected because of its better strength and oxidation resistance at elevated temperatures and because it is easily welded.

An unusual structural aspect is concerned with the support of the four ducts. Each duct is supported on a 12-in.-diam steel shaft supported by two bearings. Roller bearings are used and the races for the bearings are formed directly on the steel tube and in the supporting rib structures.

Structural integrity will be demonstrated by 1) static test of major airframe components; 2) drop tests of the landing gear; 3) instrumentation of the aircraft to check stress levels at critical locations; 4) fatigue testing of critical components; and 5) wind-tunnel flutter tests of a complete airplane model in which structural stiffness, mass distribution and aerodynamic characteristics are completely reproduced. In addition, element tests will be conducted of the duct support structure and rotation mechanism since the structural concepts are unique.

One-Seventh-Scale Flutter Model

Wind-tunnel flutter tests were performed on the $\frac{1}{7}$-scale X-22A complete flutter model shown in Fig. 10. No ten

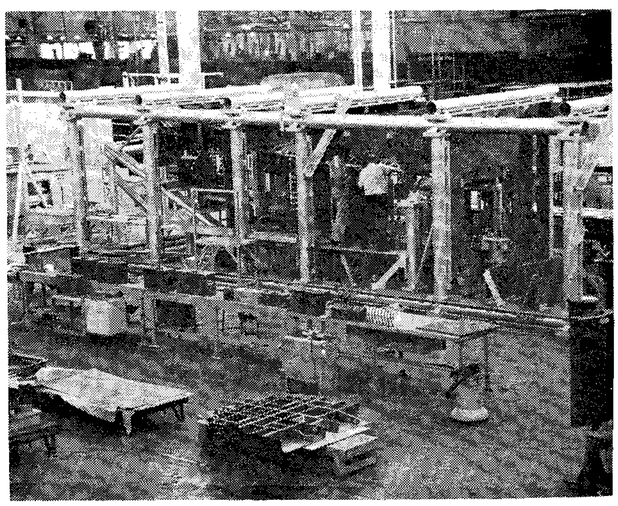

Fig. 12 Fuselage assembly.

dency toward flutter was observed over a realistic range of duct pitch and elevon rotation frequencies. Free play introduced into the duct pitch control system did not produce any buzz or instability at wind-tunnel velocities corresponding to 25% above limit dive speed of the aircraft. The effect of powering the propellers during these tests indicate no adverse effect associated with thrust.

Possible buffeting due to induced flow separation was investigated. For a maximum duct rotation angle of 30°, no buffeting was experienced through velocities corresponding to 185 knots on the aircraft.

Propeller Blade Vibratory Stresses

Large vibratory stresses in the propeller blades will occur if the aircraft is operated with the ducts in a stalled condition. An extensive analysis, using all available tunnel test data on ducted propeller units, has been conducted to determine whether duct stall could be experienced in maneuvers or in transition flight. This study indicated that it was unlikely that duct stall would be encountered in any flight condition, including the most severe landing transition.

The ducted propeller wind-tunnel program is being conducted to determine which, if any, vehicle operating conditions could produce duct stall. Propeller blade stresses at these conditions will be measured on the full-scale model to obtain data on the vibratory blade stresses and the resulting blade fatigue life. If necessary, the aircraft transition flight envelope will be restricted to exclude any conditions at which the tests indicate that the duct inlet is approaching an unacceptable stalled condition.

Duct Acoustic Specimen Tests

Several duct acoustic test specimens have been tested under accelerated conditions. A typical specimen is shown in Fig. 11. These tests are being conducted to determine a structural configuration, which will assure the required aircraft life with adequate margin for the predicted acoustic environment. This environment is based on calculations and test measurements conducted on the Navy SKMR-1 built by Bell Aerosystems and on the X-22A development test ducts. It was possible to correlate the analytical methods used for noise prediction with actual experiments (Ref. 2).

In the initial acoustic test, fatigue failures began to occur in the first several hours of test time. The results of this test emphasized the difficulties in designing a lightweight duct structure with adequate acoustic fatigue life. Redesign of the structure for increased fatigue life was considered and the use of an acoustic damping material, Aquaplas, for increasing fatigue life was also considered.

The recommended redesigns were incorporated in two

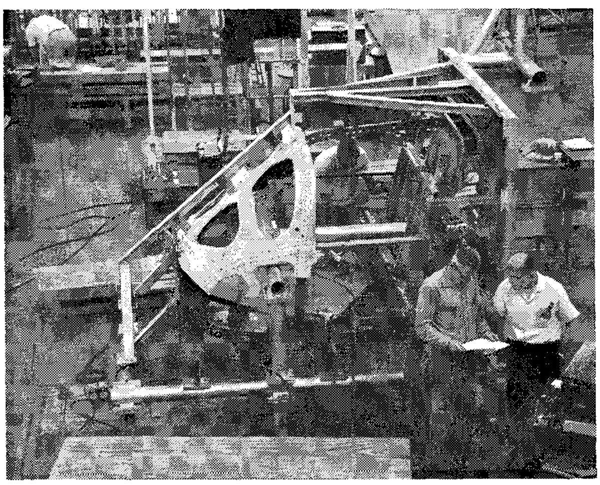

Fig. 13 Cockpit assembly.

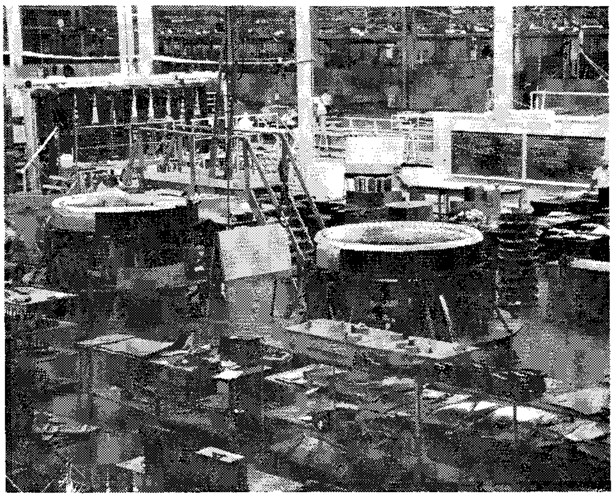

Fig. 14 Duct assembly.

specimens. The first of these with stiffened structure failed to meet the required accelerated life test.

The second modified test specimen was treated with Aquaplas, a commercially available vibration damping material. This specimen survived the required endurance testing without failure. From this test it was concluded that the duct structure adequately treated with damping material such as Aquaplas should provide fatigue resistance for the life of the structure. An additional test to determine the optimum distribution of the damping material has been completed and the design data incorporated into the duct structure.

Airframe Fabrication

Design of the X-22A airframe has been completed and fabrication of details and installation on the major assembly fixtures has been initiated. Top and bottom panel assemblies for the fuselage have been completed and they have been placed in the main fuselage fixture for final build-up and mating with the cockpit. Progress on the assembly of the fuselage is shown in Fig. 12. The cockpit assembly, shown in Fig. 13, is well advanced, and the canopies for the first aircraft have been completed. The final assembly of the ducts for the first aircraft is progressing well as shown in Fig. 14. All other major airframe components are in comparable stages of final assembly.

Cockpit Arrangement

The configuration of the components, controls, and displays for the X-22A cockpit was developed by means of functional analyses and actual evaluations using human subjects and

Fig. 15 X-22A cockpit mockup.

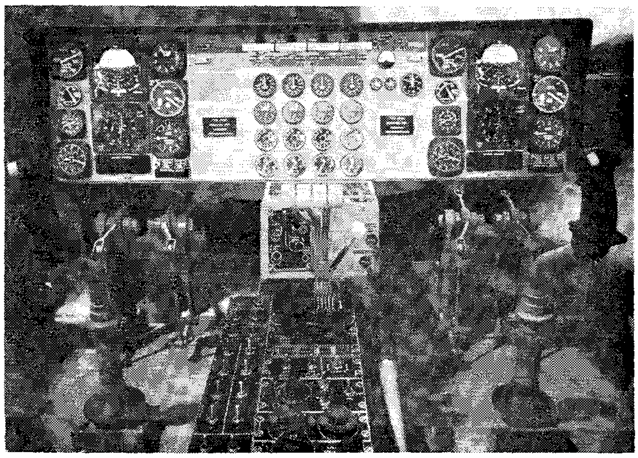

Fig. 16 Instrument panel.

simple mockups. The results of this activity and the fixed equipment installation studies culminated in the construction and inspection of the X-22A cockpit as described in Ref. 1. The formal inspection of the mockup was completed in September 1963.

The X-22A cockpit is shown in Fig. 15. Normal entrance and egress for either pilot is through an independently raised canopy. Two rocket boosted zero-zero ejection seats are installed and ejection is through the upper cast acrylic panels of the canopy. Good visibility is afforded by wide expanses of plexiglass and the cockpit geometry and instrument layout results from a melding of helicopter and aircraft specifications.

Figure 16 shows a view of the instrument panel. Identical flight groupings are provided for both pilots with a basic engine cluster centrally located. Large areas are available for installation of special flight test instrumentation.

The flight instrument groups include airspeed, altimeter, radio altimeter instantaneous rate of climb, attitude reference, situation display, and a clock. A master tachometer is installed as in helicopter practice and reads propeller revolutions per minute. This will become a major flight instrument during beta control flights but will probably be used as a monitor when power control is used in the vertical mode.

The one new instrument in the flight group is the duct angle indicator. It is mounted immediately below the airspeed indicator because of the interrelationship of duct angle with velocity. The engine instrument grouping, reading from top to bottom, are turbine revolutions per minute, torque, exhaust gas temperature, and fuel flow.

In Fig. 17, which shows the left-hand or evaluation pilot's seat, the dual throttles, propeller controls, and collective pitch levers are visible. The far left console contains a communication control panel and recording instrumentation controls. The majority of the controls are grouped in the center console readily accessible to both pilots. These are engine starting, electrical control panel, major communications, and navigation aids.

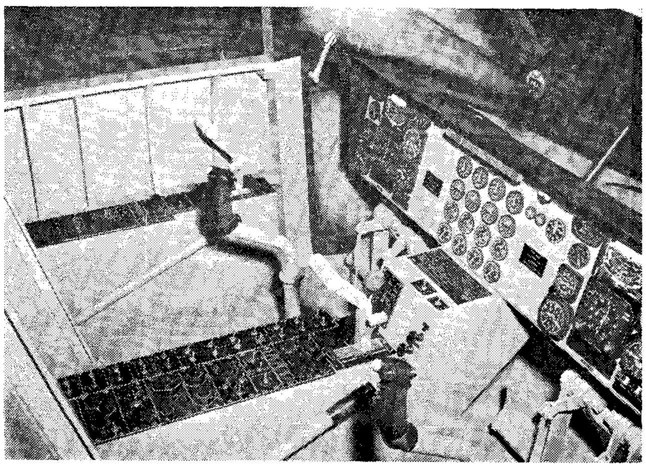

Fig. 17 Cockpit left hand seat.

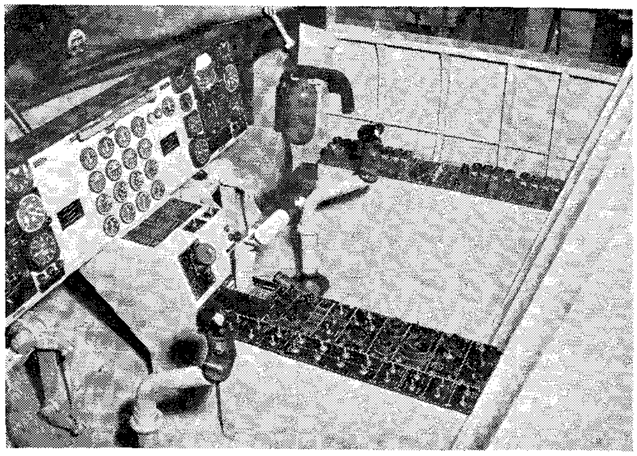

Fig. 18 Cockpit right-hand seat.

In Fig. 18, which shows the right-hand or safety pilot's station, one can see the numerous potentiometers grouped along the right console which are used for the variable stability system adjustments.

The white switches that are visible on the stick grips are the duct rotation controls. Additional controls on the sticks include force trim in roll and pitch and variable stability engage/disengage.

All circuit breakers are mounted on an overhead panel easily accessible to both pilots. The high-priority circuit breakers are at the forward end with decreasing priority aft.

Summary

The X-22A is being designed to provide an outstanding VTOL research potential. The variable stability system in conjunction with the high control power and high thrust to weight ratio will permit a thorough handling qualities research program to be conducted. In addition to exploring the full handling qualities spectrum of the X-22A aircraft, it will be possible to perform similar research on other types o VTOL aircraft by simulation of their stability and contro characteristics.

As a new aerodynamic configuration, the tandem ductec concept offers wide c.g. travels, high control power, and com pact size. The ducts are useful in both takeoff and leve flight, resulting in substantial weight savings, a high usefu load capability, and thus an ability to perform a number o important military and civil missions.

The design of the basic X-22A aircraft and all system has been completed, and the fabrication of the airframe as semblies and development of propulsion, control, and sub system components are well advanced. Rollout of the firs aircraft is scheduled for December 1964 with the second ai craft following about two months later. First flight of th X-22A is expected in the spring of 1965, flight demonstra tion will be completed, and the aircraft delivered to the tr services in mid 1966.

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