# V/STOL Development of the C-130 Hercules

T. Dansby,* W. C. J. Garrard,† D. M. Ryle,‡ and L. J. Sullivan§
*Lockheed-Georgia Company, Marietta, Ga.*

**Flight tests have established techniques required to obtain short takeoff and landing distances (STOL) for the C-130. The usable STOL performance is limited by the lateral and directional flying qualities of the airplane at low speeds. Minor modifications permit improved STOL performance and, in the STOL regime, safer and easier operation. The BLC-130, a test-bed version of which flew in 1960, incorporates blowing BLC on the flaps and control surfaces and provides further improvement in STOL performance and low-speed flying qualities. Study indicates that the C-130 can be provided with VTOL capability by the use of lift engines mounted in pods on the wings. At the midpoint of a typical assault mission the production C-130E can land on takeoff over a 50-ft obstacle in approximately 2000 ft. As the airplane is progressively modified to improve the STOL performance, the unit procurement cost of 100 airplanes increases and reaches twice that of the production C-130E at an STOL distance of 700 ft, and for VTOL midpoint performance, the unit cost exceeds the production version by two and one half times.**

## Introduction

THE continual improvement in one or more facets of performance is an important aspect of the history of any successful aircraft. For the production C-130 Hercules, this improvement has consisted of increased payload-range capability obtained by increased power and gross weight. The recent emphasis on close support or assault transport aircraft prompted study and development of C-130 growth for operation from smaller, unimproved fields. The C-130 with blowing boundary-layer control, of which a test-bed version flew in 1960, was the first successful approach to attaining STOL performance in an aircraft with a large cargo-carrying capacity. With this concept, C-130 configurations have been studied which cover the gamut of airport performance, from conventional and assault airport performance of the basic C-130 to zero field length or VTOL.

In this paper the design features and problems pertinent to the various concepts, and their relative merits from operational and cost viewpoints, are presented. Although we do not intend to give generalized results, it is believed that many aspects are applicable to the growth of other aircraft.

The developemental problems associated with V/STOL performance which were involved in the C-130 development can be summarized as follows: 1) developing the aerodynamic and propulsive characteristics necessary to achieve the desired performance (basic airframe capability); 2) establishing criteria for and providing the necessary safety margins for the operational concept (safety of flight); 3) determining and providing the control and flight characteristics that allow the pilot to realize the full airplane capability (stability and control); and 4) developing the proper flight technique compatible with the first three requirements (pilot-airframe compatibility). It is easy to neglect the latter three aspects. The result is often an unacceptable aircraft from an operational point of view.

The growth pattern of an aircraft design sometimes resembles the history of the farmer's axe! "I've used the same axe for twenty years and I've only had four new heads and six new handles in all that time." However, the versions of the C-130 presented here retain a significant portion of the original. In addition, the modified V/STOL versions retain much of the existing logistics capability.

Presented as Preprint 64-184 at the AIAA General Aviation Aircraft Design and Operations Meeting, Wichita, Kans., May 25–27, 1964.

* Group Engineer, Logistics Aircraft. Member AIAA.
† Preliminary Design Division Engineer. Member AIAA.
‡ Group Engineer, Advanced Design Aerodynamics.
§ Chief Engineering Test Pilot.

## C-130 Hercules

The C-130 Hercules was developed to meet the need for a medium-range logistics and assault transport with straight-in-truckbed height loading and airdrop capability. The general arrangement, shown in Fig. 1, is essentially the same now as it was in 1954, the year of the first flight. The original version, the C-130A, has a gross weight of 124,200 lb and is powered by four Allison T56-A-1 turboprop engines of 3750 equivalent shaft horsepower (eshp). The growth pattern that followed was the typical one of power and weight increases and additional fuel tanks. Modification to the C-130B involved installation of T56-A-7 engines of 4050 eshp, bladder fuel cells in the wing center section, and an increase in takeoff weight to 135,000 lb. The addition of wing pylon

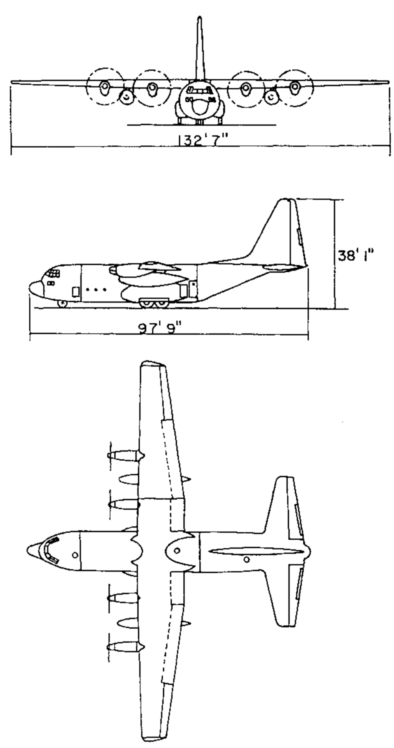



**Fig. 1 C-130E Hercules.**

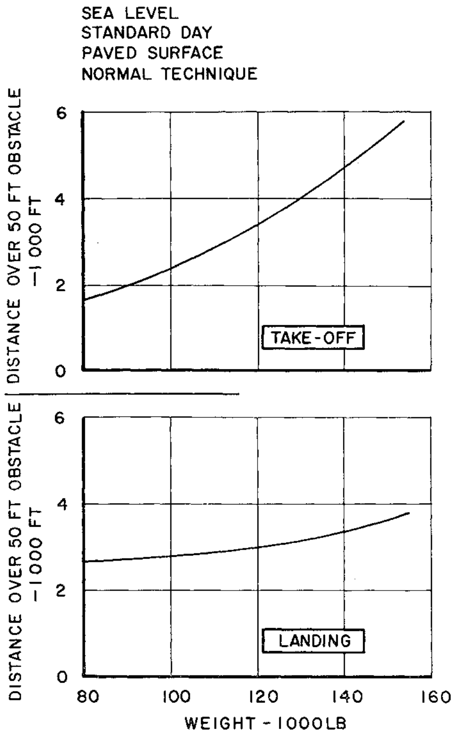



**Fig. 2 C-130 airport performance.**

mounted fuel tanks and an increase in the takeoff weight to 155,000 lb characterizes the present production C-130E version. Such growth was accompanied by equipment changes and modifications to maintain the structural integrity and fatigue life.

Throughout this growth process no particular emphasis was placed on airport performance, since the desired improvements were increases in payload-range characteristics and the available airport performance was consistent with field lengths for logistics-type transports. However, rocket-assisted takeoff (RATO) attachment points are provided so that takeoff distances can be reduced if required. The normal takeoff and landing performance of the basic C-130B is shown in Fig. 2. Speeds at the 50-ft obstacle are based on power-off stall speeds and for takeoff and landing are 120 and 128%, respectively.

For assault operations, especially in emergency or wartime conditions, a trained pilot with familiarity and confidence in his aircraft can achieve much better performance than that shown as "normal." In order to determine the possible improvements in airport performance, proper techniques, and pertinent problem areas, a test program was conducted by Air Force and Lockheed pilots.

The straightforward technique of reducing liftoff speeds to 110–115% of power-on stall speed can result in significant improvements over the "normal" technique, as shown in Fig. 3. Since these speeds are below engine-out minimum-control speeds, the acceleration capability is important and the normal pilot rightfully interprets the acceleration as a safety factor. The result is that the lighter gross weights show the greater percentage improvement. Systems such as speed control approach takeoff (SCAT), which aid the pilot in allowing a sufficient stall margin, can be of benefit especially if the rate of acceleration is low.

The landing maneuver, especially the minimum distance "spot" landing over an obstacle, is the most pilot-dependent of all phases of aircraft performance and requires the greatest degree of training. Although some reductions in speed are permissible and can result in reduced distances, the ultimate in performance results from the pilot's performing a series of functions in an exact manner. These functions must also be matched to the aircraft, recognizing its particular characteristics. Figure 4 presents a graphical comparison of a normal- and minimum-distance landing maneuver and some of the significant characteristics of the techniques.

In order to attain this performance consistently, several factors pertaining to the aircraft and its systems are important. The airspeed and rate-of-sink indications should be both accurate and sensitive at the flight conditions for minimum distance. Neither of the present standard systems is as precise as desired. Since power is normally used to adjust the rate-of-sink, it is desirable that the power-response

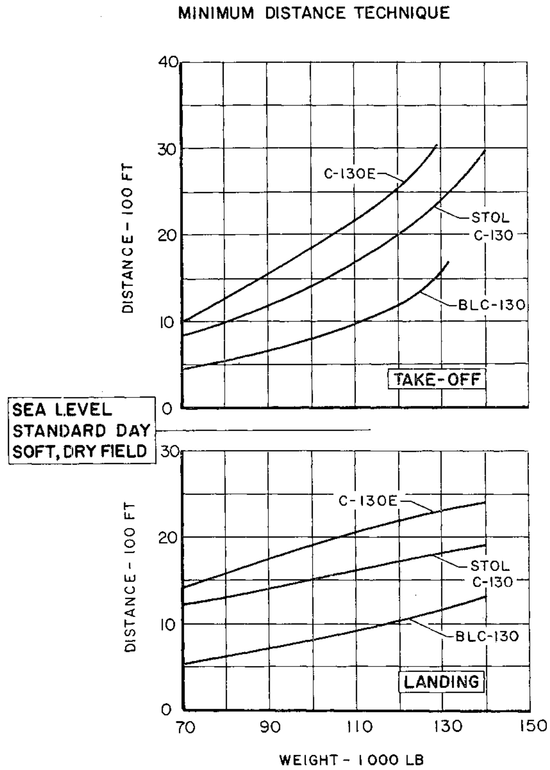
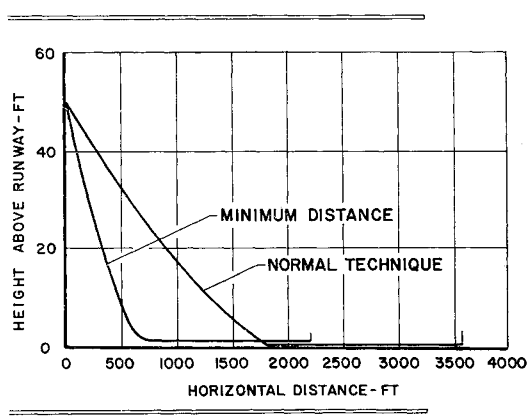



**Fig. 3 Takeoff and landing comparisons.**

- WEIGHT = 110,000 LB
- MAXIMUM REVERSE THRUST AND BRAKING ON HARD SURFACE RUNWAY
- 2 SECONDS PILOT REACTION TIME AFTER TOUCHDOWN FOR ACTUATION OF BRAKES AND REVERSE THRUST




| CONDS | NORMAL TECHNIQUE | MINIMUM DISTANCE |
|---|---|---|
| FINAL APPROACH | +1.28 VS / ++310 * | +1.2 VS / ++1000 |
| TOUCHDOWN | +1.2 VS / ++310 * | +1.15 VS / ++300 |

+ SPEED
* AVERAGE
++ RATE OF SINK FPM

**Fig. 4 Landing distance comparison.**

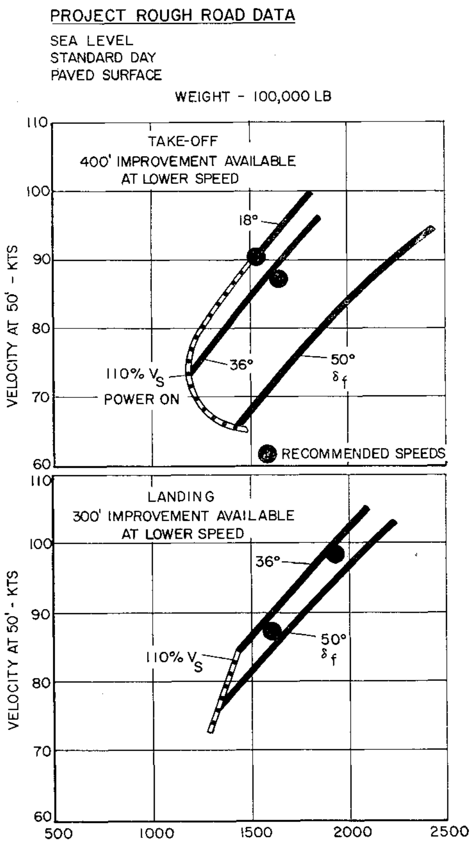



**Fig. 5 Airport performance.**

sensitivity be low in the approach range. The present arrangement tends to be too sensitive, resulting in overcorrections by the pilot. A certain amount of "flying into the ground" is mandatory for minimum air distance, but a too-hard impact can result in bounce. It is also imperative that the flying qualities and flight-control systems be such that the pilot can devote his major attention to maintaining the proper flight conditions. Excessive amounts of pedal or wheel movement either for trim or in response to gusts, sluggish reaction of the aircraft, or unnatural aircraft behavior or control system requirements (such as negative dihedral effects that require crossed controls) are not necessarily dangerous but are very distracting. All of the foregoing are evident to some degree when operating the basic C-130 at the conditions for minimum distance.

In summary, the improvement in takeoff results in reducing liftoff speeds to those consistent with a safety margin over stall based on power-on characteristcs. Landing improvements result from 1) higher rates-of-sink at approach combined with some reduction in approach speeds; 2) flare performed at the proper altitude with power reduction to allow rates-of-sink at touchdown of 300–500 fpm; 3) rapid response of pilot and systems, allowing quick application of reverse thrust and braking; and 4) instrumentation providing instantaneous precise indications of airspeed and rate-of-sink.

These techniques and performances were developed primarily for reductions of the total distance from a 50-ft obstacle. Techniques for minimum ground distances, with or without spot touchdown, would be somewhat different. For actual field operations the soil conditions significantly affect both the takeoff and landing distances. However, the effect of soil conditions appears to have a secondary effect on the actual flight techniques used.

**Table 1 Aero Recommendations I**

| Directional stability and control mods | | | |
|---|---|---|---|
| 40% rudder chord increase | | | |
| Dorsal size increased to 84 ft² | | | |
| Fail-safe yaw damper and fully powered rudder system | | | |
| Results | | | |
| | $W$ = 100,000 lb | | |
| Case | Desired | Basic | Mod |
| Min control speed, $V_{MC}$ − $KN$ | 73 | 92 | 73 |
| Sideslide angle for vert tail stall, $\beta$ | 25 | 18 | 28 |
| Directional control response, $\ddot{\psi}/F_P$ | 0.0008 | 0.0008 | 0.0008 |
| Pedal force gradient, $dPF/d\beta$ | 5.0 | 3.4 | 5.0 |

## Modified C-130 for STOL Operation

Studies have been conducted for a number of years in an effort to further improve the STOL capability of the basic C-130 through certain modifications. The results of these studies were quite promising and prompted the U. S. Air Force in 1962 to contract for a minimally modified aircraft for purposes of flight verification in a program called Rough Road. A C-130B was used to accomplish this purpose. The modifications included an increased flap deflection to 50°, more thrust through the use of a 12.54 to 1 gear box ratio, and installation of a drag parachute for landing. The aircraft was evaluated by both the Lockheed-Georgia Co. and the Air Force, and results indicated that the expected basic performance capability was available if certain restrictions or compromises were accepted with respect to safety and flying qualities.

Specific performance results based on Air Force flight-test evaluation are shown in Fig. 5, which portrays takeoff and landing performance at a gross weight of 100,000 lb at sea-level standard-day conditions on a paved runway. For a constant flap deflection it can be seen that the distance obviously decreases as the speed is reduced. However, the Air Force chose to recommend speeds represented by the dots because of the marginal flying qualities at the desired operating speed of 110% of stall. These flying qualities are represented by low roll response, insufficient directional stability, high surface deflections required for trim, crossed controls or negative dihedral effect, as well as minimum control speeds greater than 110% of power on stall speed. The principal conclusion to be derived from these results is that while the airplane performance capability exists, as represented by the dotted lines, the pilot-aircraft system is considered marginal and must operate at a higher speed in order to achieve an adequate level of safety. This higher operational speed causes an increase of approximately 400 ft in takeoff distance for 36° flap setting and 300 ft in landing for a 50° flap setting. A complete evaluation of the Air Force flight-test results of this modified aircraft and the basic C-130E has been published in Refs. 1–3.

Because of the reduced pilot-aircraft system performance, it was decided to conduct a wind-tunnel test of the STOL C-130 in order to help determine the necessary steps for correcting this situation. The first step was to obtain data on the basic C-130 configuration in the STOL flight regime. This was necessary in order to account for the effects of extremely low-speed operation and high-thrust levels. These two factors combine to produce a large value of thrust coefficient which, because of slipstream torque and velocity dependency, is responsible for adverse flying qualities at STOL speeds.

Allied with this first purpose is the objective of determining specific flow-field problems and their causes through visual flow techniques and other measures. Of equal importance is the second purpose of the wind-tunnel test, which was to determine those aspects of the problem areas which are correctable and to test modifications to determine their effectiveness as corrective measures.

As an example of the results of this wind-tunnel program, some aspects of the lateral control investigations are discussed herein. The aircraft modifications designed to improve lateral control and tested in the wind tunnel include extended aileron chord, flap eyebrow or turning vanes, spoilers, differential flap deflection, outboard-wing Krueger flaps, and outboard-wing increased leading edge radius.

A comparison of some of the various modifications is shown in Fig. 6 in terms of the bank angle attained in 2 sec for maximum aileron deflection, and the rolling acceleration per degree of wheel throw, $\ddot{\phi}/\theta_w$. The former is a measure of maximum control power and the latter respresents response or sensitivity as experienced by the pilot. These comparisons are made for the landing case with 50° of flap at a weight of 100,000 lb and a speed of approximately 75 knots. The improvement in bank angle attained in 2 sec is from 6.6° to 10° for the extended chord aileron, whereas the response is increased by 19%. The other modifications shown herein are stacked to show the incremental effect of considering each modification separately. It can be seen that the largest single improvement, with respect to both control and response, is obtained with the spoiler, which is located just forward of the outboard flap. This arrangement has the disadvantage of reducing the aircraft lift, which is, by definition, marginal at STOL speeds. The differential outboard flap is operated from a nominal position of 36° in both the landing and takeoff cases. The inboard flaps are deflected 50° for landing and 36° for takeoff. Roll control is achieved by deflecting the flap to a larger deflection on the wing, which requires raising while the opposite flap remains fixed at 36°. This nominal setting of 36°, as compared to 50° for landing, reduces the maximum lift slightly but does not result in significant landing-speed penalties. The advantage of this system is that no lift is destroyed in a roll maneuver. This flap operation must be at a rapid rate, comparable to that of a conventional aileron.

The background of analytical, flight test, and wind-tunnel results which were available made it possible to propose a C-130 STOL aircraft that satisfies the following basic goal: the aircraft must possess improved STOL performance capability when compared with the basic C-130E, and this performance must be achieved with satisfactory handling characteristics during STOL operation. These handling characteristics include minimum control speed no greater than the desired operating speed. Recognizing the development difficulties and costs associated with aircraft changes, attempts were made to find the most practical modifications to the aircraft which would accomplish this goal. The aircraft that incorporates these modifications is designated as the GL 298-10.

The first of these recommendations (see Table 1) is pertinent to directional stability and control. Recommended are a 40% increase in rudder chord, an increase in dorsal size from 27 to 84 ft$^2$, the installation of a "fail-safe" yaw damper, or stability augmentor, and a duplicated, fully powered rudder-control system. Incorporation of these modifications produces the results shown on the lower half of the figure at a weight of 100,000 lb with power effects appropriate to a speed of 75 knots, except when consideration is given to minimum-control speed. The minimum-control speed is reduced from 92 knots for the basic C-130E to 73 knots. This is for a takeoff configuration with 36° flaps with the desired speed being 110% of the power-on stall speed for sea level, hot-day (103.6°F) conditions. The sideslip angle for vertical tail stall on the present C-130 aircraft in the landing configuration is approximately 18°. This is increased to 28°, which is greater than an arbitrarily selected desirable value of 25°. Aircraft response as sensed by the pilot is shown as yawing acceleration in rad/sec$^2$/lb of pedal force $\ddot{\psi}/F_p$. With a fully powered rudder system this can be established at any value within the limitations of the system. The present airplane is regarded as satisfactory in pedal force response, and no change is proposed. Pedal force gradient expressed as pounds of pedal force per degree of sideslip can, like response, be adjusted to any desired value by virtue of the fully powered rudder system. The value of 5.0 is typical for conventional aircraft and is considered satisfactory.

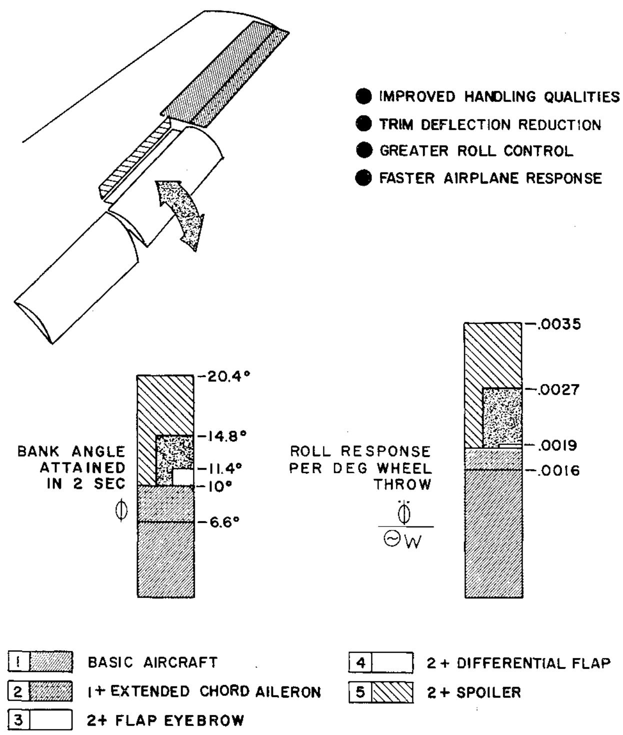



**Fig. 6 Lateral controls.**

The second set of recommendations (see Table 2) are for improving lateral control and consist of a 30% increase in aileron chord and either an outboard flap spoiler or differential outboard flaps. No specific spoiler is recommended with respect to span, although the data shown previously are for a spoiler with the same span as the outboard flap and located just forward of the flap's leading edge. Obviously, the degree of effectiveness can be varied with spoiler span to any reasonable desired level. Qualitatively, these modifications improve the pilots' capability for precise handling, reduce the amount of control deflection required for trim, and increase the capability of rolling the airplane rapidly in response to a disturbance or other upset. Specifically, at a weight of 100,000 lb, the modifications produce the results shown on Table 2. In the landing configuration the rolling acceleration per degree of wheel angle $\ddot{\phi}/\theta_w$ is increased on the basic airplane from 0.0016 to 0.0027, if differential outboard flaps are incorporated, or an upper limit of 0.0035, if spoilers are employed. The desired value, based on Lockheed pilot opinion, is that sensitivity should be increased approximately 100%

**Table 2 Aero recommendations II**

Lateral control mods

30% aileron chord increase
Outboard flap spoiler or differential outboard flaps

| Results<br>Ve-75 KN<br>Case | $W$ — 100,000 lb<br>Desired | Basic | Mod |
|---|---|---|---|
| Roll response per deg Wheel throw, $\ddot{\Phi}/\theta\omega$ | 0.003 | 0.0016 | (0.0035)<br>0.0027 |
| Bank angle attainable in 2 sec, $\Phi$ | 10° | 6.6° | (20.4)°<br>14.8° |

**Table 3 Aero recommendations III**

| Performance mods | | |
|---|---|---|
| Allison A-15 engine with 12.54:1 gear box | | |
| Increased flap deflection to 50° | | |
| Results | | |
| $W$ – 100,000 lb | S.L., hot day, soft field | |
| Case | Basic aircraft | Mod aircraft |
| Takeoff speed, keas | 73 | 73 |
| Takeoff distance, ft | 1920 | 1500 |
| Landing speed, keas | 81 | 76 |
| Landing distance, ft | 1620 | 1460 |

in the STOL regime. The bank angle attainable in 2 sec is increased well beyond the desired value of 10° for both the outboard flap spoiler or differential outboard flaps.

The last set of recommendations is associated with aircraft performance capability. These recommendations are shown in Table 3 and include incorporation of the Allison T56-A-15 engine with a $12\frac{1}{2}$ to 1 gear box ratio and increased flap deflection to 50°. The A-15 version of the T56 engine, which will be installed on certain future production versions of the C-130, incorporates an air-cooled turbine and develops 4910 eshp for takeoff. The T56-A-7 engine presently used on the C-130B and E develops 4050 eshp for takeoff and is used with a 13.54 gear box ratio. The A-15 engine and higher propeller rpm provide improved thrust during takeoff, which is especially important on hot days and soft fields. On standard day, hard-field conditions, the takeoff and landing field lengths tend to be balanced. However, increasing temperature, increasing altitude, and soft fields, or any combination thereof, tend to make the takeoff distance considerably longer than the landing distance, which is undesirable since the longest distance defines the field length. Although the increased power is not a flying quality per se, there is an inherent improvement in pilot confidence and hence pilot-aircraft system performance, due to the better capability for go-around and the increased acceleration after liftoff. However, this pilot-aircraft system improvement is not necessarily true unless the aircraft incorporates the flying qualities modifications previously recommended for high-power effects. The increased flap deflection to 50° reduces the landing speeds, improves the attitude for landing, and increases drag during landing.

In addition to these major recommendations, there are a number of other modifications to the aircraft. These include structural beef-up in the wing, landing gear, and support structure; installation of improved rate-of-sink, angle of attack, and airspeed instrumentation; use of modulating anti-skid brakes with increased energy absorption capability; and installation of a drag parachute for approach and landing. The proposed drag parachute is 22 ft in deployed diam, which, based on flight tests, permits adequate go-around capability in the event of an engine failure. The use of the chute during approach requires greater power which, because of slipstream effects, increases the power-on maximum lift coefficient. Its use also creates a higher degree of directional stability.

The results of the use of the recommended performance modifications are shown in Table 3 for sea level, hot-day, soft-field conditions. The basic aircraft is the C-130E, incorporating all of the proposed flying qualities modifications. It is emphasized that the performance shown is not valid unless these modifications are included. The basic aircraft incorporates 36° of flap for both takeoff and landing, whereas the modified aircraft uses 36° of flap for takeoff and 50° for landing. The takeoff speed is 73 knots in both cases, which is the minimum control speed as previously discussed. There is an improvement of 420 ft in takeoff distance as a result of these performance modifications. For landing, speed is reduced 5 knots because of the additional power and flap deflection, and landing distance is reduced by 160 ft. The techniques employed in developing these data are the same as those described previously for the C-130.

Perhaps the most significant conclusion to be derived from this information is that for the basic aircraft, the takeoff field length is 300 ft longer than that required for landing under hot-day, soft-field conditions. The modified aircraft takeoff and landing distances are mutually consistent at a level of approximately 1500 ft, because of the improved takeoff capability brought about by incorporation of the A-15 engine and 12.5 to 1 gear box. The unbalanced field-length situation is aggravated considerably as weight is increased above 100,000 lb.

Table 4 summarizes the benefits that accrue to the recommended STOL C-130 airplane. These benefits are shown as takeoff and landing distances for sea level, hot-day, soft-field conditions at a weight of 100,000 lb. Higher weights serve to amplify the effects shown herein. In the first column the C-130E is shown operating at the speeds recommended in the Rough Road test program. It will be remembered that these speeds were selected in order to provide reasonable flying qualities. A 2400 ft field length is required at a weight of 100,000 lb. In the next column the same performance is shown for a C-130E, incorporating only the flying qualities modifications. There is a 450-ft reduction in field length as a result of the reduced operating speed. Further, it is considered that the flying qualities at these reduced speeds of 73 and 81 knots are equivalent or better than those represented by the C-130E at 88 and 98 knots. Finally, in the last column the takeoff and landing speeds and distances are shown for an aircraft incorporating both the flying qualities and perform-

**Table 4 C-130E: summary performance—sea level, hot day, soft field; wt = 100,000 lb**

| Case | As is | With flying qualities mods | With flying qualities and performance mods |
|---|---|---|---|
| Takeoff speed, keas | 88 | 73 | 73 |
| Takeoff distance over 50, ft | 2370 | 1920 | 1500 |
| Landing speed, keas | 98 | 81 | 76 |
| Landing distance over 50, ft | 2040 | 1620 | 1460 |

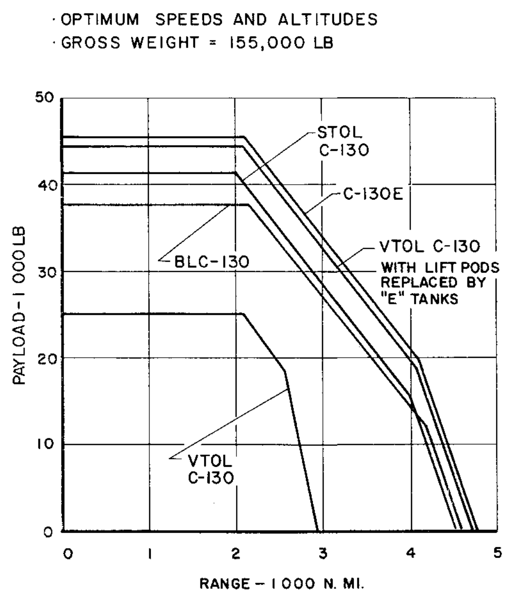



**Fig. 7 Payload-range, conventional operation.**

ance modifications. The field length is reduced approximately 400 ft in this step. A total reduction in field length of 900 ft (from approximately 2400 to 1500 ft) is achieved with the recommended airplane, as compared with that of the standard C-130E. Further, and perhaps even more important than this reduction in field length, is the fact that the gains are achieved through a safer pilot-aircraft system which is easier to operate.

The aircraft that incorporates all of the proposed recommendations is designated the GL 298-10. Its minimum-distance airport performance and payload-range capabilities are summarized in Figs. 3 and 7, respectively. The airport performance information in Fig. 3 is for sea level standard-day conditions on a soft field. The foregoing discussion has been concerned with the more critical hot-day conditions, which emphasize the desirability for performance as well as stability and control improvements.

## BLC 130

Study of the application of high-lift boundary-layer control to the C-130 started in 1955, with the object of developing a version of the airplane with very high STOL performance. The initial studies indicated that of the various possible boundary-layer control (BLC) systems, which include area suction, flap leading-edge suction, combined blowing and suction, and blowing; the latter is the most suitable for application to the C-130. In 1958 a contract was obtained from the U. S. Air Force for the development and flight test of a test-bed version of the C-130 using a blowing BLC system. The development of the test-bed BLC-130 airplane, which included a comprehensive wind-tunnel program, a simple flight simulator, and a flight-test program directed toward demonstration of the performance, is described in detail in Ref. 4. The test-bed BLC airplane first flew in 1960 and closely approached the predicted STOL performance. The airplane worked well during the flight tests; in particular, no difficulties were experienced with the main BLC ducts. During the summer of 1961 the test bed was flown on a demonstration tour in England, West Germany, Italy, and France, during which the airplane and BLC system behaved in a reliable and satisfactory manner. The test bed is now undergoing further flight tests at the NASA Ames Research Center.

Several different production versions of the BLC-130 have been proposed using separate engines, or compressors driven by the main propulsion engines, to provide the blowing flow. The latter system is technically the most efficient, and a version using this system, designated the Lockheed GL 128-17, is considered here. A cutaway view showing the arrangement of the BLC system of this design is shown on Fig. 8. The GL 128-17 is equipped with four of the proposed Allison 501-M5 turboprop engines driving Hamilton Standard four-bladed 15-ft-diam propellers. To supply the blowing flow, this engine incorporates an auxiliary axial flow compressor which is driven, through a clutch, from the propeller gear box. The installation of this engine is shown in Fig. 9.

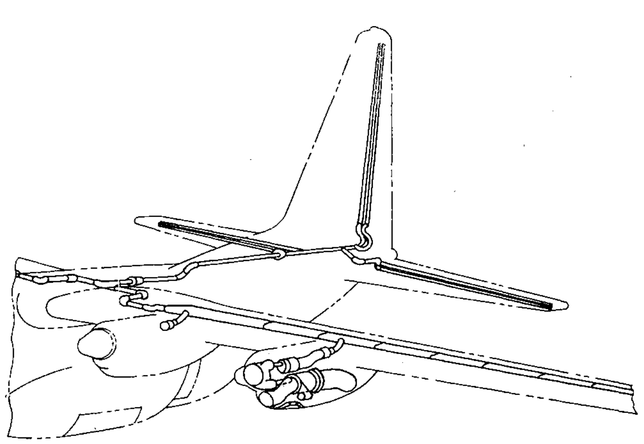


**Fig. 8 BLC-130 duct schematic.**

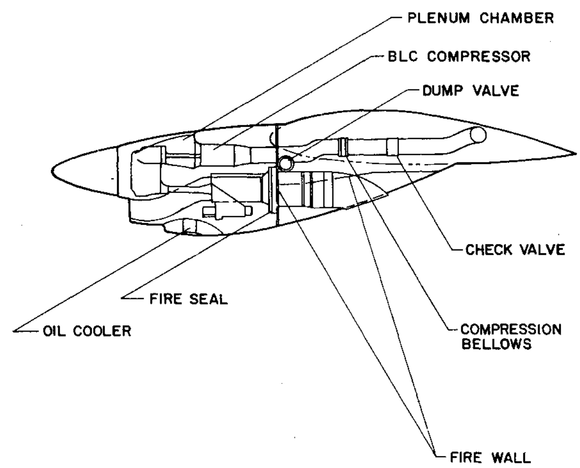



**Fig. 9 BLC-130 Allison 501-M5 engine installation.**

The nacelle is similar to that of the T56 engine in the standard C-130. For starting, and for maximum-effort landing shutoff, a dump valve is provided in the compressor outlet duct, exhausting out the side of the nacelle. A shutoff valve is also provided to prevent loss of blowing flow from the wing supply duct in the event of compressor failure.

Each compressor delivers 20 lb of air per sec at a pressure ratio of 3.8, or 41 psig. The compressor delivery is carried to the wing supply duct that extends across the wing behind the rear spar. From this duct small tubes carry the air to a continuous nozzle that extends across the span of the wing, from which the blowing flow impinges on the leading edge of the flaps and ailerons, as illustrated in Fig. 10, which shows a section of the aileron and BLC duct. Plain-hinged 25% flaps are used, with a maximum deflection of 90°. The low flight speeds possible with the blown flaps require a considerable increase in the control power about all three axes for adequate control. To obtain this, blowing BLC is used on both sides of the rudder and elevator and on the top surface of the ailerons, and the control deflections are approximately twice those of the standard C-130. The maximum control deflections are compared with those of the standard airplane on Table 5. The use of BLC on the controls prevents flow separation and loss of effectiveness at large control deflections. When the BLC system is in use, the ailerons are drooped 30° to provide a further increase in lift. This is accomplished by a

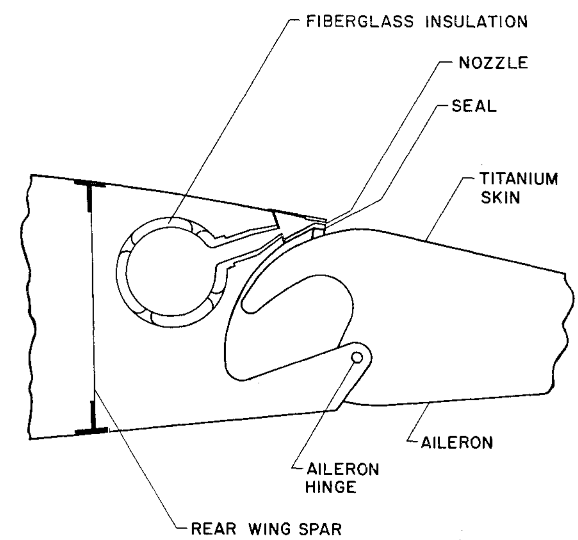



**Fig. 10 BLC duct typical section.**

combined gear ratio changer and drooping mechanism, which approximately doubles the aileron deflection per unit control wheel deflection when the ailerons are drooped. The effects of propeller slipstream and boundary-layer control flow provide erratic hinge-moments on the surfaces. Because of this, full-power duplicated control systems are used with artificial feel.

The blowing flow is carried to the empennage in a duct connected to the center of the wing supply duct. The BLC ducts are continuous, and the pressure losses are small, so that large asymmetric rolling moments do not occur in the event of failure of one engine or compressor.

At maximum power at sea level the 501-M5 engine develops 6500 shp, of which 2000 hp is absorbed by the BLC compressor when the clutch is engaged; the remaining 4500 shp drives the propeller. When the clutch is disengaged, and the BLC system is not in use, all of the power of the engine drives the propeller with a limitation of 5000 shp, which is imposed by the gear box capacity. This reduces the size and weight of the gear box, and the power limitation does not restrict the altitude cruise performance.

## Flying Qualities

### *General*

The BLC-130 can achieve flight speeds as low as 50 knots at high power with the BLC system in operation. Under these conditions the slipstream effects reduce the static longitudinal stability to neutral or slightly negative, and the dihedral effect is negative. The concept of the BLC airplane design is that at low speeds, despite the negative longitudinal and lateral stability, the airplane can be satisfactorily flown with highly effective controls. The similarity to helicopter operation is apparent and natural as the speed is reduced toward zero. The test-bed simulator and flight-test programs indicated that this concept is valid provided that the controls are light and responsive. The use of full power operation of the controls, with artificial feel, provides the light control forces, and the use of BLC on the surfaces and large deflections provides the necessary control power for adequate response. At speeds of approximately 70 knots and above, flight tests of the test-bed airplane show that the stability and control are more than adequate. Low-altitude flights with the ramp door open, simulating aerial drop capability, have been made at 70 knots with a flap deflection of 40°. Below this speed, there is a gradual deterioration of stability until the airplane stalls.

The stalls on the BLC airplane with power are characterized by wingtip stall outboard of the propeller. Because of the propeller slipstream, no significant stalling occurs over the flap. With the tip stall, a corresponding decrease in aileron effectiveness occurs. This decrease in aileron effectiveness limits the minimum speed available. The estimated stalling speed of the GL 128-17 at a gross weight of 100,000 lb at maximum power in the landing configuration with the flaps deflected 90°, ailerons drooped 30°, and the BLC system in use, is of the order of 45 knots at sea level.

**Table 5 BLC-130: control deflections**

| Case | | Standard C-130E, deg | BLC-130, deg |
|---|---|---|---|
| Flaps | Takeoff | 18 | 60 |
| | Landing | 36 | 90 |
| Ailerons | Droop | None | 30 |
| | Up | 25 | BLC30 normal 30 |
| | Down | 15 | BLC60 normal 18 |
| Elevator | Up | 40 | 50 |
| | Down | 15 | 39 |
| Rudder | Right | 35 | 60 |
| | Left | 35 | 60 |

### *Engine or compressor failure*

For the GL 128-17 the loss of one BLC compressor results in automatic operation of the shutoff valve in the compressor outlet duct so that the remaining three operating compressors are subjected to an exhaust exit area (that of the BLC nozzles) which is one-third greater than the design value.

This increases the mass flow and decreases the pressure ratio of the operating compressors. The net effect is that the blowing momentum coefficient

$$\frac{\text{mass flow} \times \text{nozzle jet velocity}}{\text{freestream dynamic pressure} \times \text{wing area affected}}$$

is reduced to approximately 65% of the four-compressor value. This reduces the wing lift slightly, because at the approach and takeoff speeds the blowing flow is well in excess of that required to prevent flow separation on the flaps, and the variation of lift with momentum coefficient is small. The effect of the reduced blowing flow on the control surfaces is negligible, since the reduced flow is adequate to prevent flow separation at maximum surface deflection at takeoff and approach speeds. For the GL 128-17 at maximum power in the landing configuration, the estimated stalling speed is increased approximately 5 knots by the failure of one BLC compressor.

The failure of an outboard engine was considered at length in the design of the BLC-130. For the GL 128-17 the loss of an engine is accompanied by the loss of one BLC compressor. As has been discussed, this involves a small increase in stall speed and no significant loss of control effectiveness. Because of the high rudder and aileron control power, the rolling and yawing moments produced by an outboard engine failure can be trimmed at very low speeds. The estimated minimum control speed at all gross weights at maximum power is of the order of 55–60 knots.

## Performance

Figure 3 shows the estimated minimum takeoff distance of the GL 128-17, with the BLC system in use, using STOL techniques that have been developed for the test-bed BLC-130 which are consistent with those of the non-BLC version. The takeoff and climb speed is the greater of the minimum-control speed or 110 % of the power on stall speed. Rotation is made using 90% of the power on $C_{L\max}$.

Figure 3 also shows the estimated minimum landing distance of the GL 128-17 with the BLC system in use, using the proposed BLC-130 STOL techniques. The approach is made at a rate-of-sink between 900 and 1200 fpm at the greater of the minimum control speed or 110% of the power on stall speed, at the power used during the approach. The high profile drag of the flaps, which are deflected 90°, the ailerons, which are drooped 30°, and the high induced drag due to the low speed, require considerable power during the approach. At the maximum landing weight of 130,000 lb, the approach power required is close to the maximum power available. The airplane is flared slightly close to the ground and strikes the ground at the approach speed at a rate-of-sink of approximately 300–500 fpm. At touchdown, the BLC system is deactivated by opening the dump valves; reverse thrust is initiated, and the brakes are applied. Based on flight tests, 2 sec of free roll are allowed after touchdown before the brakes and reverse thrust become effective.

Figure 7 shows the payload-range performance of the GL 128-17 at a gross weight of 155,000 lb. The equipped weight empty is approximately 8000 lb greater than that of the C-130E, and this has the most significant effect on the payload for long ranges. Because of the greater power, at high altitude at a given gross weight, the cruise speed is about 25 knots greater and the cruise altitude about 10,000 ft higher than the corresponding values for the standard C-130E.

## VTOL C-130

The feasibility of extending the performance of the C-130E by the addition of VTOL capability has been under examination for several years. Consideration of the various methods by which VTOL can be obtained for the C-130 indicates that the most simple and practical method is by the application of direct-lift jet engines mounted in pods on the wings. Previous studies, applying the then current lift-engine technology, indicated that the performance was not sufficient to make the application of VTOL worthwhile. Recent advances in lift-engine technology have, however, increased the thrust/weight and thrust/volume ratios of projected lift engines to levels which, when applied to the C-130 airplane, now offer usable performance capabilities.

A proposed production version of the VTOL C-130 concept offers several advantages. The airplane may be used either in the VTOL configuration or the conventional configuration without the lift pods, and it may be readily converted from one to the other. For long-range deployment the pods can be carried in the cargo compartment, together with the necessary ground-handling equipment. The estimated development cost is considerably less than that of an all-new design with the same capability, because the C-130 is a proven vehicle in the normal flight regime. It is emphasized that this aircraft is not an optimum VTOL design; it represents what can be accomplished utilizing an existing aircraft.

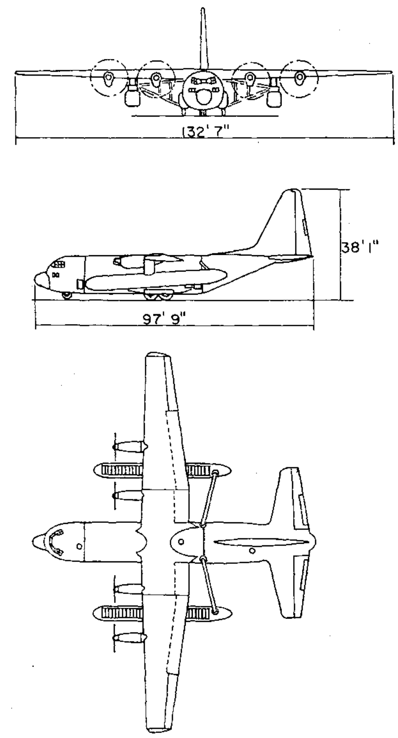



**Fig. 11 VTOL C-130.**

### Description

The proposed GL 293-11 production VTOL C-130 is basically a C-130E airplane with structural modifications, equipped with two identical and interchangeable lift pods, each containing 11 of the proposed Allison 610-D1 10,000-lb thrust turbofan lift engines, together with the systems and instrumentation necessary for their operation. The lift pods are located beneath the wing midway between the T56 engines and are attached to the wing by two struts and to the rear fuselage by two additional struts, forming an A frame. This pod support system prevents the wing loads imposed by the lift engines from exceeding the standard C-130E design loads. The general arrangement of the GL 293-11 VTOL C-130 is shown in Fig. 11. The pods are designed to be removable from the airplane and to be readily stowed within the airplane cargo compartment for deployment. The rear fairing is arranged to hinge for stowage and maintenance purposes.

In order to minimize the weight of the VTOL systems, full use is made of the systems existing in the airplane. The VTOL systems included a lift-engine air start and intake anti-icing system using bleed air from the T56-A-7 engines, a hydraulic system for the actuation of the lift-engine intake flaps and exhaust bay vanes utilizing the airplane utility system, a fire detection and extinguishing system that augments the existing airplane system, and a fuel system that requires the addition of three booster pumps to the center-section auxiliary tanks. Self-contained systems are provided in each lift engine for lubrication.

Control of the airplane in hover and transition is accomplished by lift-engine thrust modulation, for pitch and roll, and thrust vectoring by deflecting the exhaust bay vanes, for yaw. The forward and rear groups of three engines each are used to generate pitching movements, and all engines in each pod are used for roll and contribute to yaw control. The existing flight controls are directly connected to pitch, roll, and yaw coordinators through which the lift-engine thrusts are differentially modulated and vectored to obtain control about these axes.

The pilots are each provided with a collective throttle adjacent to the existing T56 power levers. Each collective throttle is servooperated using hydraulic power from duplicated systems, and it controls the thrust levels of all lift engines simultaneously.

Forward thrust during transition can be obtained by deflecting the exhaust bay vanes rearward by a servopowered twist grip mounted on the collective throttle levers. These servounits are also operated by duplicate hydraulic systems.

A single-channel limited-authority automatic stabilization system is provided in pitch, roll, and yaw. For height control a single-channel lift compensator is provided, which, operating through the collective throttle, permits VTOL operation at a preset rate of climb or descent.

Eleven Allison 610-D1 turbofan lift engines are installed in each pod, together with an induction system and exhaust system for each engine. The proposed Allison 610-D1 engine is a turbofan with an over-all pressure ratio of 6, a bypass ratio of 2.5, and a mass flow of 286 lb/sec. At the maximum thrust of 10,000 lb at sea level on a standard day, the specific fuel consumption is 0.638 lb/hr/lb. The thrust-to-weight ratio is 23.3 to 1. The induction systems comprise the intake flaps mounted on the pods, three of which are provided for each engine, and an air intake bell mouth, splitter vanes, and central dome assembly attached to the pod structure.

The exhaust bay system is composed of control vanes and a two-part operating system. Each engine exhausts through four vanes connected to a common operating system. One part of the system is actuated hydraulically and rotates the vanes 90° from the horizontal, closed position, to the vertical, open position. The second part of the system is a hydraulically powered servo-operated mechanism that allows the pilot to generate yawing moments through the rudder pedals by differential operation of the vanes in the two pods, or a forward component of thrust during transition by symmetric vane operation controlled by the collective throttle twist grips.

### Performance

#### *VTOL performance*

The design mission selected for the GL 293-11 is at a 350 naut-mile radius at sea level with the payload carried on both inbound and outbound legs. Initial takeoff and final landing are accomplished by using either the conventional or STOL technique, whereas VTOL operation is required at the midpoint. Cruise operation is consistent with an optimum speed at sea level of approximately 240 knots. Under these conditions, the design payload is 24,200 lb, as shown in Table 6.

The weight at the start of midpoint-landing transition is 132,700 lb, which is the maximum weight for which the arbitrarily selected control criteria are satisfied at sea-level pressure altitude, 103.6°F hot-day conditions. This gross weight includes fuel for 3-min VTOL operation at midpoint based on maximum thrust for all lift engines. Since the total lift capability is approximately 200,000 lb for the assumed atmospheric conditions, it is obvious that the assumption of maximum thrust represents a conservative approach. In actual operation the fuel flow depends upon control usage and is therefore somewhere between that for thrust equal to weight and that for maximum thrust. The payload-radius curve for the GL 293-11, operating under these conditions with VTOL at the midpoint, is presented in Fig. 12.

#### *Conventional performance*

The conventional performance depends upon whether the lift pods are retained or replaced by the C-130E auxiliary tanks. For the latter case, the equipped weight empty is approximately 1000 lb greater than that of the corresponding C-130E aircraft, due to permanently installed equipment and structure. A payload reduction of 1000 lb or a reduction in maximum range of 40 naut miles ensues. The conventional payload-range with lift pods installed is further reduced because of pod weight and additional aerodynamic drag. These data are shown in Fig. 7.

### Stability and Control

#### *VTOL hover control criteria*

In recent years, the Lockheed-Georgia Company, along with other companies and governmental agencies, has conducted extensive studies in an effort to establish realistic control criteria for extremely low-speed and hovering operation. These studies have resulted in a divergence of opinion in certain instances. As a consequence, the control criteria for the GL 293-6 have been arbitrarily selected as those previously established by the U. S. Air Force for an airplane of similar size and mission capability. These criteria, expressed as angular acceleration about the appropriate axis, in rad/sec$^2$, are: roll, 1.0; pitch, 0.6; and yaw, 0.5. In addition, it is further required that at least half of these values be available simultaneously about any two axes while maintaining the maximum value about the remaining axis.

**Table 6 VTOL C-130: Design mission summary[a]**

| | |
|---|---|
| Initial takeoff weight | 142,053 lb |
| Initial takeoff distance | 6600 ft |
| Radius | 350 naut miles |
| Midpoint landing weight | 132,700 lb,[b] |
| Payload, outbound and inbound | 24,200 lb |
| Average cruise speed | 230 knots |
| Average cruise altitude, ft | Sea level |
| Final landing weight | 117,610 lb |
| Final landing distance | 2880 lb |

[a] All airport operation at sea level, 103.6°F; conventional initial take-off and final landing, VTOL at Midpoint; soft-field conditions; $\mu$ = 0.10.
[b] Weight at start of landing transition, including fuel for 3-min. VTOL operation.

#### *Hover-control accelerations*

The acceleration about each axis is calculated at time zero with motion restrained about the remaining axes, which does not account for cross-coupling effects. However, these effects are relatively small, since products of inertia are small compared with polar moments of inertia at small angles of pitch.

The hover-control angular accelerations, which are shown in Figs. 13 and 14, are based on moments of inertia which include a 24,200-lb payload loaded uniformly over the length of the cargo compartment. As can be seen in Fig. 13, the desired yaw acceleration value of 0.5 rad/sec$^2$ is met or exceeded in the normal range of operating weights. The pitch and roll acceleration requirements are met at a gross weight of 132,700 lb at sea level on a 103.6°F day.

## Cost

During recent years a number of cost estimates have been prepared for normal U. S. Air Force consideration for various STOL, BLC, and VTOL versions of the C-130. Based on these studies, estimates have been prepared of the development and procurement cost of 100 production versions of the GL 298-10 STOL, the GL 128-17 BLC, and the GL 293-11 VTOL. These costs are summarized on Table 7 in terms of the present cost of the standard production C-130E. The

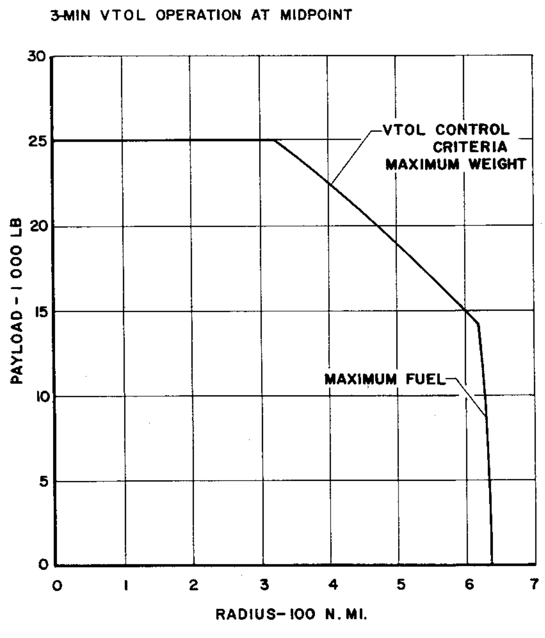



Fig. 12 VTOL C-130 payload vs radius at sea level.

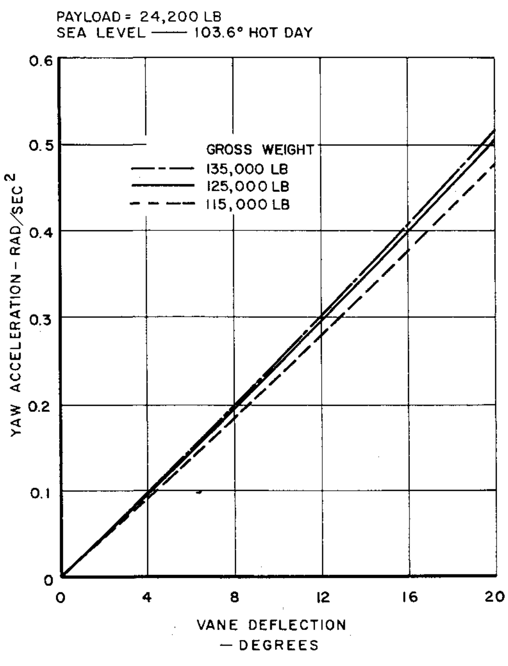



Fig. 13 VTOL C-130, yaw acceleration vs vane deflection.

costs shown are flyaway costs, including development (the prototype design and manufacture, static tests, and flight tests), airframe, engines, propellers, and equipment, and they reflect the design differences between the various versions. The assumed communications, navigation, cargo loading, and other basic equipment costs are the same for all versions. The development cost of the Allison T56-A-15 engine of the GL 298-10 is not included, because this engine is in production and will be used on a new production version of the C-130. The development cost of the Allison 501-M5 engine is included in the estimated costs for the GL 128-17, because this is a new engine specifically designed for use on this airplane. With these and other assumptions, it is believed that Table 7 shows a realistic comparison of the present relative cost of developing and procuring 100 of each of the different airplanes. When considering these costs, it is significant that the present production cost per pound of weight of the C-130E is very low since large numbers have been produced.

The GL 298-10 STOL version involves a relatively small development cost, and the unit cost is only slightly greater than that of the standard C-130E airplane. The unit cost of the GL 293-11 VTOL version approaches three times that of the standard airplane, mainly because of the cost of the lift engines.

One measure of the cost effectiveness of assault transport airplanes is the relationship between the airplane cost and the field length required on an assault mission. Figure 15 shows this relationship for the four C-130 versions discussed. The estimated unit cost of each version, based on a production run of 100, in terms of the unit cost of the standard production C-130E airplane, is plotted against the minimum field length required at the midpoint of a typical assault mission. The minimum field length is the greater of the landing or takeoff distance over a 50-ft obstacle. The chosen mission consists of the carriage of a 20,000-lb payload in both directions, for a 500-naut-mile radius. At the midpoint a sea level standard day and a soft field for which the rolling friction coefficient is 0.1, is assumed. For the VTOL C-130, conventional takeoff and landing is assumed at the base and VTOL at the midpoint, for which a total of 3 min of hover fuel is allowed.

Study has shown that for certain assault missions the VTOL C-130 is less expensive to procure and operate than a new and

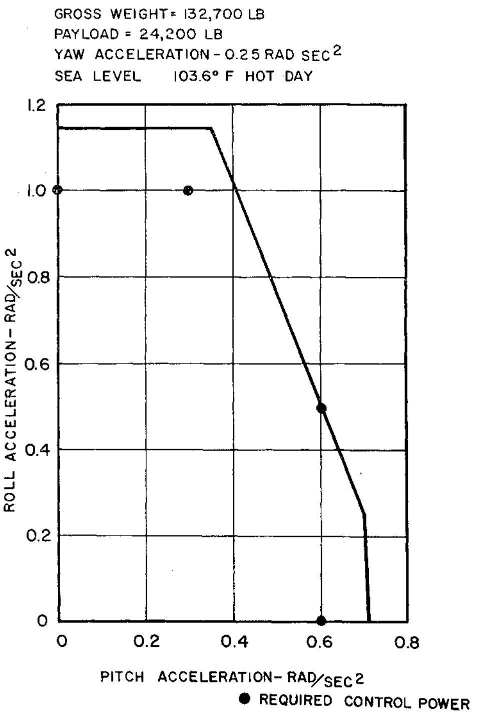



**Fig. 14 VTOL C-130 control accelerations.**

**Table 7 Cost summary: C-130 STOL and VTOL versions estimated cost 100 aircraft**

| Performance | STOL C-130 | BLC-130 | VTOL C-130 |
|---|---|---|---|
| Development | | | |
| Design | 2.63 | 10.62 | 14.35 |
| Static and flight test | 1.71 | 2.77 | 6.16 |
| Production (additional to standard C-130E) | | | |
| Tooling | 3.48 | 5.49 | 9.55 |
| Material | 2.71 | 24.57 | 123.05 |
| Labor, overhead and misc. | 6.65 | 11.89 | 15.52 |
| Standard C-130E | 100.00 | 100.00 | 100.00 |
| Unit cost, 100 aircraft[a] | 117.23 | 155.34 | 268.63 |

[a] Unit (flyaway) cost includes the airframe, engines, propellers, and equipment.

optimized VTOL transport design. This is to be expected since the C-130 airframe is presently operative. However, the differential in costs is relatively small, reflecting the inefficiency of adapting an existing airframe to VTOL operation.

## Conclusions

The C-130 was originally designed as an assault transport with a configuration ideally suited for design improvements to improve the STOL characteristics without significant sacrifice of the payload-range capability. By an increase in power and flap deflection and the use of a drag parachute for approach and landing, a significant improvement in STOL performance can be achieved. However, this improvement is of no operational value unless a corresponding improvement of the low-speed flying qualities is incorporated, which can be achieved by relatively simple modifications.

A further improvement in the STOL characteristics is most readily achieved by the use of a blowing BLC system, which, as well as reducing the takeoff and landing speeds, permits a large increase in control effectiveness, which is essential for satisfactory flying qualities at the low operating speeds.

VTOL capability can be obtained with the C-130 by the use of lift engines contained in removable pods that can be stowed in the cargo compartment for deployment. Lift-engine thrust modulation and vectoring is the only feasible low-speed control system, and this requires a high airplane thrust-to-weight ratio to permit meeting arbitrarily established control criteria.

STOL performance for the C-130 corresponds to taking off or landing over a 50-ft obstacle in less than approximately 2000, at the midpoint of a typical assault mission at sea level standard-day conditions on a soft field. As the airplane is progressively modified to obtain improved STOL performance, the unit procurement cost of 100 units increases and reaches

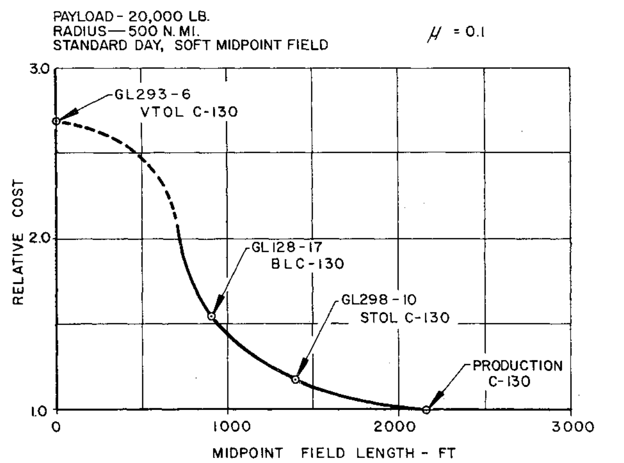



**Fig. 15 Relative cost of V/STOL capabilities.**

twice that of the standard C-130E at an STOL distance of about 700 ft on a typical assault mission. The unit cost of 100 VTOL C-130 airplanes is in excess of two and one half times that of the standard version.

The design theme emerging from these studies is that V/STOL performance for the C-130, which is a function of power, lift, and drag, is readily obtained. The achievement of adequate low-speed flying qualities presents the critical design problem, the solution of which constitutes the major portion of the design and development effort involved.

## References


[1] Hendrickson, C. L., Johnson, R. L., Loewe, W. R., and Schiele, J. S., "Phase I project rough road—an evaluation of C-130B short field take-off and landing capabilities on unprepared surfaces," Edwards Air Force Base, Calif., Tech. Documentary Rept. 62-25 (August 1962).

[2] Hendrickson, C. L., Johnson, R. L., Loewe, W. R., and Schiele, J. S., "Phase II project rough road—an evaluation of the short field take-off and landing capabilities of a modified C-130B," Edwards Air Force Base, Calif., Tech. Documentary Rept. 62-25, Supplement 1 (August 1962).

[3] Hendrickson, C. L., and Schiele, J., "Project rough road alpha take-off and landing capabilities of C-130B, JC-130B, NC-130B (BLC), C-123B, and YC-123H aircraft on off-runway (unprepared) surfaces," Edwards Air Force Base, Calif., Tech. Documentary Rept. 63-8 (April 1963).

[4] Dickerman, F. N. and Branson, C. F., "The Lockheed BLC Hercules: a practical STOL transport," Society of Automotive Engineers Paper S259 (November 1, 1960).


SEPT.-OCT. 1964 J. AIRCRAFT VOL. 1, NO. 5

# Some Problems of Design and Operation of a 250-Knot Compound Helicopter Rotor

WATSON H. TANNER* AND RUSSELL R. BERGQUIST*
*United Aircraft Corporation, Stratford, Conn.*

**A theoretical computer study revealed that a compound helicopter rotor having a value of blade twist approaching zero can be operated at speeds as high as 300 knots at sea level standard conditions. Excessive vibratory stresses and performance penalties are avoided, provided that proper design variables and operating conditions are selected. Among the most important of these are rotor lift, rotor blade twist, and rotor tip speed. The study also revealed that autorotation of the rotor of the compound helicopter is not possible in sustained forward flight without exceeding the vibratory stress limitation.**

## Nomenclature

| | |
|---|---|
| $a_1$ | = first harmonic longitudinal flapping coefficient |
| $b_1$ | = first harmonic lateral flapping coefficient |
| $D_E$ | = rotor equivalent drag |
| hp | = horsepower |
| $L$ | = lift |
| $M_{(1.0,90.)}$ | = advancing blade tip Mach number |
| $q$ | = dynamic pressure |
| $R$ | = rotor radius |
| $V$ | = forward speed |
| $V_L$ | = local velocity |
| $\alpha_c$ | = control axis angle of attack |
| $\theta_{0.75R}$ | = collective pitch at 0.75 radius |
| $\psi$ | = azimuth position |
| $\omega$ | = frequency |
| $\Omega$ | = rotor angular velocity |
| $\Omega R$ | = rotor tip speed |

## Introduction

STUDIES have shown the compound helicopter to be capable of achieving a speed of 250 knots or more, while retaining many of the low-speed advantages of the pure helicopter over high disk loading VTOL's. Among the advantages are low downwash velocity, low noise level, good low-speed handling qualities, and inherent safety in the event of total power failure. Several studies[1–6] investigated rotor behavior at high forward speeds but were restricted to aerodynamic considerations only. Earlier studies that considered the rotor's aeroelastic characteristics[7, 8] contained restricting aerodynamic assumptions.

Recently, theoretical techniques have been developed by Sikorsky Aircraft and United Aircraft Research Laboratories to account simultaneously for the aerodynamic and elastic characteristics of a rotor blade, without placing restrictions on tip speed, forward speed, or blade design characteristics. These techniques were used to study some of the design and operation problems of a single-rotor compound helicopter at a forward speed of 250 knots.

## Review of Rotor Aerodynamics

Prior to the discussion of coupled rotor aerodynamics and aeroelasticity, some of the aerodynamic considerations of a rotor will be briefly reviewed. The probable variation of rotor tip speed with forward speed is shown in Fig. 1, in which a limiting advancing tip Mach number of 0.9 has been assumed. It is useful to divide rotary winged machines into the three categories shown on the figure: moderate-performance helicopters, high-performance helicopters, and high-performance compound helicopters. Each type of machine has different rotor problems, which one can understand by looking at the rotor environment in each speed range.

The rotor environment for a typical moderate-performance helicopter is shown in Fig. 2. The forward speed is 100 knots with a tip speed of 400 knots (675 fps) giving an advance ratio (ratio of forward speed to tip speed) of 0.25. The shaded circle is the reversed velocity region where the flow is from trailing edge to leading edge. The dashed line is the distribu-

Presented as Preprint 64-195 at the AIAA General Aviation Aircraft Design and Operations Meeting, Wichita, Kans.; revision received August 19, 1964.

* Senior Research Engineer, Aircraft Advanced Research Section, Sikorsky Aircraft Division.