Aerodynamic Design Philosophy of the Boeing 737

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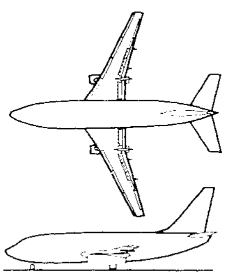
Profitable short-range and through-stop operations require excellent short runway performance. The empty weight, balance, stall characteristics, and systems advantages of wing-mounted engines dictated the engine location. The wing-nacelle geometry relationship was the major consideration in deciding to mount the nacelles so close to the wing. A strut "tailored" to accommodate the natural airflow between the wing and nacelle, and extensive testing of wing section-nacelle-strut combinations, led to a configuration with minimum wing-engine interference drag. Stall characteristics present no problems. Engine-out control is straightforward based on the Boeing "tameness" criteria. High-speed cruise at low altitude required minimum wing span and area and maximum sweep. Thus the inherent takeoff performance limitations of the twin-engine airplane required flap system efficiency and increased flap size. The 737 design incorporates a three-position leading edge and an expanding triple-slotted Fowler flap, similar to that on the 727, to eliminate all possible airfield performance limitations.

Introduction

THE 737 is a small two-engined airplane designed primarily to operate from short runways and over relatively short distances. To realize its full potential, the airplane must be able to make several short hops in and out of the small and less developed airfields without refueling. If an airfield limitation produces a takeoff weight limit for one of the hops, the operation is severely penalized because payload is limited. A landing-field-length limitation has the same effect as a takeoff-field limitation, because the following takeoff must be made at a gross weight that is less than desired. Removing all possible airfield limitations was the biggest challenge faced by the aerodynamicist in the 737 design effort.

General Arrangement

Figure 1 shows the general arrangement of the 737 and its principal characteristics. The wing has 25° of sweep, 7° less than the 727 and 10° less than the 707, and its thickness ratio is 20% greater than that of the 707 and 727 wings. This configuration was established because the basic 737 missions do not involve flight at Mach numbers as great as those of the 727 and 707. The thicker, unswept wing sufficiently relieved wing aeroelastic effects, so that an outboard aileron could be used over the entire flight regime without encountering excessive wing torsional deflections. Thus, the traditional, small, inboard ailerons as used on the 707 and 727 were not required. The entire wing leading edge incorporates slats and Krueger flaps, whereas the trailing edge has large triple-slotted flaps with extensive Fowler-type motion out to 74% span. The fuselage is as wide as the 707's and is offered in two lengths; the 737-100 is 76 in. shorter than the 737-200 shown in Fig. 1. In our opinion, the tail is completely conventional.



MAXIMUM TAKEOFF WEIGHT	85, 000 LB*
OPERATING WEIGHT EMPTY	52, 000 LB
MAXIMUM LANDING WEIGHT	85, 000 LB*
WING AREA	980 FT^2
WING SPAN	93 FT
SWEEP	25
ASPECT RATIO	8. 8

*HIGHER OPTIONS AVAILABLE

Fig. 1 General arrangement.

Probably the most often asked question regarding the 737 is: "Why did Boeing decide to install the engines on the wing, while the 727 and other commercial airplanes designed in the past few years have aft-mounted engines and T-tails?" A number of very favorable technical reasons for mounting engines on the wing are: greater structural efficiency and therefore less weight, good stall characteristics, more passengers for the same length, eye level maintainence, and good balance characteristics. Many of these reasons also could apply to the 727. Considering, however, that three engines are required on the 727 for performance and economic reasons, and that one engine had to be placed on the centerline to preserve symmetry, the best over-all compromise was to group the three engines together on the aft body. With an even number of engines, however, the benefits first given clearly dictate the use of wing-mounted engines for the 737.

High-Speed Configuration

Although the 737 is not designed to fly at Mach numbers as high as the 727 or 707, the compressibility effects on the wing-engine combination required careful consideration. Experience obtained during the development of the 707 airplane indicated that tucking the nacelles in closely under the wing created unfavorable interference effects resulting in shocks and high drag at high Mach numbers. The pressure coeffi-

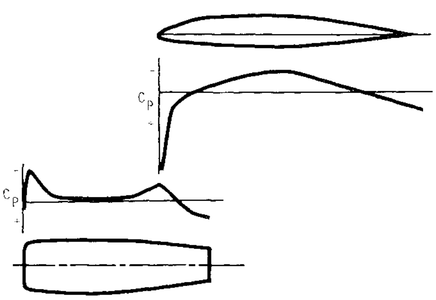


Fig. 2 707 geometry relationship.

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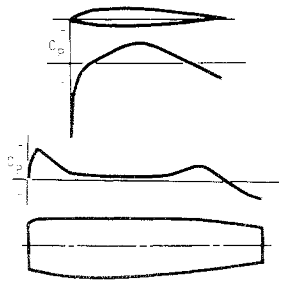

Fig. 3 737 geometry relationship.

cient distribution of a typical nacelle and of the lower surface of a 707 airfoil section are shown in Fig. 2. It is apparent that if an engine the size of the 707's were located in the proximity of a 707 airfoil section with the front or aft portions of the nacelle positioned close to the wing, pressure peaks (high local velocities) would be additive. Therefore, it was necessary to mount the 707 engines on struts in front of the wing so that the pressure fields were somewhat independent. However, the 737 nacelle is so large relative to the airfoil section that closely joining the two seemed feasible, provided that the wing section could fit between the front and rear pressure peaks of the nacelle as shown in Fig. 3. This was the major consideration of nacelle placement, although the lower design Mach number and the reduced wing sweep also contributed to the feasibility of mounting the nacelles so close to the wing.

This wing-nacelle arrangement did require an optimum strut design to accommodate the resulting airflow pattern. The strut section centerlines or the centerline surface is not planar but is a curved surface developed to accommodate the natural airflow with minimum interference. In Fig. 4, the plan view of a strut section midway between the nacelle and wing shows how the meanline of this section is "tailored" to follow a natural streamline, the forward portion being swept inboard and the aft portion being swept outboard. In addition to the "strut tailoring," the forward portion of the nacelle cowling was turned inboard 4° to further accommodate the airflow, particularly for takeoff and climb conditions and for long-range cruise conditions. The leading edge of the strut is well rounded to accept large variations in airflow direction which occur at various aircraft angles of attack.

Many thickness variations for the strut were tested in the wind tunnel, and the most desirable shape for high speed proved to be a relatively thick one that filled the narrow channels that were formed between the wing and the top of the nacelle, particularly on the outboard side. A large strut thickness at the trailing edge of the wing also proved desirable. This aerodynamically desirable shape was very advantageous, since the flap support structure and operating mechanism for the inboard flap could be housed in this strut area. Also, the large strut thickness near the forward portion of the engine provided space for engine controls and bleed ducts.

Originally, span arrangement of the airfoil sections of the 737 wing was planned to be very similar to that of the 707 and 727, simply utilizing somewhat thicker sections. However, a substantial improvement in drag at high Mach numbers was achieved by altering these sections near the nacelle. The results of altering and testing approximately 50 configurations of the wing, nacelle, and strut combinations in an

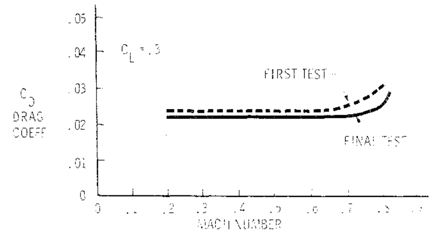

Fig. 5 Drag improvement.

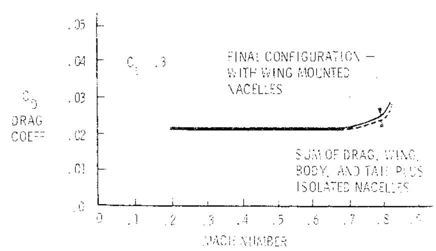

Fig. 6 Nacelle drag.

attempt to satisfy both mechanical and aerodynamic requirements are shown in Fig. 5. The change from the first to the final configuration shows that a lot of testing and trying can pay large dividends. Figure 6 compares the drag of the final airplane configuration with a synthesized drag curve that represents the sum of the drag of the wing, body, and tail plus the drag of nacelles tested under isolated conditions. The interference drag of these wing-mounted nacelles is very small. The high-speed development of the other portions of the airplane was very conventional.

Stability and Control

With the 737 configuration, the center of gravity of the empty airplane coincides very closely to the centroid of the passenger compartment and the centroid of the fuel system. A center of gravity range from 15–35% mean aerodynamic chord (MAC) is expected to cover typical loading conditions, despite the relatively large 737 body and small MAC.

With the engines on the wing, it is possible to mount the horizontal tail on the aft fuselage and completely avoid the deep stall problem. The tail is below the wing wake during stalls and produces a strong recovery pitching moment. Figure 7 shows the flaps-up pitching-moment curve obtained from wind-tunnel tests of the 737. The stable break above angles of attack for maximum lift (approximately 16°) is a good indication that the tail is very effective during stall recovery, and that it is well clear of adverse influences of the wings and engines. Stall characteristics are expected to be entirely conventional, making it unnecessary to use fences or "stick pushers". The nacelles actually have a favorable effect in controlling the stall pattern at high angles of attack.

Designing for engine-out control for the 737 was similar to that for a four-engined aircraft. However, with only one

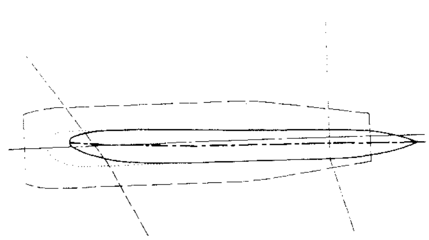

Fig. 4 Nacelle strut contour.

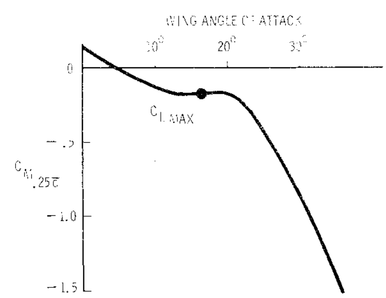

Fig. 7 Pitching-moment characteristics, flaps up.

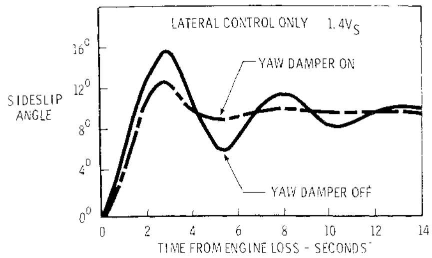

Fig. 8 Asymmetric power, wing-mounted engines.

engine per wing, it is possible to mount the engines well inboard. In fact, the 737 engines are located only 6 ft further from the fuselage centerline than those of the 727.

The size of the vertical tail surface was actually established using the "tameness" criteria adopted at Boeing during the early phases of the 707 program. These criteria require sufficient directional stability to limit the sideslip developed in the event of a sudden engine failure at low speed, so that the airplane can maintain heading using the lateral control system alone, i.e., without any rudder input. Figure 8 shows the results from simulator studies based on the previous criteria,

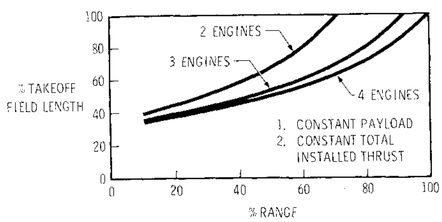

Fig. 9 Effect of number of engines.

with and without the use of a yaw damper. The airplane will achieve a steady sideslip condition of approximately 10° with considerably less swinging if the yaw damper is engaged. Although this condition is not expected to be encountered in normal flight, this basic design capability will provide a degree of "tameness" that should relieve concern regarding engine-out control of an airplane such as the 737 with wing-mounted engines.

In addition, the large fin provides very good Dutch roll-damping. An electronic yaw damper will be provided, but it is considered to be a "ride smoother" rather than a stability augmenter; we intend to certify the airplane without it. The yaw damper is a series type that adds an incremental rudder motion without moving the rudder pedals. The yaw damper can operate continually without interfering with the pilot's pedal operation.

Landing Configuration

In designing to avoid airfield landing restrictions, the 737 design borrows heavily from the 727 design. Operational experience convinces us that the 737 landing-field length and approach-speed performance must match that of the 727.

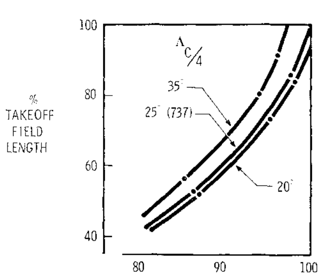

Fig. 10 Effect of sweep.

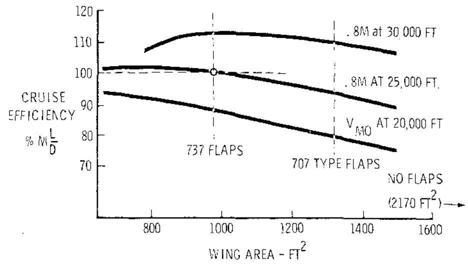

Fig. 11 Cruise efficiency.

Reduced wing sweep and increased relative flap size will give the 737 a landing stall lift coefficient of 3.1, compared to 2.9 on the 727. The design of the 737 landing flap was fairly straightforward in view of the 727 experience and will not be described in detail.

Two Engine Takeoff Problem

The two-engine design formula was quickly chosen for the 737 based on strong economic reasons. In attempting to remove all airfield takeoff limitations, the 737 design aerodynamicists then had to solve the takeoff problem inherent with a two-engine airplane—that the loss of one engine at takeoff produces a 50% loss of total installed aircraft thrust. This fundamental effect is shown in Fig. 9 where the range (or gross weight) capability from a given takeoff field length is given as a function of the number of engines. Total installed thrust, payload, and airframe are constant. Other parameters being equal, the range of the two-engine airplane is only 60–70% that of the four-engine airplane.

Takeoff Design Considerations

One of the basic tools used by the aerodynamicist to solve the two-engine take-off problem is wing span. Increased wing span reduces the induced drag, so that a greater takeoff flap angle may be used before a climb limit is encountered. The wing span has a great effect on weight empty, however, and must be chosen with care. In addition, on a low-altitude high-speed airplane, rough air ride comfort must be considered.

Wing sweep has an effect on takeoff performance as shown in Fig. 10. These data are empirical. However, the effect involves both induced and parasitic drag: the flap angle must be increased as sweep is increased to produce the same lift. Fortunately, the 737 cruise Mach number does not require more than the 25° of sweep chosen. However, the sweep could not have been much less than 25° without compromising cruise speed, increasing wing weight, or affecting ride comfort.

Wing area has a first-order effect on takeoff and landing performance. In the design of a long-range airplane, it is usually possible to exploit the cruise capability of any wing area needed for landing or takeoff by increasing cruise altitude until the airplane cruises near maximum lift/drag (L/D). However, in the short-range airplane, designed to fly at

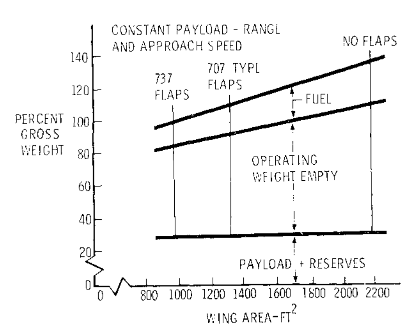

Fig. 12 Gross weight required.

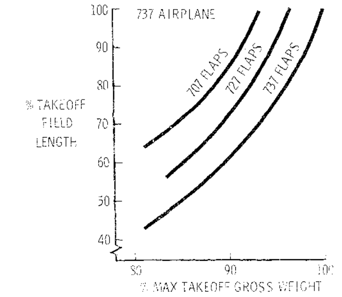

Fig. 13 Effect of flap technology.

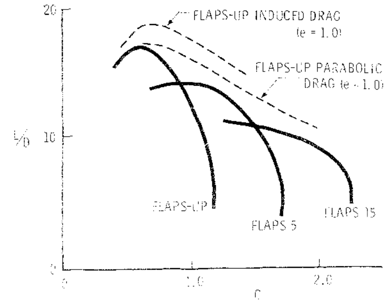

Fig. 15 Takeoff aerodynamics, potential.

placard speed at low altitude, excessive wing area is a penalty both in cruise drag and weight empty. In Fig. 11, the effect of wing area on cruise efficiency is shown for several cruise conditions. The wing areas required to match the 737 takeoff and landing performance using 707-type flaps and with no flaps are indicated. Figure 12 gives the results of an airplane configuration study based on trading flap technology for wing area, where the effect of weight empty is included, with the requirement that the airplane must cruise at 0.8 Mach at 25,000 ft. For a short-range airplane, the disadvantages of too much wing area are obvious.

The most fruitful method for the design aerodynamicist to overcome the takeoff limitations of the two-engine airplane is to improve flap system technology. The effect of flap technology advances is shown in Fig. 13, where 707, 727, and 737 flaps are compared, with wing area constant. By increasing flap system performance, the whole airplane design is improved, wing area and span can be held to a minimum, and maximum wing sweep can be maintained for cruise. All these factors have a favorable effect on airplane weight empty. The following sections describe the means by which these performance and airplane improvements were obtained.

Flap System Technology

The fundamental goal of flap system design is to maintain the highest possible L/D ratio at the highest possible lift coefficient, as illustrated in Fig. 14 where progress in flap system technology lies upward and to the right.

Flap system technology progress can be measured relative to theoretical limits. Obviously, if a clean flaps-up wing did not stall, a flap system would not be needed, except perhaps to reduce nose-up attitude (more correctly, angle of attack) in low-speed flight. The ultimate in L/D ratio is obtained when total drag (C_D) is equal only to minimum parasitic drag (C_{D_0}) plus induced drag [$C_{D_i} = C_L^2/(\pi AR)$], where AR is aspect ratio. This theoretical case in which the span loading is elliptical (span efficiency, $e = 1.0$) is shown in Fig. 15. Assuming a good cruise design, a typical span efficiency is approximately $e = 0.85$. This curve, labeled "flaps-up parabolic drag ($e < 1.0$)" in Fig. 15, is a practical reference and will be included on succeeding plots. Notice that the flaps-up polar begins to deviate from the parabolic line at a lift coefficient (C_L) just above that for maximum L/D ratio. This results as the boundary layer thickens and separation or stalling begins. Typically, as flaps are extended, each flap angle is best over a fairly narrow range of C_L. In addition, the flaps-down polars do not reach the parabolic drag reference at any point. This is because a certain amount of parasitic drag is created when the flaps are extended and flap span is less than full wing span, creating additional induced drag.

The flap system functions to: 1) increase effective wing area, 2) create camber that produces lift at constant angle of attack, 3) provide leading-edge camber to help prevent leading-edge stall, and 4) provide boundary-layer control through slots.

Figure 16 illustrates the theoretical effect of a Fowler flap extended straight aft without angular motion, increasing the effective wing area. Figure 17 gives the area increases available from using a plain or aileron type of flap, a circular motion flap similar to that on a 707, and a 737 flap. The large increase in area for the 737-type flap is the sum of: 1) aft motion of the entire flap, 2) aft motion of the main flap from the fore flap, and 3) motion of the aft or auxiliary flap. The leading-edge devices also contribute additional wing area. The area-increasing feature also contributes directly to the camber in that flap chord is thereby increased, producing more lift at constant angle of attack. In addition, the resulting large radius of curvature makes the boundary-layer control task of the slots easier.

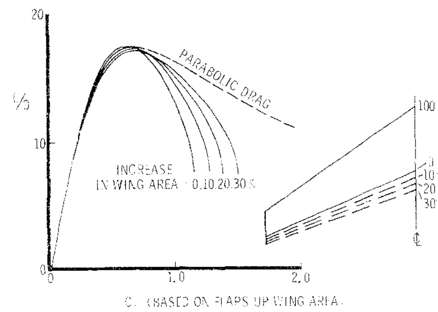

Fig. 16 Theoretical effect of Fowler action.

Returning to the general consideration of takeoff aerodynamics, Fig. 18 shows a complete set of polars for a specific flap system. The flaps-up parabolic drag ($e < 1.0$) is shown

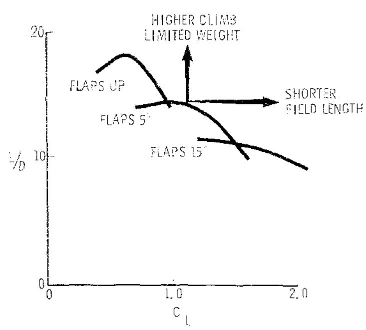

Fig. 14 Takeoff aerodynamics.

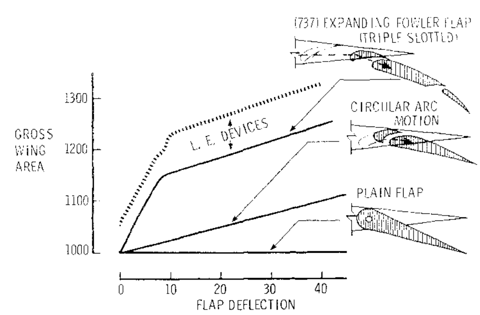

Fig. 17 Wing area increase from flaps.

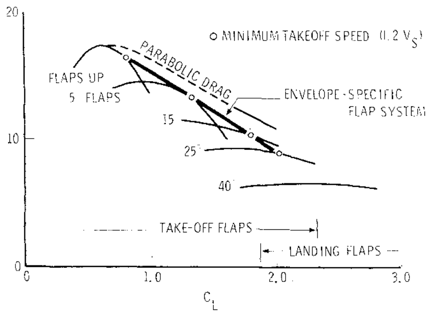

Fig. 18 Takeoff aerodynamics, polar envelope.

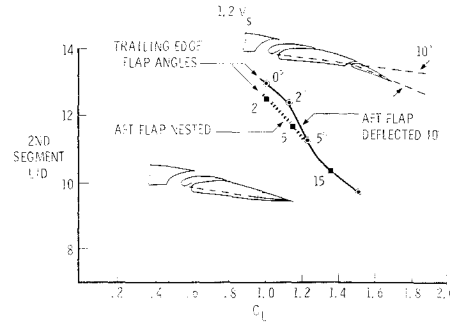

Fig. 21 Effect of aft flap deflection, 727 flight test results.

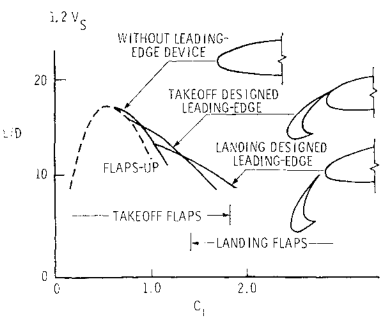

Fig. 19 Polar envelopes, effect of leading edge, 737 trailing-edge flaps.

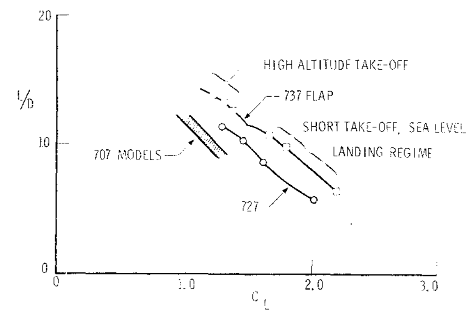

Fig. 22 Polar envelopes, airplane comparison.

for reference. The minimum takeoff speed points ($1.2V_S$) for each takeoff flap angle are indicated on the curves. The envelope or locus formed by connecting these points summarizes the characteristics of a particular flap system and is useful in comparing one flap system with another.

Leading-Edge Devices

The optimum trailing-edge configuration varies depending on the lift coefficient or airspeed range over which it is intended to be used. In much the same fashion, the leading edge of the wing must match the trailing-edge configuration. The same leading edge is not optimum for cruise, takeoff, and landing. The Boeing philosophy is to design the basic wing airfoils for the cruise condition. Changes in leading-edge geometry are then made for landing and takeoff by means of leading-edge slats or flaps. These changes are made as radical as necessary to accommodate the loading induced by the trailing-edge flaps.

737 Flap System

The polar envelopes attained using three types of leading-edge treatments with the 737's trailing-edge flap are shown in Fig. 19 with the simple flaps-up polar for reference. The trailing-edge flap angle varies along each envelope since these are loci of 1.2 V_S points. Depending on the range of C_L considered, one configuration is superior to the others by more than one unit of L/D. For the 737, one unit of L/D is equivalent to 5000 lb of climb-limited takeoff weight which is equivalent to 25 passengers or 400 miles of range. Takeoff weight from a given field length is improved by about 2500 lb. These gains are too great to be ignored. The high L/D, low C_L part of the takeoff envelope is utilized for high-altitude airports. Takeoff speeds are high, and drag during the takeoff run is a factor to be considered. Fortunately, the same flap configurations that produce high L/D at low C_L also reduce ground-roll drag.

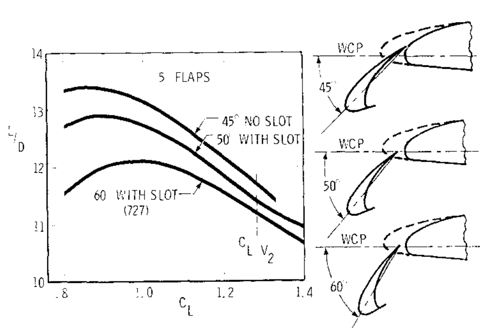

Fig. 20 Effect of slat position, 727 flight test results.

The 737 will incorporate a three-position leading-edge device very similar to that shown in Fig. 19. Starting at the cruise position (flaps-up), the device extends to approximately the takeoff position shown at the first trailing-edge flap detent. The device remains in this position until about 10° of trailing-edge flap, when it moves to the full-down position, becoming a slat. Thus, the best available performance is obtained for cruise, takeoff, and landing. Before committing to this feature, a 727 flight test was conducted to verify the 737 wind-tunnel tests. These results (Fig. 20) checked very closely with the wind-tunnel data. An additional 737 flap innovation, flight tested on the 727, is shown in Fig. 21. At small trailing-edge angles (0–5°), deflecting the aft flap segment immediately to about 10° increases the polar envelope L/D.

The 737 design incorporates several takeoff flap system advances over the 727. The 737 landing system is essentially the same as the 727, but has performance improvement from sweep and span effects. Figure 22 compares the airfield performance of Boeing transport airplanes on a polar envelope (1.2 V_S) basis. The portions of the envelope applicable to various airfield problems are indicated. Small portions of the differences between airplanes are attributable to relative span, sweep, and fuselage size. Once flap-system technology was improved as much as possible, the 737 wing area and span were chosen so as to remove all possible airfield performance problems.