BLENDED WINGLETS

FOR IMPROVED AIRPLANE PERFORMANCE

New blended winglets on the Boeing Business Jet and the 737-800 commercial airplane offer operational benefits to customers. Besides giving the airplanes a distinctive appearance, the winglets create more efficient flight characteristics in cruise and during takeoff and climbout, which translate into additional range with the same fuel and payload.

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TECHNOLOGY/PRODUCT DEVELOPMENT

Boeing offers blended winglets — upward-swept extensions to airplane wings — as standard equipment on its Boeing Business Jet (BBJ) and as optional equipment on its 737-800 commercial airplane. Winglets also are available for retrofit on in-service airplanes. The 8-ft, carbon graphite winglets allow an airplane to extend its range, carry as much as 6,000 lb more payload from takeoff-limited airports, and save on fuel.

Understanding the benefits of blended winglets requires knowledge of the following:

1. Aerodynamics of winglets.
2. Structural design considerations.
3. Design and testing.
4. Retrofit and maintenance.

BBJ TECHNICAL CHARACTERISTICS

Passengers	Not applicable
Cargo	Not applicable
Engines	CFM56-7
Maximum thrust	27,300 lb (12,394 kg)
Maximum fuel capacity	
BBJ	10,695 U.S. gal (40,480 L)
BBJ 2	10,443 U.S. gal (39,525 L)
Maximum takeoff weight	
BBJ	171,000 lb (77,565 kg)
BBJ 2	174,200 lb (79,015 kg)
Maximum range	
BBJ	6,200 nmi (11,480 km)
BBJ 2	5,750 nmi (10,650 km)
Cruise speed at 35,000 ft	0.785 Mach (530 mi/h)
Basic dimensions	
Wingspan (with winglets)	117 ft 5 in (35.79 m)
Overall length	
BBJ	110 ft 4 in (33.63 m)
BBJ 2	129 ft 6 in (39.48 m)
Tail height	41 ft 2 in (12.55 m)
Interior cabin width	11 ft 7 in (3.53 m)

The Boeing Business Jet (BBJ) was launched in 1996 as a joint venture between Boeing and General Electric. Designed for corporate and individual use, the BBJ is a high-performance derivative of the 737-700 commercial airplane. The BBJ marries the 737-700 fuselage with the stronger wing and gear of the 737-800 commercial airplane. A second version of the BBJ, called BBJ 2, was launched in 1999. Based on the 737-800 commercial airplane, the BBJ 2 has 25 percent more cabin space and twice the cargo space of the BBJ. Both provide the highest levels of space, comfort, and utility. BBJ customers are individuals, corporations, governments, armed forces, and heads of state.

1 AERODYNAMICS OF WINGLETS

From an engineering point of view — and ultimately that of mission capability and operating economics — the main purpose and direct benefit of winglets are reduced airplane drag.

Winglets affect the part of drag called induced drag. As air is deflected by the lift of the wing, the total lift vector tilts back. The aft component of this lift vector is the induced drag (fig. 1). The magnitude of the induced drag is determined by the spanwise distribution of vortices shed downstream of the wing trailing edge (TE), which is related in turn to the spanwise lift distribution. Induced drag can be reduced by increasing the horizontal span or the vertical height of the lifting system (i.e., increasing the length of the TE that sheds the vortices). The winglets increase the spread of the vortices along the TE, creating more lift at the wingtips (figs. 2 and 3). The result is a reduction in induced drag (fig. 4). The maximum benefit of the induced drag reduction depends on the spanwise lift distribution on the wing. Theoretically, for a planar wing, induced drag is optimized with an elliptical lift distribution that minimizes the change in vorticity along the span. For the same amount of structural material, nonplanar wingtip devices can achieve a similar induced drag benefit as a planar span increase; however, new Boeing airplane designs focus on minimizing induced drag with wingspan influenced by additional design benefits.

On derivative airplanes, performance can be improved by using wingtip devices to reduce induced drag (see “Wingtip Devices” on p. 30). Selection of the wingtip device depends on the specific situation and the airplane model.

An important consideration when designing the wingtip device for the BBJ was that it could be retrofitted on BBJs already in service. A blended winglet configuration (patented and designed by Dr. L. B. Gratzer of Aviation Partners, Inc., Seattle, Washington) was selected because it required fewer changes to the wing structure. The aerodynamic advantage of a blended winglet is in the transition from the existing wingtip to the vertical winglet. The blended winglet allows for the chord distribution to change smoothly from the wingtip to the winglet, which optimizes the distribution of the span load lift and minimizes any aerodynamic interference or airflow separation.

2 STRUCTURAL DESIGN CONSIDERATIONS

The aerodynamic benefits of a winglet application are determined in part by the extent of the wing modifications made to accommodate the winglet. This especially is the case when an airplane model has been designed and certified without winglets. The magnitude of the

737-800 TECHNICAL CHARACTERISTICS

Passengers	
3-class configuration	Not applicable
2-class configuration	162
1-class configuration	189
Cargo	1,555 ft^3 (44 m^3)
Engines	CFM56-7
Maximum thrust	27,300 lb (12,394 kg)
Maximum fuel capacity	6,875 U.S. gal (26,035 L)
Maximum takeoff weight	174,200 lb (79,015 kg)
Maximum range	3,383 statute mi (5,449 km)
Cruise speed at 35,000 ft	0.785 Mach (530 mi/h)
Basic dimensions	
Wingspan (with winglets)	117 ft 5 in (35.79 m)
Overall length	129 ft 6 in (39.48 m)
Tail height	41 ft 2 in (12.55 m)
Interior cabin width	11 ft 7 in (3.53 m)

The 737-800 commercial airplane is one of four 737s introduced in the late 1990s for short- to medium-range commercial airline operations. Demonstrating exceptional flexibility in size and mission, the four models — 737-600/-700/-800/-900 — essentially are four sizes of the same airplane. Two convertible models are available for conversion to an all-freighter configuration. All the new 737s can fly high-frequency, high-utilization flights as well as transcontinental and extended-range twin-engine operation missions.

FIGURE 1 INDUCED DRAG

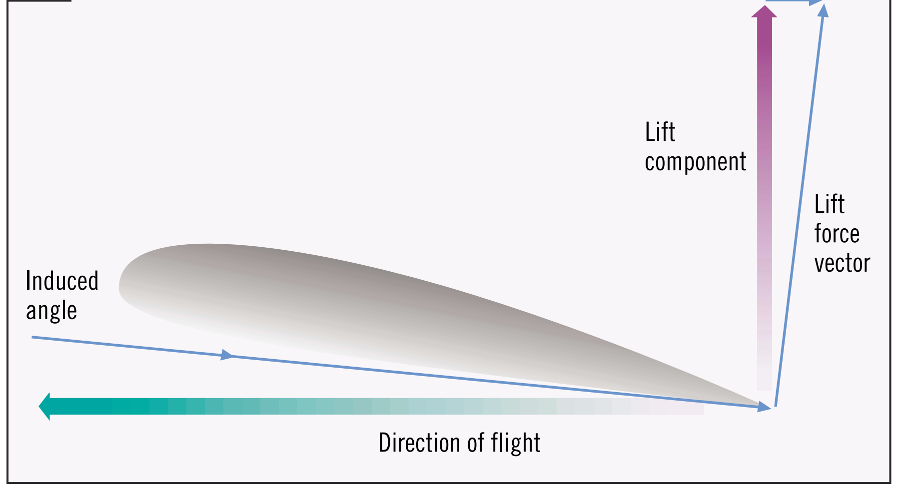


FIGURE 2 VORTICITY CONTOURS BEHIND WING TE WITH AND WITHOUT WINGLETS

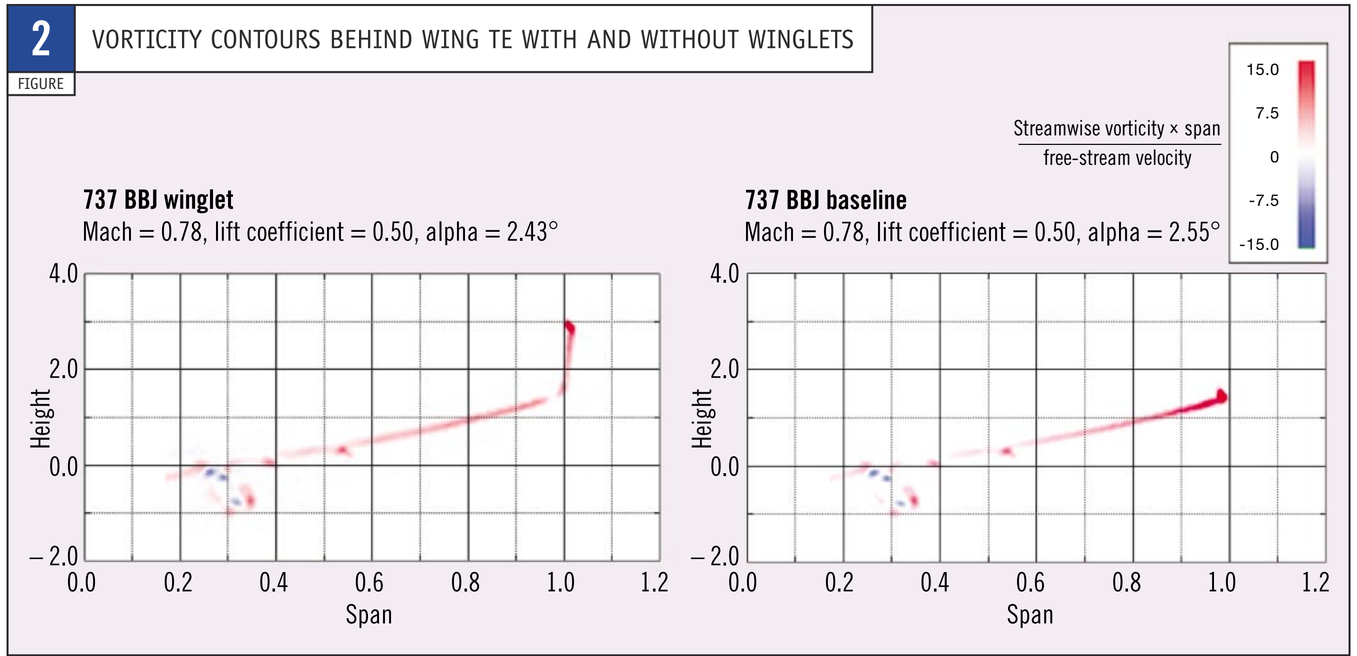


FIGURE 3 SPANWISE LIFT DISTRIBUTION

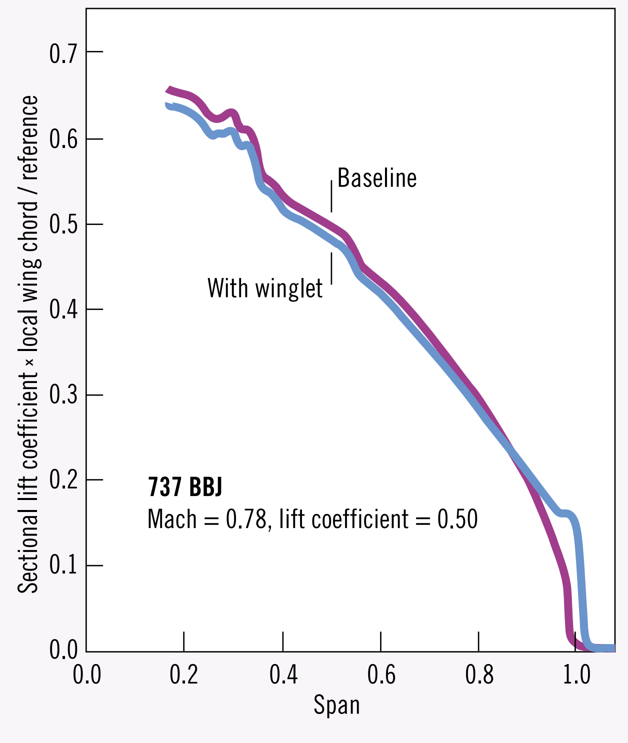
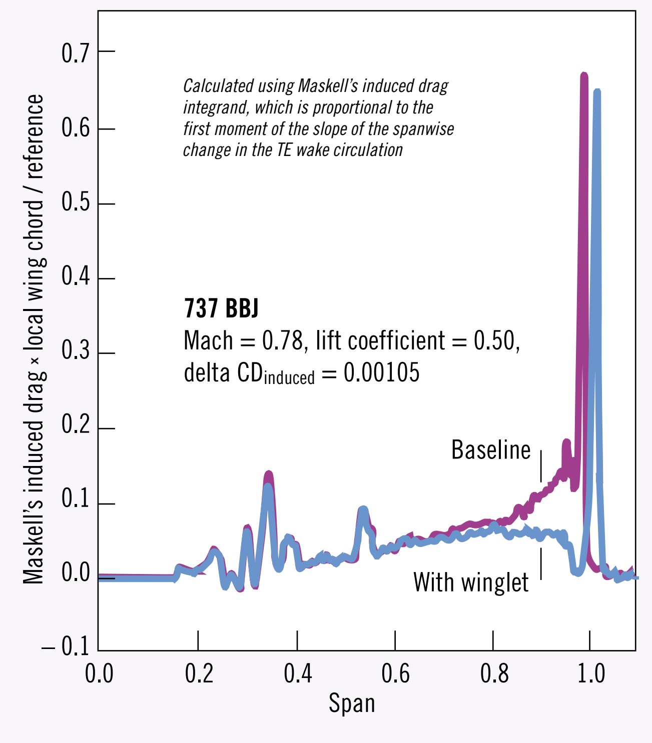


FIGURE 4 REDUCTION IN INDUCED DRAG



winglet-induced load increase and its distribution along the wing can significantly affect the cost of modifying the wing structure. From the perspective of loads and dynamics, the three areas that affect structural change are static loads, dynamic flight loads, and flutter.

Static loads.

Static loads are determined by Boeing and U.S. Federal Aviation Administration (FAA) design requirements, such as a symmetric 2.5-g maneuver, a roll maneuver, or an abrupt rudder input that results in a sideslip maneuver. Although these maneuvers all contribute to the wingbox design, most of the wingbox is designed for 2.5-g maneuvers. The highest loads on the mid- to outboard part of the wing occur when speed brakes are extended. The inboard portion of the wing reaches its highest loads in the clean wing configuration (i.e., with speed brakes retracted).

The outboard tip of the wing generally is designed for roll maneuvers. However, when winglets are added, the high loads on the winglets during sideslip maneuvers cause the wingtip area to be more highly loaded. Therefore, sideslip maneuvers became the design case for the wingtip and winglet.

Dynamic flight loads.

Dynamic flight loads also contribute to the maximum load envelope of the outboard wing. The response of the airframe to gusts or turbulence creates dynamic flight loads on the wing and winglet. During turbulence, the airframe responds at different frequencies depending on its aerodynamics, inertia, and stiffness. Modifications to these parameters change how the airframe responds to turbulence, which in turn changes the loads. In addition to the winglet-induced increase in air load, the weight of the winglet itself and its extreme outboard location also increase the loads for the outboard wing. The heavier the winglets are, the higher the dynamic loads.

Flutter.

The flutter characteristics of an airplane are evident at high speed when the combined structural and aerodynamic interaction can produce a destabilizing or divergent condition. Under such circumstances, an airplane with winglets is sensitive to the weight and center of gravity (CG) of the winglets and associated structural wing changes. Additional weight near the wingtip, either higher than or aft of the wing structural neutral axis, will adversely affect flutter.

3 DESIGN AND TESTING

To design a satisfactory product that integrated performance and structural requirements, the design team gathered technical data on aerodynamics, loads, and flutter through wind tunnel and flight tests.

The loads on a 737-600/-700/-800/-900 airplane with winglets were analyzed through wind tunnel testing using a standard model constructed in the 1.0-g cruise shape and a unique model. The unique wing model, complete with a full set of pressure ports, was built in the deflected shape for the 2.5-g design maneuver condition (fig. 5). The test data from this configuration were used to determine the change in air load distribution on the wing in the deflected shape. This information was used to refine the analysis and helped minimize the adverse effects of the higher loads that resulted from the winglets.

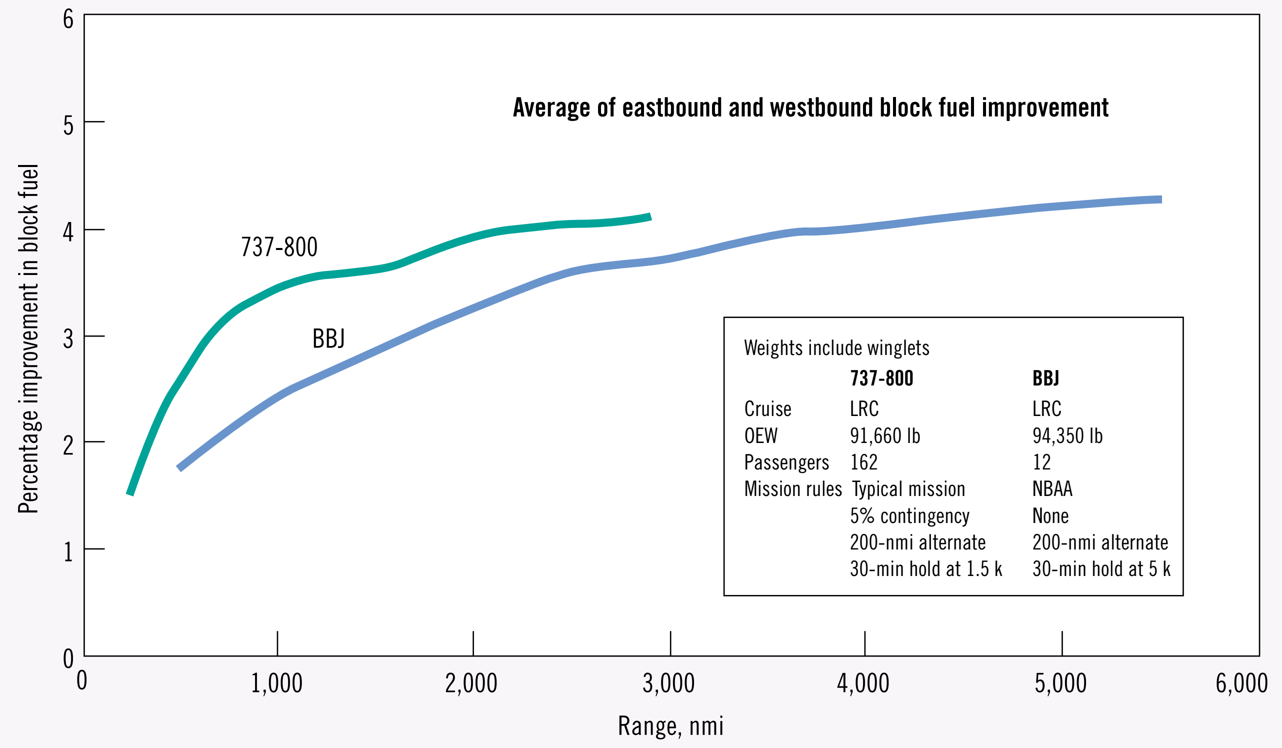
Flight tests were conducted to determine the cruise drag reduction of the winglets and provide data on loads, handling qualities, and aerodynamic performance. Strain gages and rows of pressure taps placed on the winglet and outboard wing were used to indicate the changes in bending moment on the outboard wing resulting from the winglet. Data from these flight tests were used to adjust and validate the aerodynamic database derived from the wind tunnel tests. Table 1 summarizes the aerodynamic flight test results.

Gross fuel mileage improvement with winglets was recorded in the range of 4 to 5 percent. Taking into account the weight of the winglet and the related wing structural modifications, the net performance improvement was approximately 4 percent for long-range flights (fig. 6). Low-speed testing showed a significant reduction in takeoff and

FIGURE 5 WIND TUNNEL TEST

Image of wind tunnel model constructed in the shape of the 2.5-g deflected wing superimposed over an image of the wing in the nominal 1.0-g cruise shape

6 FIGURE BLOCK FUEL IMPROVEMENTS RESULTING FROM WINGLETS



Weights include winglets

	737-800	**BBJ**
Cruise	LRC	LRC
OEW	91,660 lb	94,350 lb
Passengers	162	12
Mission rules	Typical mission	NBAA
	5% contingency	None
	200-nmi alternate	200-nmi alternate
	30-min hold at 1.5 k	30-min hold at 5 k

1 TABLE PROTOTYPE WINGLET AERODYNAMIC FLIGHT TEST RESULTS

Performance

- Four to five percent cruise drag reduction
- No change to initial buffet boundary
- No change to stall speeds
- No pilot-perceived buffet before stick shaker
- Flaps-down lift increase
- Significant drag reduction for takeoff flaps

Handling qualities

- Improved Mach tuck
- Improved directional stability
- Improved longitudinal and lateral trim stability
- Increased pitch stability
- No degradation of stall characteristics and stall identification
- Unchanged rudder crossover speed
- Unchanged Dutch roll damping
- Unchanged manual reversion roll characteristics

landing drag and a significant benefit in payload capability for certain operations (fig. 7).

Using the information gleaned from the wind tunnel and flight tests, a winglet configuration was developed that balanced the benefits of aerodynamic performance against the weight and cost of modifying the airplane. The optimal configuration reduced loads and minimized weight and structural modifications without sacrificing significant winglet performance. It was achieved by an iterative process during which tradeoffs among critical design functions were continually reviewed by experts in aerodynamics, loads, flutter, design, and stress (fig. 8).

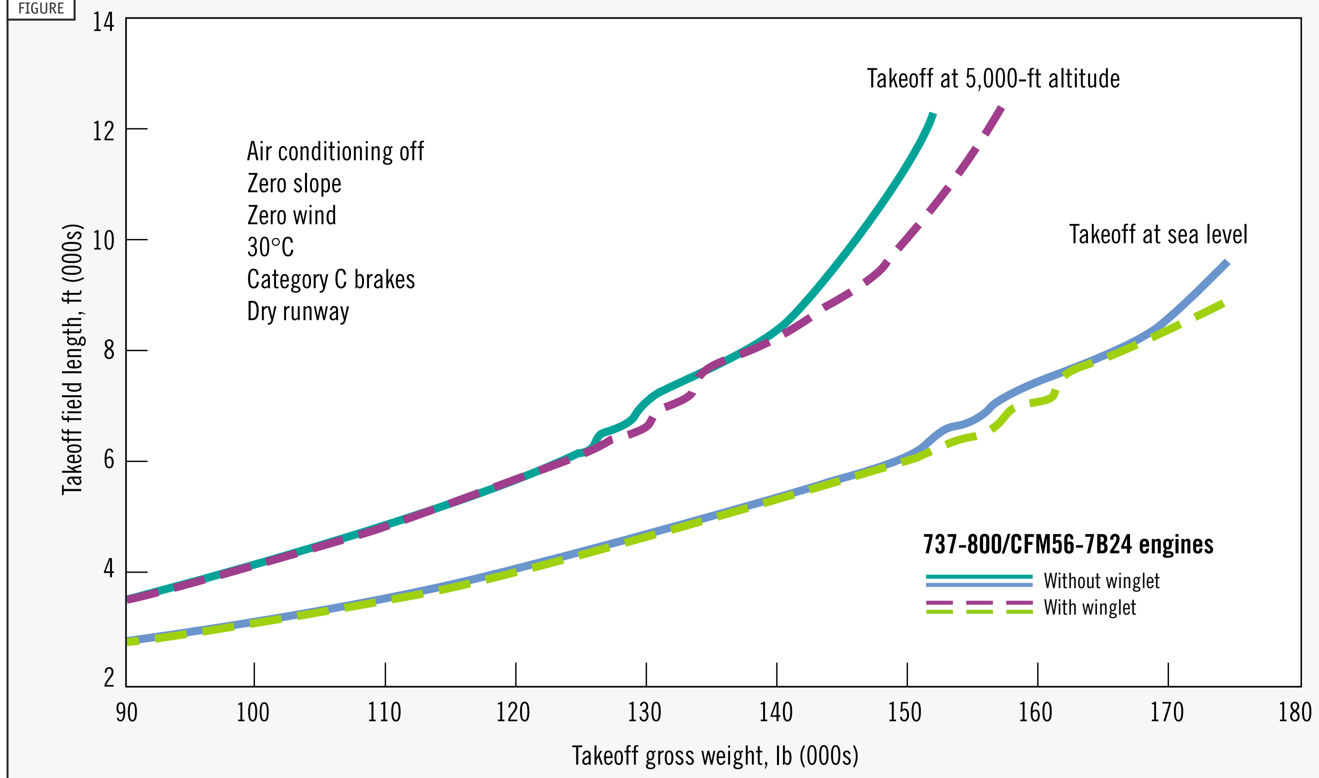
Five major issues were addressed in the development of the optimal winglet configuration.

Toe angle.

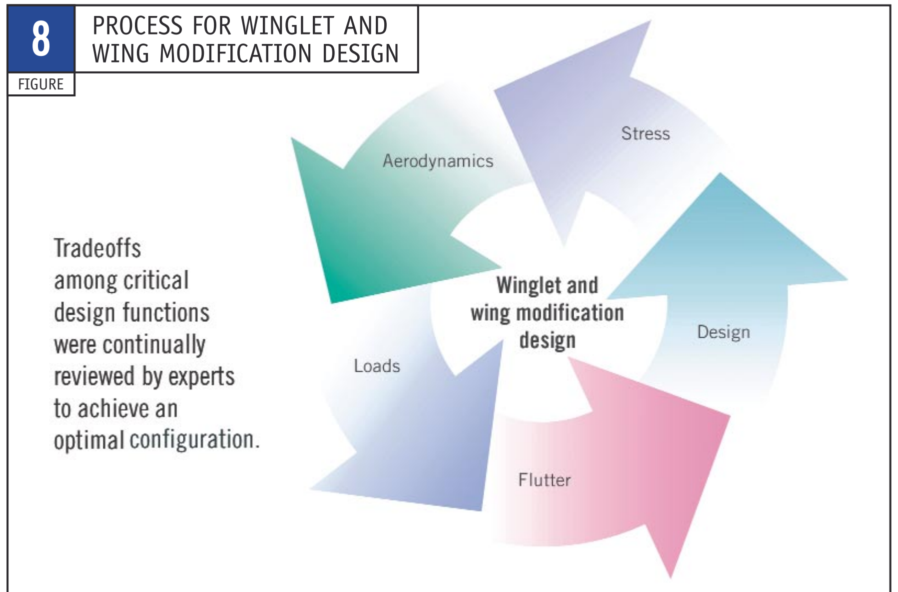
The initial winglet configuration with a 0-deg toe angle was designed to minimize induced drag but resulted in high wing loads. Therefore, the winglet was toed out 2 deg to reduce wing-bending loads. The 2-deg toe angle, while reducing the loads, did not compromise the cruise drag. Figure 9 shows a breakdown of the total drag of the winglet installation as a function of toe-out angle at the cruise condition. The increase in induced drag from unloading the winglet was offset by the reduction in trim, profile, and wave drag. A performance flight test showed the drag was equivalent for a 0-deg toe angle and a 2-deg toe-out angle.

The toe-out angle change did slightly reduce the winglet-induced lift when the flaps were down. Induced drag is much greater during flaps-down operation than at cruise because of the higher lift of the wing. However, this loss in improved performance during flaps-down operation was considered an acceptable tradeoff for reduced structural modifications.

7 FIGURE EFFECT OF WINGLETS ON TAKEOFF FIELD LENGTH



8 FIGURE PROCESS FOR WINGLET AND WING MODIFICATION DESIGN



Speed-brake angle.

The mid- to outboard portion of the wing was designed for speed-brakes-up maneuver loads of 2.5 g. Loads in this area can be lowered by reducing the in-flight speed-brake angle. The reduction in the acceptable speed-brake angle depended on airplane utilization by the operators: The angle was reduced by 50 percent for the BBJ; the 737-800 commercial airplane required full use of the speed brakes to the in-flight detent position for emergency descent certification requirements. For 737-800 retrofits, a load alleviation system was developed to reduce the speed-brake angle automatically at heavy weights and high speeds for critical design load conditions. For airplanes in production, a strengthened wing allows for full speed-brake capability to be retained. Figure 10, which shows the net load reduction from changing the toe angle and reducing the speed-brake angle, depicts how structural changes to the wing were minimized.

Structural changes.

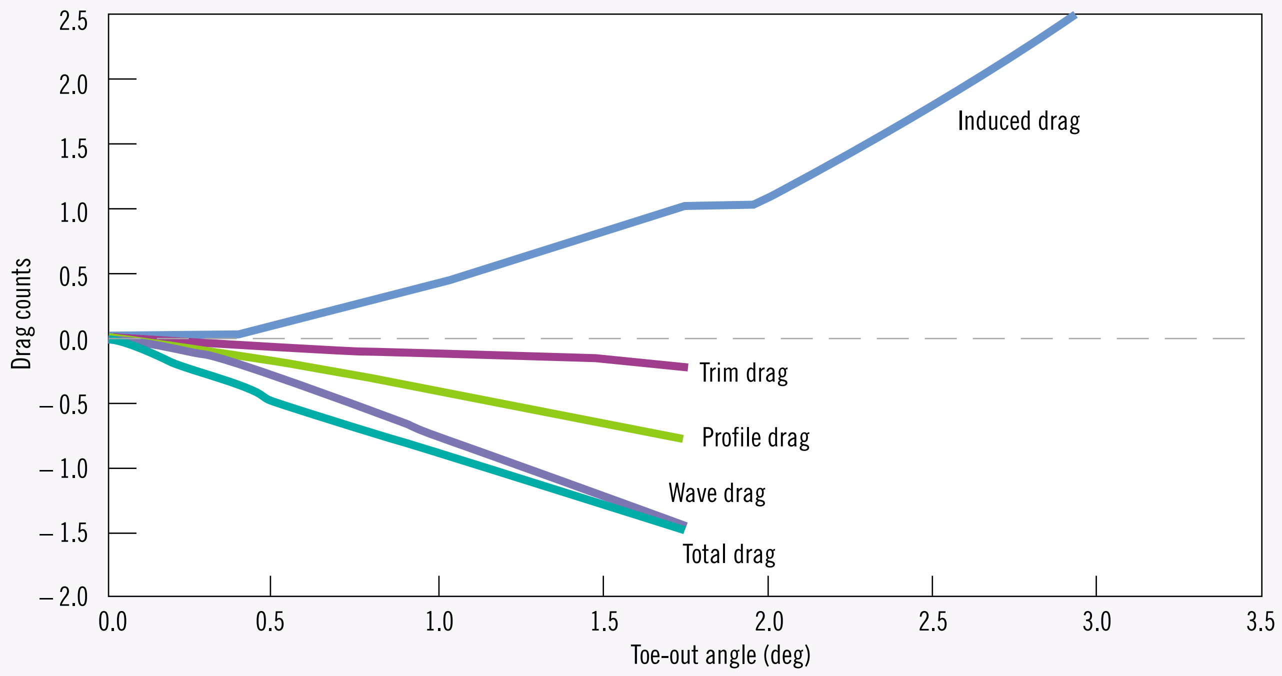
After completing the studies of the toe angle and speed-brake angle, structural material for the mid- to outboard wing-box was still required. (Because the inboard wing had sufficient strength margins, structural changes to that area were minimal or unnecessary.) To minimize the adverse effects of the wing structural modifications on flutter, wing torsional stiffness was maximized in relation to bending stiffness.

Weight and CG control.

To address the effects of both flutter and dynamic load, the weight and CG control of the winglet were considered

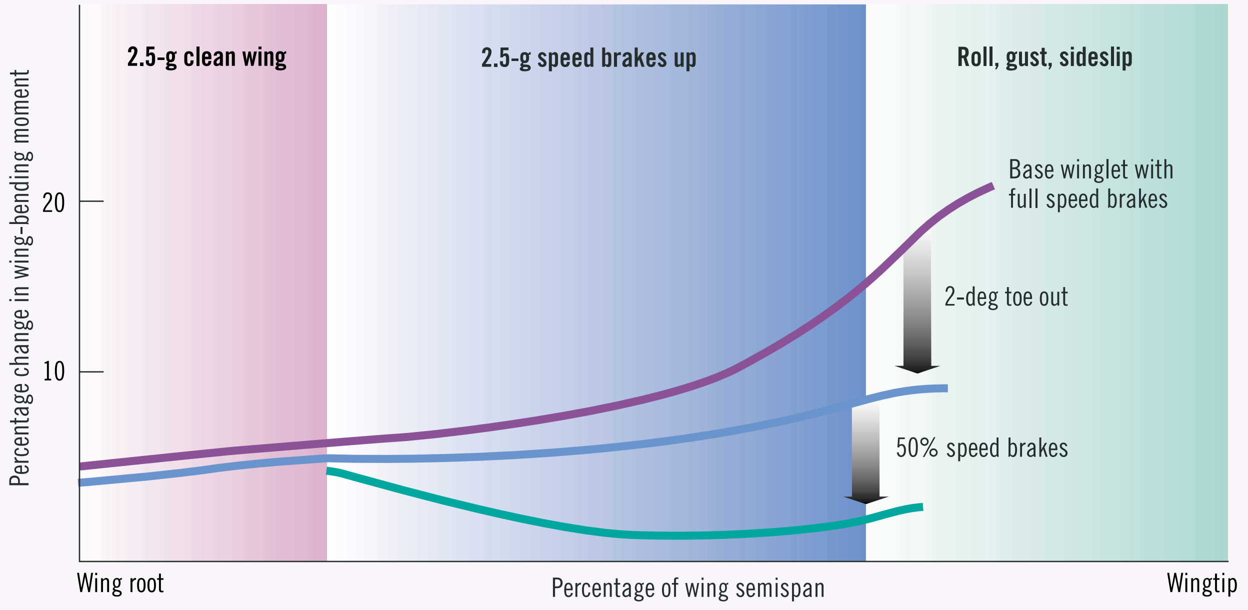
9 FIGURE

TOTAL DRAG OF THE WINGLET INSTALLATION AS A FUNCTION OF TOE-OUT ANGLE AT THE CRUISE CONDITION



10 FIGURE

WINGSPAN DESIGN CONDITIONS

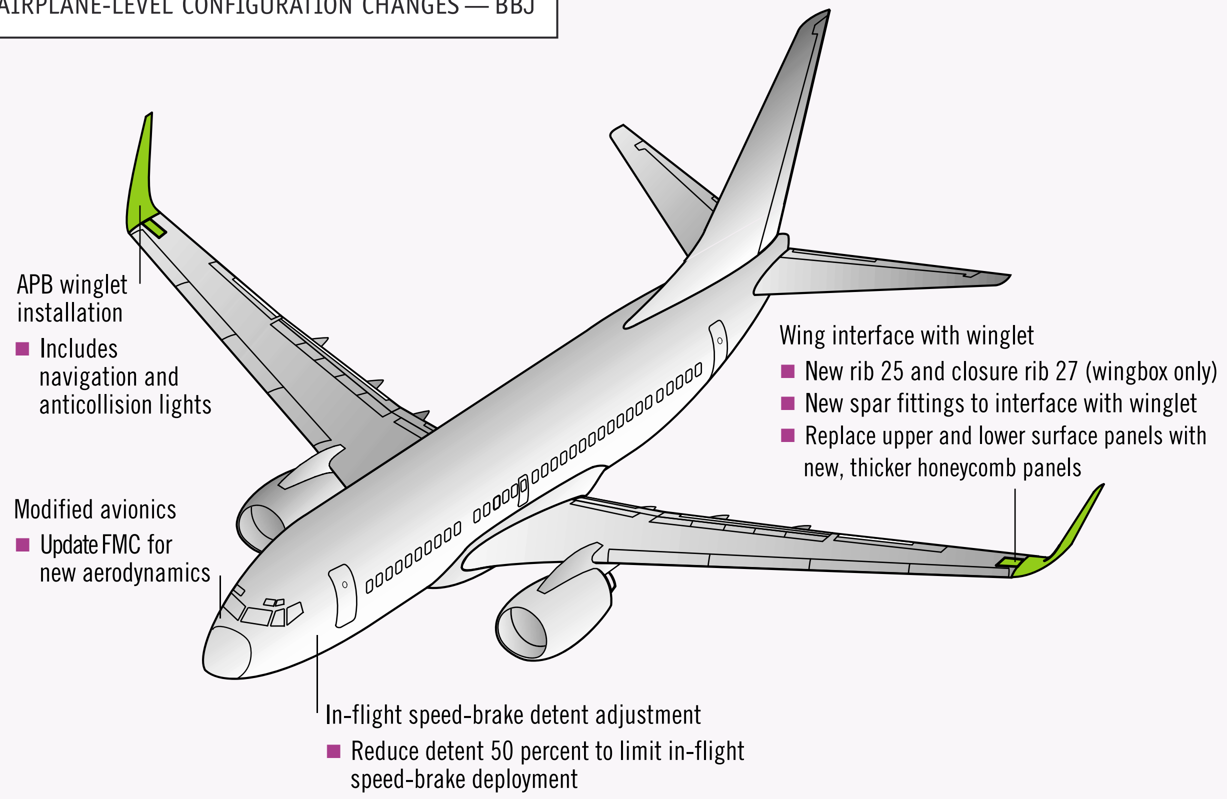


Design conditions typically vary throughout the wingspan.

- Inboard wing: symmetric 2.5-g maneuver
- Midwing: 2.5-g speed brakes deployed
- Outboard wing: roll, gust, or sideslip maneuver

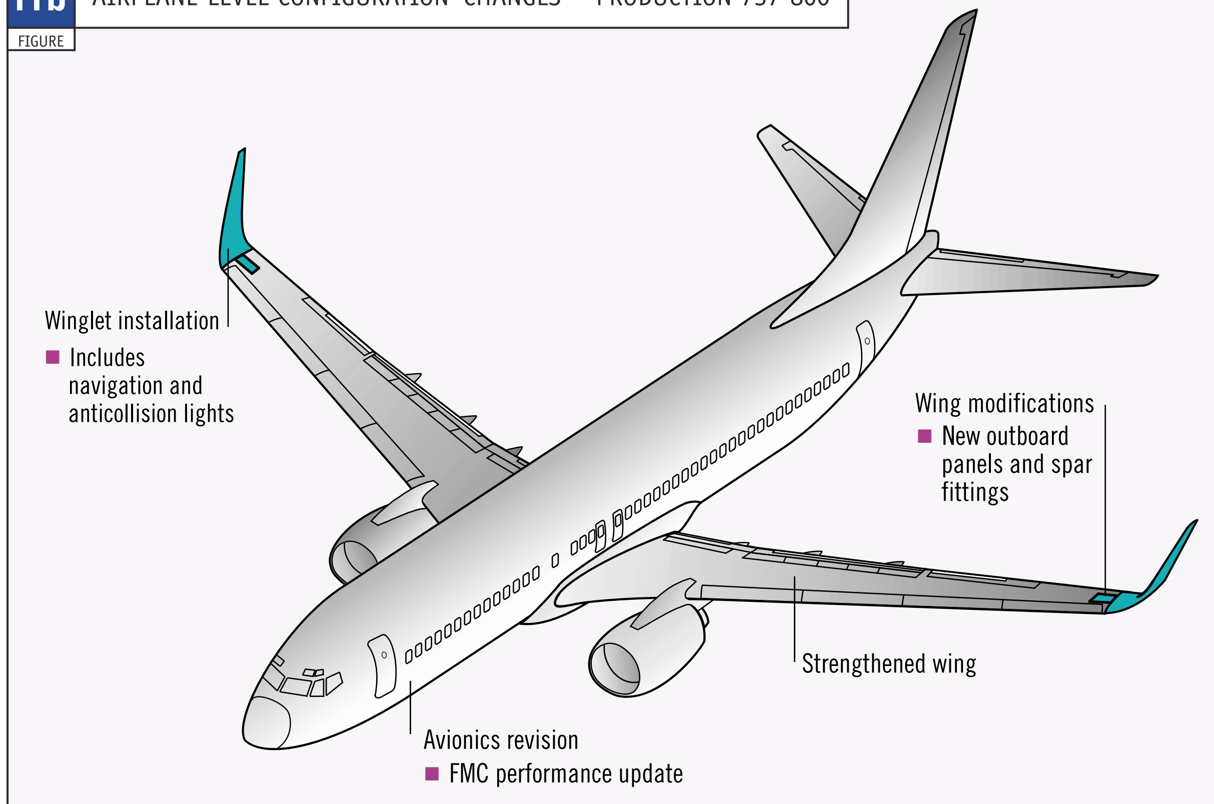
11a FIGURE

AIRPLANE-LEVEL CONFIGURATION CHANGES — BBJ

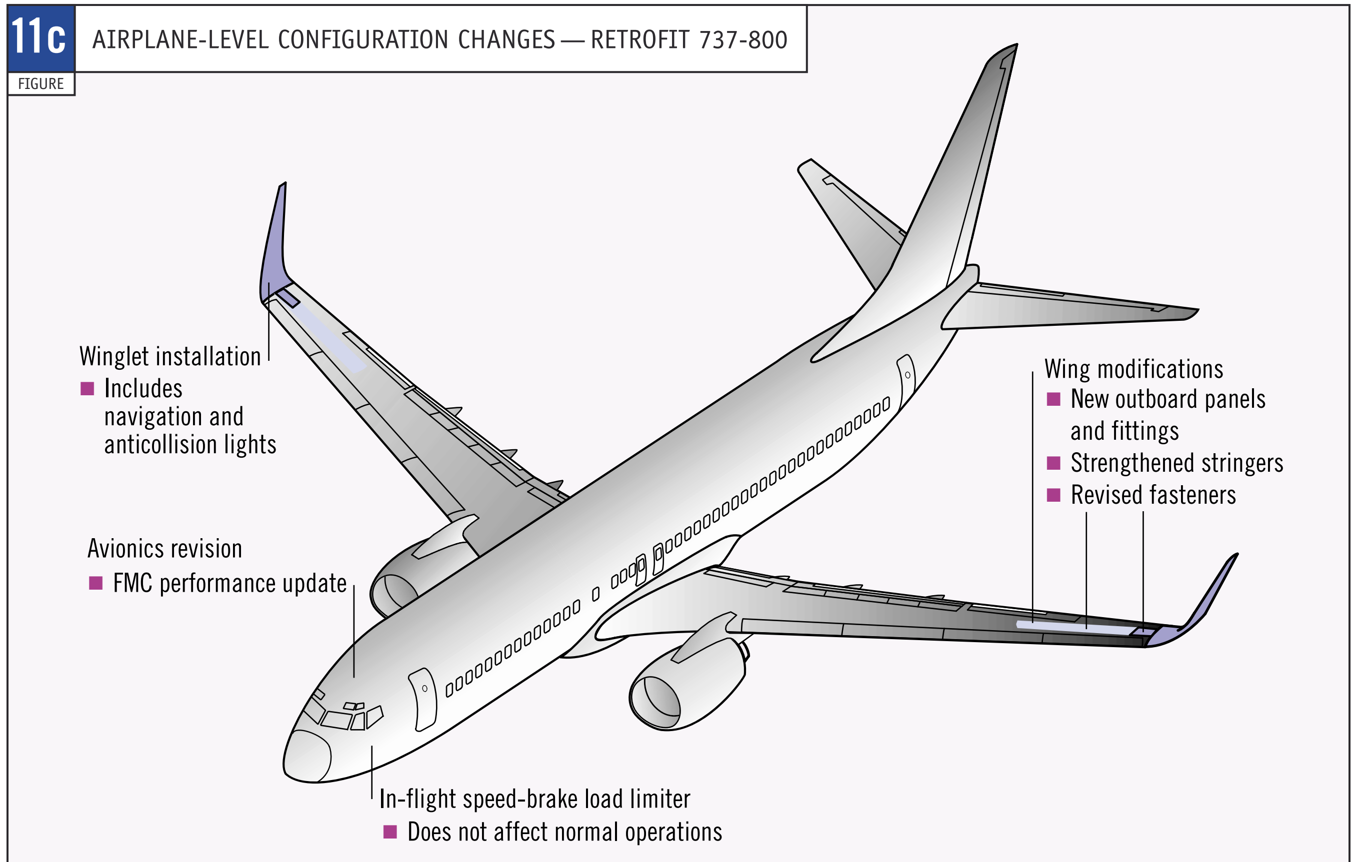


11b FIGURE

AIRPLANE-LEVEL CONFIGURATION CHANGES — PRODUCTION 737-800



11c FIGURE AIRPLANE-LEVEL CONFIGURATION CHANGES — RETROFIT 737-800



carefully, including the location of the winglet lights and specifications for the painting and possible repair of the winglet. To meet flutter requirements with minimal structural changes, additional wingtip ballast was mounted on the front spar to counteract the incremental weight of the winglet located aft on the wing. The use of wingtip ballast depended on the structural configuration of the wing. In some cases, ballast was simpler and more cost effective than structural modification of the wingbox. No wingtip ballast is required for the BBJ configuration; 75 lb of ballast per wing is required for each production winglet on the 737-800 commercial airplane; 90 lb of ballast is required per wing for 737-800 retrofit.

Damage tolerance and fatigue.

The winglet and the wing modifications were designed to meet Boeing and FAA criteria for damage tolerance and fatigue. Any unchanged structure affected by the increased loads was analyzed to ensure that all requirements were met. Analysis indicated that no additional rework was required for the BBJ. Because of the higher cycles of airplane utilization and takeoff weights of the 737-800 commercial airplane, some wing panel fastener holes require rework for fatigue considerations on retrofitted airplanes. The inspection intervals for the wing modification and winglet structure are the same as those for all 737-600/-700/-800/-900 airplanes.

The overall scope of the wing modification for the BBJ involves 10 percent of the outboard wing. This small percentage results from the 2-deg change in winglet toe angle and the 50 percent reduction in the in-flight speed-brake angle. For the 737-800 retrofit, the modification involves 35 percent of the outboard wing. The production airplane with full speed-brake capability involved wing panel changes that affect 60 percent of the span. Figure 11 shows airplane-level configuration changes.

4 RETROFIT AND MAINTENANCE

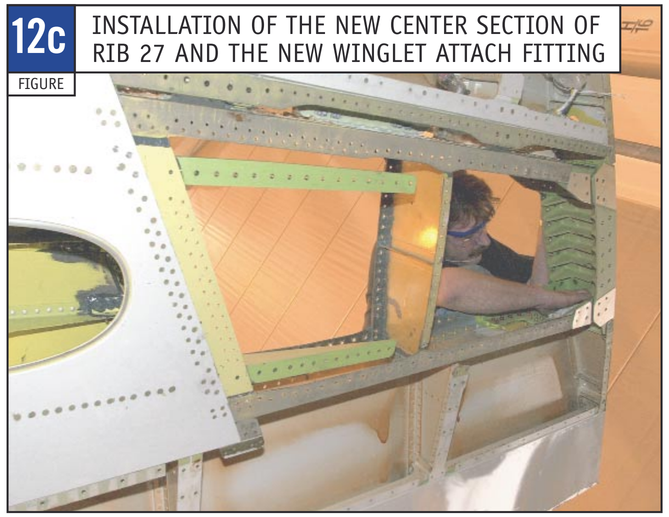
The wing modification was designed with retrofit in mind. Once the wing has been modified for winglets, the winglet itself can be replaced within three hours. The more time-consuming part of the retrofit is installation of the wing modification to accommodate the winglet. For example, a BBJ retrofit, accomplished according to an FAA supplemental-type certificate, involves the following tasks. (This listing does not constitute a complete work instruction package.)

- Removal and replacement of the outboard upper and lower skin panels (fig. 12a).
- Removal and replacement of rib 25, which is third from the outermost rib (fig. 12b).
- Installation of stiffeners across rib 25.
- Cutting of the closure rib (rib 27) and trimming of the two spars (fig. 12b).
- Installation of the new center section of rib 27 and the new winglet attach fitting (fig. 12c).
- Installation of the spar attach fittings (fig. 12d).
- Installation of the aft-position light.
- Installation of the winglet (fig. 12e).

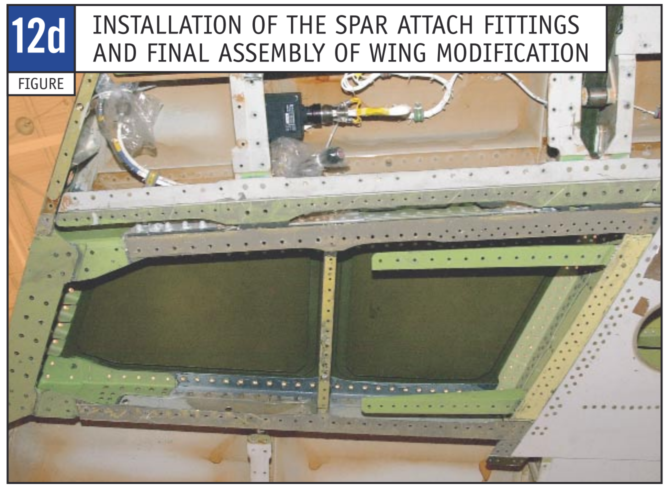
12a FIGURE REMOVAL OF OUTBOARD UPPER AND LOWER SKIN PANELS

12b FIGURE REMOVAL AND REPLACEMENT OF RIB 25 AND THE CENTER SECTION OF RIB 27

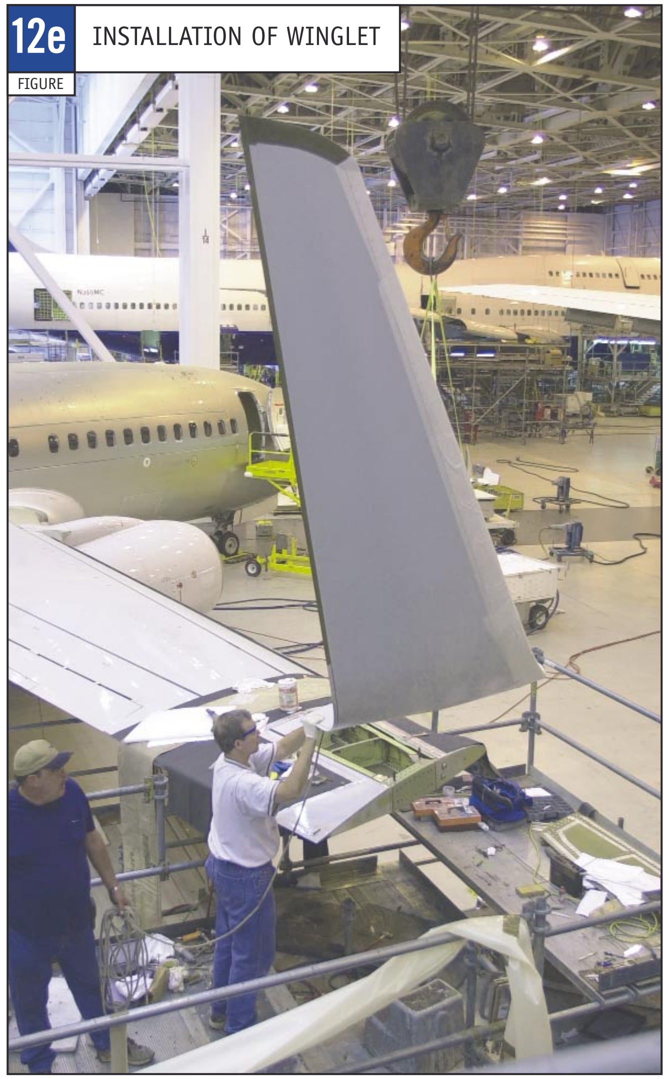
12c FIGURE INSTALLATION OF THE NEW CENTER SECTION OF RIB 27 AND THE NEW WINGLET ATTACH FITTING



12d FIGURE INSTALLATION OF THE SPAR ATTACH FITTINGS AND FINAL ASSEMBLY OF WING MODIFICATION



12e FIGURE INSTALLATION OF WINGLET



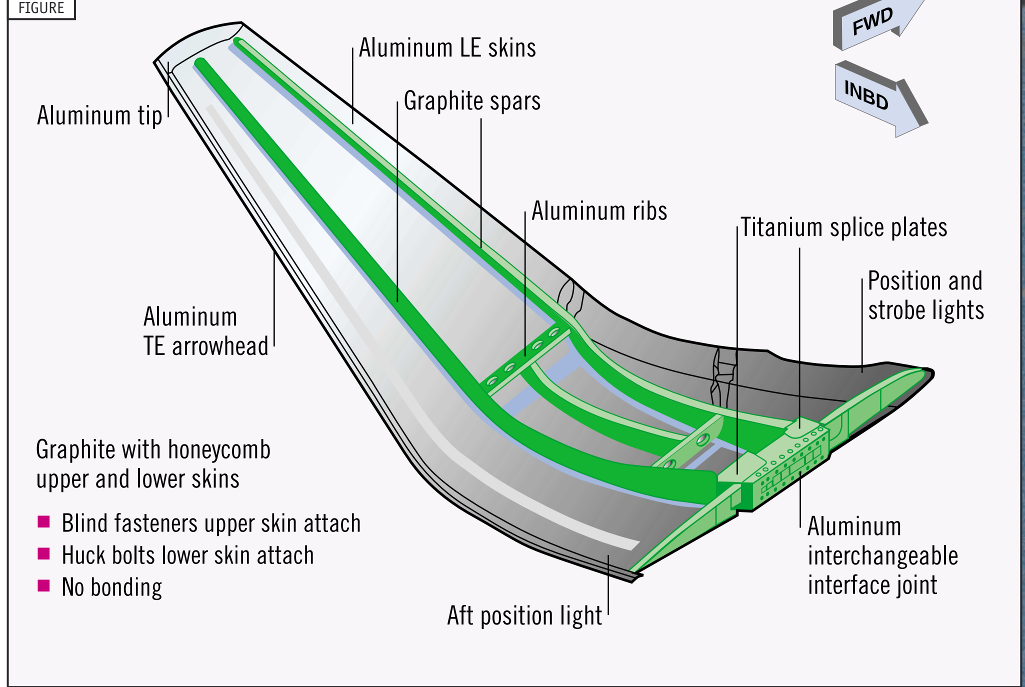
Retrofit of the 737-800 commercial airplane includes a load alleviation system to obtain full use of the speed brakes to the in-flight detent position during typical airline operations. The system, which is installed in the flight deck aisle stand, arms at heavy weights and high speeds at extreme portions of the flight envelope. When armed, the system actuates the in-flight speed-brake handles and retracts them to 50 percent.

For airplanes in production, the wings are strengthened throughout the wingbox to accommodate the winglet loads with full use of the speed brakes to the in-flight detent position. The in-production modification meets the same design criteria as those for the retrofit. However, during production, structural strengthening is accomplished by increasing the gage of spars, stringers, ribs, and panels. Rib 27 incorporates bolt hole patterns that allow attachment of either a winglet or a standard wingtip. The winglet is installed in final assembly.

Navigation and strobe lights are mounted on the leading edge (LE) of the winglet in a way similar to that of the basic wingtip for production. Replacement of the winglet forward-position light, strobe light, and lens requires removal of the LE assembly from the winglet. The winglet aft-position lights are easily accessible for maintenance.

Except for replacement of the winglet forward-position lights and strobe lights, the winglets minimally affect in-service maintenance of the airplane, and the design allows for a wide range of structural repairs. Primary materials are graphite spars, honeycomb graphite panels, and aluminum LE and interface joints (fig. 13). Designed to meet Boeing and FAA criteria for fatigue and damage tolerance, the winglet structure and systems fit within current airplane maintenance intervals and life cycles, with the exception of the 737-800 lens, which has a temporary certification maintenance requirement.

13 FIGURE BLENDED WINGLET STRUCTURE



SUMMARY

Blended winglets offer operational and economic benefits to BBJ and 737-800 customers. Mission block fuel is improved approximately 4 percent. Range capability is increased by as much as 200 nmi on the BBJ and 130 nmi on the 737-800 commercial airplane. The reduction in takeoff flap drag during the second segment of climb allows increased payload capability at takeoff-limited airports.

Environmental benefits include a 6.5 percent reduction in noise levels around airports on takeoff and a 4 percent reduction in nitrogen dioxide emissions on a 2,000-nmi flight.

The blended winglets now are available as standard equipment on BBJs, as optional equipment on 737-800 commercial airplanes, and by retrofit for BBJs, 737-800, and 737-700 commercial airplanes already in service. Because the winglet structure and systems follow established maintenance intervals and life cycles, winglets have a minimal effect on airplane maintenance.

Editor's note: The 737 BBJ blended winglets are patented by Dr. L. B. Gratzer of Aviation Partners, Inc. (API), Seattle, Washington. Boeing and API formed a joint venture, Aviation Partners Boeing, during the development of the 737 BBJ blended winglet design. This article was provided solely by Boeing.

WINGTIP DEVICES

Wingtip devices on derivative airplanes can improve performance by reducing induced drag. Selection of the wingtip device depends on the specific situation and the airplane model.

747-400.
The 747-400 commercial airplane needed a significant span increase to meet the range requirement. However, structural constraints prevented the total span increase, so a combination of winglet and span increase was used.

767-400.
Following a business-case study of the benefits of adding winglets or increasing wingspan, the 767-400 program chose a span increase in the form of a raked tip.

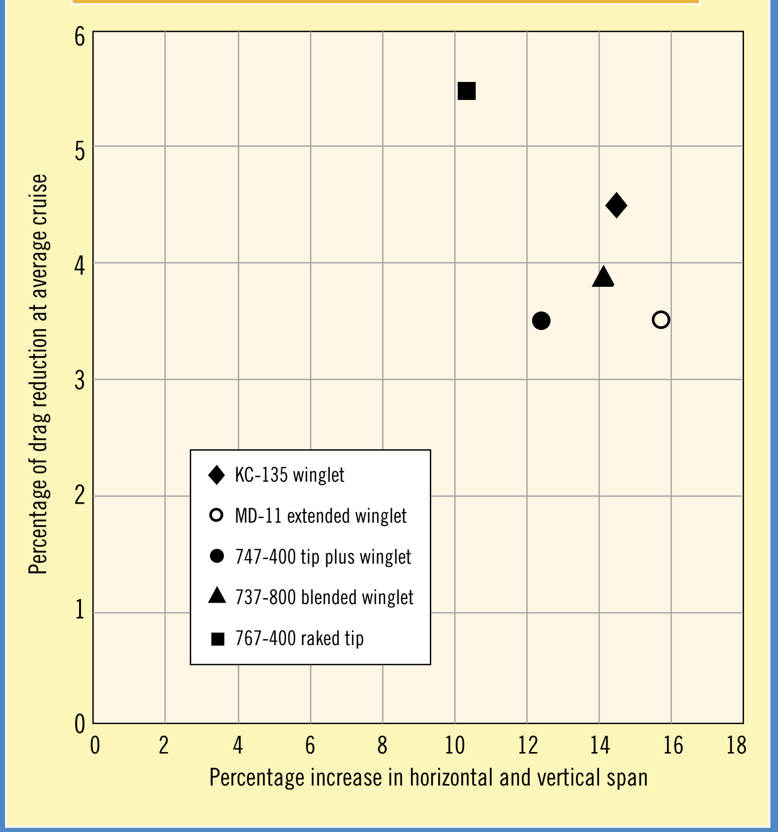
BBJ and 737-800.
The wingtip device for the BBJ and 737-800 commercial airplane involved a retrofit of existing wings. The blended winglet was selected because it required minimal changes to the wing structure and provided improved aesthetic appeal for the BBJ.

MD-11.
The MD-11 program chose a winglet based on wingspan constraints and minimum structural weight.

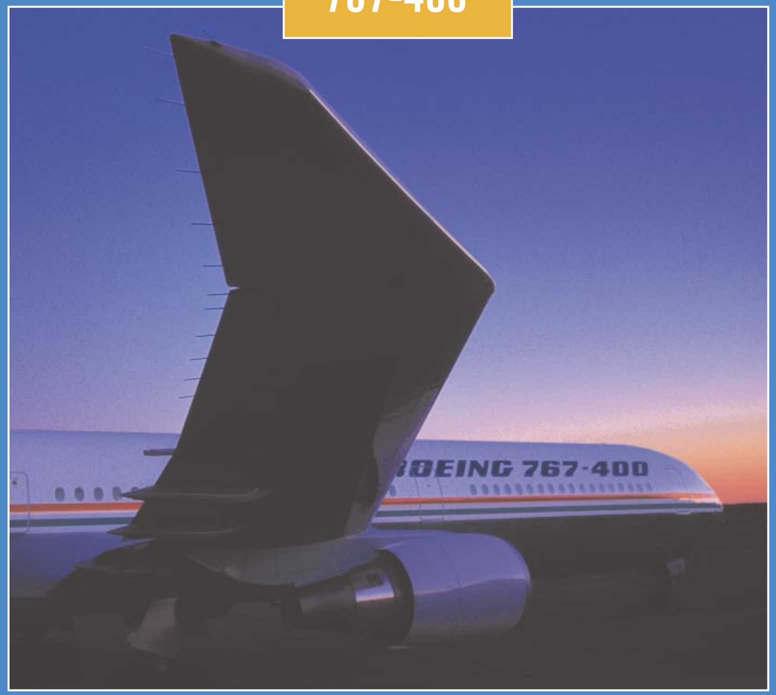
KC-135.
The U.S. Air Force and the National Aeronautics and Space Administration conducted a winglet development program in 1978 to understand how winglets could improve performance.

747-400

Drag Reduction of Wingtip Device



767-400



BBJ and 737-800

MD-11

KC-135