APPLICATION OF WINGLETS AND/OR WING TIP EXTENSIONS WITH ACTIVE LOAD CONTROL ON THE BOEING 747 *

Robert L. Allison, Brian R. Perkin and Richard L. Schoenman
Boeing Commercial Airplane Company

SUMMARY

This paper describes and presents early results of a study program to consider the application of wing tip modifications and active control technology to the Boeing 747 airplane for the purpose of improving fuel efficiency. Wing tip extensions, wing tip winglets, and the use of the outboard ailerons for active wing load alleviation are the concepts being considered. Results to date indicate modest performance improvements can be expected. A costs versus benefits approach is being taken to decide which, if any, of the concepts warrant further development and flight test leading to possible incorporation into production airplanes.

INTRODUCTION

As part of the Aircraft Energy Efficiency (ACEE) Energy Efficient Transport (EET) program (refs. 1 and 2), Boeing is investigating applications to the 747 of modified wing tips to improve aerodynamic efficiency, and active ailerons to reduce wing loads. The study configurations are illustrated in figure 1. If determined to be commercially attractive, these concepts, individually or in combination, could have near term application to 747 derivative models. In the long term, the work will provide a technology base for application to new airplane designs. The objective is to improve fuel efficiency.

Improved fuel efficiency can be realized either in terms of fuel saved for fixed range, a range improvement, or an increased payload capability. In the case of wing tip modifications this performance improvement is achieved primarily by increased aerodynamic efficiency in terms of lift over drag (L/D) of the wing. As a rough approximation, the maximum performance benefits accrued from the wing tip modifications would be those resulting from the increase in L/D with no structural weight penalty. The application of Active Control Technology concepts in the form of active wing load alleviation systems can help to eliminate or reduce the structural weight penalties associated with wing tip modifications or with airplane gross weight increases.

This paper presents preliminary estimates of the potential benefits for the 747, a general discussion of the active control concepts, and more specific discussions of the current 747 EET study program. Emphasis is placed on the engineering approach, design requirements and objectives, and constraints on the potential benefits. Only limited results are included.

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SYMBOLS AND ABBREVIATIONS

Values are given in both SI and U.S. Customary Units. Calculations and measurements were made in U.S. Customary Units.

BM	Bending Moment
BTWT	Boeing Transonic Wind Tunnel
C_L	Lift Coefficient
$\bar{c}$	Mean Aerodynamic Chord
EET	Energy Efficient Transport
FMC	Flutter Mode Control
g	Gravitational Acceleration
GA	Gust Load Alleviation
K	Gain
L/D	Lift to Drag ratio
M	Mach Number
MLC	Maneuver Load Control
OEW	Operating Empty Weight
T	Torsion
UWAL	University of Washington Aeronautical Laboratory
V_e	Equivalent Airspeed
WLA	Wing Load Alleviation
WTE	Wing Tip Extension
WTW	Wing Tip Winglet
δ_A	Aileron Deflection, positive trailing edge down
δ_T	Tab Deflection
η	Wing Spanwise Station, fraction of semispan

Subscripts:

δ_A	Aileron Deflected for MLC
o	Aileron Neutral

POTENTIAL BENEFITS

A thorough assessment of the fuel savings attainable for the study configurations is planned for completion later in the 747 EET program. However, to bring this approach into perspective from the outset, it is worthwhile to determine on a gross basis the approximate magnitude of performance benefits attainable with the concepts being considered.

Using the 747-200B as an example, consider that the wing box weight, excluding the landing gear support beam, represents about 18 percent of the Operating Empty Weight (OEW) of the airplane. Preliminary estimates indicate that a 5 percent reduction in wing box weight is a reasonable goal for a wing load alleviation system utilizing active outboard ailerons. This represents approximately a 1 percent reduction in OEW which can be translated into reduced trip fuel or into increased range or payload. This estimate pertains to the basic wing without the addition of tip extensions or winglets.

Wing load alleviation is more likely to be applied to an existing airplane either to increase the allowable takeoff gross weight or to minimize the additional structural weight associated with wing tip modifications. Consequently, let us now take the example of an improvement which is to be made by increasing the aerodynamic efficiency of the wing by means of wing tip extensions and/or winglets. Assuming for the moment that this could be done with no increase in structural weight, the improvement in L/D could be translated directly into either reduced fuel burned or increased range. Preliminary estimates indicate that the improvements in L/D attainable from wing tip modifications are on the order of 2 to 4 percent for practical configurations. These translate approximately into an increase in range of 75-150 nautical miles assuming maximum takeoff gross weight, or a trip fuel reduction of 2 to 4 percent for fixed range/payload. The trip fuel reductions represent fuel cost savings, based on current fuel prices, in the order of $100,000 to $200,000 per year per airplane for typical 747 operations.

The previous example provides a gross estimate of what the potential performance benefits could be for the 747, assuming the wing load alleviation system allows the tip extensions or winglets to be installed with no change in airplane OEW. However, some increase in airplane OEW may be required, in which case the trip fuel/range/payload benefits would be reduced. There are several limitations on applying the concepts to existing airplanes, some of which are discussed in this paper, which would be less constraining for a new design.

WING LOAD ALLEVIATION CONCEPTS

Wing Load Alleviation concepts can be broken down into two categories, 1) static elastic load alleviation, and 2) structural dynamic load alleviation. The static elastic concepts are concerned with loads due primarily to angle of attack changes resulting from maneuvers or gusts, independent of structural dynamic effects. The "structural dynamic" concepts are concerned with increasing structural mode damping.

Within these two broad categories, a variety of wing load alleviation systems have been discussed in the literature (e.g., reference 3), with potential benefits indicated in the areas of maneuver and gust load reduction, fatigue, flutter suppression, and ride comfort. The 747 EET program is concentrating on three areas: maneuver load control, gust load alleviation, and flutter mode control defined as follows:

(1) Maneuver Load Control (MLC) is any method of redistributing wing lift during maneuvering flight. Incremental stresses may be reduced by deflecting wing control surfaces symmetrically during a maneuver in a manner that shifts the wing center of lift inboard, thus reducing wing bending moments.

(2) Gust Load Alleviation (GA) is any technique for reducing airframe loads resulting from gust disturbances. It encompasses control of rigid body and/or structural dynamic components of the airplane gust response.

(3) Flutter Mode Control (FMC) is any technique for actively damping flutter modes using aerodynamic control surfaces. It provides potential for weight savings and/or extending flutter placards.

The basic wing box structure of all present Boeing commercial transport aircraft is predominantly sized by maneuver loads. Additional structural material is included where necessary to satisfy gust, flutter and fatigue requirements. The existing 747 wing does not contain appreciable structural material added specifically to meet gust and flutter requirements. However, the situation may be modified by the addition of tip extensions and/or winglets, or by the reduction of strength material in the basic wing if resized to take credit for the MLC and GA systems.

Figure 2 shows a plot of wing structural box weight per unit span as a function of distance along the wing, and shows a wing which is typically designed by maneuver loads. In this particular case, it can be seen that a reduction in the magnitude of the maneuver loads by the use of a maneuver load alleviation system could result in a reduced requirement for structure. The degree to which the implementation of winglets and/or wing tip extensions can be incorporated with minimum structural impact is determined by the reduction in maneuver loads by such a system.

Figure 3 shows a wing which is not only maneuver load critical but is also gust and flutter critical. It can be concluded that for this wing a maneuver load control system would not allow any wing weight reductions since flutter clearance and gust loads requirements are predominant. In this example, a wing load alleviation system utilizing maneuver load control, gust load alleviation and flutter mode control would have to be utilized in order to attain reductions in structural weight.

An understanding of the application of active ailerons to static elastic load alleviation requires consideration of the aerodynamic load distribution over the span of the wing, and the tradeoffs between aerodynamic performance and structural requirements. Generally speaking, maximum lift/drag ratio is accomplished when the load distribution on the wing is near elliptical. However, this is not necessarily the best lift distribution for cruise performance, since wing structural weight also is a factor. The 747 lift distribution tends to be more "triangular" (i.e., lightly loaded outboard) than "elliptical" in order to achieve a reasonable compromise between L/D and structural weight so as to maximize overall performance.

While this lift distribution improves cruise performance, it does not minimize the design loads on the wing which, for the current 747, are determined primarily by a 2.5 g maneuver requirement. To reduce the corresponding wing bending moment, it is possible to modify the lift distribution somewhat between one g cruise and maneuvering flight conditions so as to shift the center of loading farther inboard for maneuvers than for cruise. This already takes place to a certain extent in existing sweptback wings due to aeroelastic effects which tend to twist the tips in a washout direction in maneuvers. Further inboard shifting of the lift distribution in maneuvers can be accomplished by active controls which unload the outboard portions of the wing.

The use of active outboard ailerons to modify the load distribution along the span of the 747 wing is illustrated in figure 4. The solid line shows the lift distribution with ailerons neutral in a steady state 2.5 g pullup. The dashed line shows how the wing loads for the same maneuver are shifted inboard by symmetrically deflecting the ailerons, trailing edge up. Shifting the lift inboard on a sweptback wing also introduces a nose-up pitching moment increment which reduces the downward tail load required for pitch trim in the maneuver. This effect is somewhat analagous to balancing the airplane to a more aft c.g., and requires pitch axis augmentation to maintain the desired stability and control characteristics. Since the direction of the tail lift is opposite that of the wing, reduction of the tail lift allows the 2.5 g limit design maneuver load factor to be achieved with a lower wing lift. It is the combined effect of the inboard shift of the lift distribution and the reduced overall wing lift that reduces the wing bending moments for the structural design maneuver cases. While other surfaces on the wing may be found to be effective in reducing these structural loads, the 747 EET Program is currently considering the use of outboard ailerons only.

A factor to be considered when using ailerons as load alleviation devices is the effectiveness of the surface at high speeds. When used as roll control devices at high dynamic pressure it is possible that a deflection of the outboard aileron will cause the wing to twist sufficiently to reverse the total rolling moment about the airplane centerline from that normally experienced. The speed at which this occurs is known as the aileron roll reversal speed. Because of this phenomenon, many commercial transport airplanes, including the 747, use the inboard aileron and spoilers for roll control at high speed. The outboard aileron is locked out at high speed and is used only for roll control with flaps down. Airplanes which use outboard ailerons for roll control at high speed require additional outer wing torsional material compared to a similar wing with an aileron lockout.

Now consider the surfaces used symmetrically as load relieving devices. Figure 5 shows the spanwise variation of the ratio of wing bending moment with ailerons deflected divided by the wing bending moment with ailerons neutral. The data are representative of a plain aileron at speeds above the aileron roll reversal speed. Results are shown for both a 2.5 g balanced maneuver condition and a constant angle of attack condition. In the 2.5 g balanced maneuver the airplane has been retrimmed after application of the ailerons for load alleviation. For the constant angle of attack condition the airplane has not been retrimmed after aileron application. Aileron roll reversal can be inferred from the constant angle of attack data which show that bending moment is increased at the wing root, although bending moment reductions are still apparent over the rest of the wing. The increased root moments shown in the constant angle of attack data (which give some insight into the effect of activating the aileron in response to a high frequency gust) occur only in an area which is not gust load critical for the 747. The 2.5 g balanced maneuver data show substantial bending moment reduction along the entire wing. Thus an outboard aileron which reverses for roll control can still be used effectively for wing load alleviation when deflected symmetrically.

Shown in figure 6 is a plot of the ratio of wing torsion with ailerons deflected divided by the wing torsion with ailerons neutral. The wing torsion is increased along most of the span. Use of a balance tab on the aileron can reduce this effect and reduce the torsional material needed in the wing for these increased loads. A wing designed with an outboard aileron for high speed roll control will still suffer increased torsion loads when using the surface for maneuver load control because increased control surface deflections are required for load alleviation. To minimize the increased torsion loading it may be advisable to reduce the aileron deflections used for maneuver load control at high speeds by making the available aileron angle a function of airplane speed.

APPLICATION OF ACTIVE AILERONS AND MODIFIED WING TIPS TO THE BOEING 747

Previous discussions have been somewhat general in nature to give some understanding of the phenomena involved. The following discussions will be more specific and relate to those studies which are presently under contract by Boeing from the NASA. Emphasis will be placed on the study approach, design requirements and objectives, and factors constraining the potential performance benefits. Some early results of general interest are also discussed.

747 EET Program Overview

The current 747 EET study program consists of engineering analyses and wind tunnel testing to examine the benefits of applying winglets and/or wing tip extensions to the 747 airplane to improve L/D, and the use of wing load alleviation systems to minimize the structural weight penalties associated with carrying these additional surfaces.

The 747-200B has been selected as the baseline model for the current effort. Pertinent characteristics of this airplane are shown in table I. The specific modifications being considered (figure 1) are as follows:

- Wing tip extensions (WTE)
- Wing tip winglets (WTW)
- Wing load alleviation (WLA) using active outboard ailerons
- A final configuration incorporating WTE and/or WTW with WLA.

The study sequence and general scope of activites are indicated in fig. 7.

The WTE, WTW, and WLA concepts are first being analyzed and evaluated separately so that the costs and benefits associated with each can be identified for reference in selecting the final configuration. Following this selection, the remainder of the analyses and evaluations, leading to a go/no-go recommendation concerning further development and flight test, will be for the final configuration.

One high speed wind tunnel force and pressure test has been conducted, and another is planned, to support development of the winglet and WLA control surface configurations, and to obtain aerodynamic performance, stability and control, and loads data for use in analyses of the concepts. Wind tunnel data from a prior Boeing test of a 1.83 meter (6 foot) tip extension are being used as a basis for the WTE studies. A flutter test is being conducted to support flutter analyses of the winglet configurations.

Study Approach

In evaluating the potential of the concepts for possible fleet implementation, a comprehensive costs versus benefits approach is being taken with some of the more significant airline operational and FAA certification concerns being addressed in addition to the fuel savings and implementation costs. For example, the potential impact of wing span increases on flight line operations and maintenance is being considered, as is the effect of additional systems on dispatch reliability and maintenance costs.

The results of aeroelastic and structural resizing analyses are being included in estimating the performance benefits of the concepts; i.e., the effects of changes in wing twist and the weight changes associated with required structural modifications will be accounted for in the performance evaluation. By identifying drag and weight increments for the concepts individually and in combination, the relative effectiveness of tip extensions versus winglets can be compared and the weight reduction provided through WLA identified.

In line with this approach, the WLA system functions have been separated into three categories with objectives for each function as follows:

WLA FUNCTION	OBJECTIVE
Maneuver Load Control (MLC)	Bending moment reduction in symmetric maneuvers
Gust Alleviation (GA)	Gust load reduction. Studies of this function will include consideration of: - aileron response to low frequency gusts (e.g., MLC may provide some gust load relief) - damping of first wing bending mode - airplane pitch response
Flutter Mode Control (FMC)	Flutter suppression at speeds above dive speed

The performance benefits and costs (including the effects on system reliability) associated with each of the functions will be considered in selecting the final WLA configuration.

While implementation costs are to be determined for the case of a production line installation for future deliveries, the feasibility of retrofit into existing fleet aircraft will also be explored. Regarding FAA certification, there is some precedent for taking credit for active controls when establishing design loads (e.g., reduction of fin loads with yaw damper operational). The impact on the basic airplane certification of the particular 747 modifications being studied will be considered in the overall assessment.

Design Requirements and Objectives

General - The general design objective is to develop a configuration that will improve fuel efficiency for routine airline operations, will be cost-effective for fleet implementation, and will meet the general design requirements that there shall be no significant adverse impact on safety, handling qualities, or dispatch reliability. Where conflicts arise between the performance/cost objectives and the safety/handling qualities/reliability requirements, priority will be given to the latter.

The added implementation or operational costs, if any, associated with meeting these requirements will be reflected in the cost versus benefit comparisons. The intent is to provide a reasonably true indication of the cost savings actually attributable to the configuration modifications, as opposed to apparent performance benefits achieved at the expense of less tangible factors. As an example, part of the wing load alleviation provided by active ailerons in a pullup maneuver results from a reduced tail load, which, in turn, resulted from a nose-up pitching moment increment introduced by the ailerons. Part of the apparent cost savings accruing from the reduced wing load will be offset by the cost of the pitch control augmentation required to retain existing stick force per g characteristics.

Aerodynamic Performance - The aerodynamic performance objective is to develop a configuration that will provide enough performance improvements to warrant fleet installation. There is no single go/no-go criterion which could be applied to all airline situations to determine if a modification is economically attractive. For example, a configuration might not be cost-effective on the basis of trip fuel cost savings, but could nevertheless be quite beneficial on a particular route if it allowed a larger payload. These and other factors will be considered by Boeing in recommending whether or not to proceed to flight test. For purposes of reporting study results, performance for the various study configurations is being compared on the basis of trip fuel savings for fixed payload/range, with no increase in the maximum takeoff weight.

Buffet - The effect of MLC control surface deflection on buffet boundaries must be considered when developing WLA concepts. The outboard aileron reduces lift on the outboard section of the wing, thereby forcing the inboard sections to fly at higher angle of attack for a given wing lift. However, due to the reduced down load on the tail (resulting from the nose-up pitching moment induced by the ailerons) less wing lift is required for a given load factor. Conditions checked to date show that the body (wing root) angle of attack for a given load factor is reduced when the outboard aileron is used for MLC. Hence, a more complete examination, including the effects of changes in section angle of attack due to differences in the aeroelastic twist distribution, must be conducted before reaching a conclusion.

Stability and Control - Wing tip modifications and/or the use of existing control surfaces for wing load alleviation could affect both the longitudinal and lateral/directional stability and control characteristics of the airplane. The requirement being used for the 747 EET is that there should be no significant change in handling qualities or automatic flight control system performance relative to the basic airplane. In general, all of the requirements considered in design and certification of the basic airplane must be reviewed.

There is nothing unique about stability and control analyses for wing tip modifications, although the low speed characteristics of winglets are not well understood at this time. In the case of the WLA system installation, a lateral control surface (outboard aileron) is being used for purposes other than lateral control, and in flight regimes (high speed) where it is locked out at present.

Since aileron deflections introduce pitching moments, the longitudinal control power and stability characteristics are affected. Consequently, pitch augmentation inputs to the elevators have been included in the WLA system configuration. Requirements concerning low speed roll control power and aileron hinge moments are of considerable importance in selecting an aileron tab configuration. The low speed control power requirements are also a prime factor in determining to what extent the MLC system can be employed during flaps down flight.

Structures - The structural criteria for design of the 747 EET are the same as used for all 747 models. These criteria meet or exceed the requirements of FAR Part 25. Included are maneuver and gust criteria for use in structural analysis of aircraft with automatic flight control systems. These criteria account for both normal and failed operations of the flight control systems.

Application of these criteria is considered sufficient for certification of an airplane incorporating a wing load alleviation system for both normal and failed operations of the system. Three operational modes of the wing load alleviation system must be considered: normal operations, passive failures and active failures. It is in the area of failures that most consideration has to be given. Failures can involve system shutdown, jams, hardovers and oscillatory failures. Criteria for the maneuver load control system involve degree of redundancy of the system and whether airplane dispatch can be allowed with a system failed, or if gross weight placards have to be applied. Oscillatory and hardover failures are covered by criteria for automatic flight control systems.

Consideration of the impact on airplane flutter stability due to a wing load alleviation system is necessary. Both the nominal wing load alleviation system and likely failure cases must be considered. The wing load alleviation system must be designed such that there is satisfactory flutter mode damping within the flight envelope with the system on or off or in a failure mode. If a flutter mode suppression system is developed for the 747 EET a basic requirement will be that it will only be used to increase stability of flutter modes above design dive speed to achieve a 20 percent margin of safety. That is, the airplane shall be flutter free to 1.2 times the dive speed with the system active, and it shall be flutter free to the design dive speed with a system failure or malfunction.

The effect of the wing load alleviation system on the fatigue requirements will be evaluated. Fatigue analysis methods will be the same as used on current 747 models but the loads used in the fatigue analysis will be revised to reflect the active control effects.

Selected Results

Wing Tip Modifications - A ground rule for the study which significantly impacts the performance benefits attainable from the wing tip modifications is that the existing baseline wing jig shape (i.e., the twist distribution of the wing during manufacture) and airfoil sections are to be retained. The aeroelastic twist distribution at cruise, selected to optimize performance for the existing wing, will be modified by the additional loads imposed by the tip extension. As a result, the net performance gains will be less than if the jig twist were reoptimized for the increased span configuration. Figures 8 and 9 illustrate this effect, which is an important difference between studies of tip extensions on existing wings as contrasted with a new wing of increased span and aspect ratio. The "existing structure" curve assumes no additional structural material has been added to accommodate the increased loads. The "resized structure" data points reflect the effects of the additional stiffness resulting when the wing structure was resized without taking credit for wing load alleviation. The added structural weight for the resized structure does not affect the L/D estimate, but would have an adverse effect on performance in terms of range or trip fuel.

Similar effects of non-optimum twist distribution are expected for the winglets. In addition, the parametric trend study of reference 4, based on the work of Dr. Whitcomb (reference 5), points out that greater benefits can be achieved from winglets if the wing/winglet combination is designed as a unit from the start. The 747 tip area is lightly loaded, which tends to limit the effectiveness of the winglet.

A number of winglet configurations had been wind tunnel tested on the 747 prior to the 747 EET program. The geometry of the best of these, designated "Z4", is compared in figure 10 to the geometry of the first winglet tested in the current program, designated "Z9". Chordwise sections illustrating the Z9 winglet camber are shown in figure 11. The geometry changes, relative to the Z4 winglet, were intended to eliminate the reductions in performance benefits due to compressibility effects which had been noted for prior winglets in the cruise Mach number regime.

The cant angle and span for the new winglet (Z9), were the same as for the Z4 but the planforms are different (figure 10). The intent was to spread the load over a longer chord so as to reduce the velocities on the winglet lifting surface, which would be favorable in reducing the Mach number penalties. However, the test data showed excessive forward velocities on both Z4 and Z9.

The first winglet (Z9) test results exhibited a reduction in performance with Mach number similar to the earlier Z4 winglet. Winglet Z9 appeared to be over-cambered near the leading edge in the wing junction region. Winglet Z10 was the result of an attempt to reduce some of this camber (figure 11), and produced a small performance gain at the cruise Mach number.

Wind tunnel test results, expressed in terms of full scale drag improvement, are compared in figure 12. The Mach number effects are clearly evident as well as a generally lower level of benefits with the Z9 and Z10 winglets. Consequently, the winglet design and test effort under the current program is being expanded somewhat to consider additional configurations.

Wing Load Alleviation - The control surfaces currently being considered for the three wing load alleviation functions (MLC, GA, FMC) are indicated in figure 13. The outboard aileron, the primary WLA control surface, is being used for maneuver and gust load alleviation, and possibly also for flutter suppression. The flutter mode control concept and the associated control surfaces have not yet been established. The surfaces indicated for FMC in figure 13 are being considered as potential candidates. The separate FMC surface (aileron segment) would be used only if the existing ailerons were ineffective due, for example, to inadequate resolution or frequency response. The lower rudder is indicated as a candidate because it might be effective in suppressing anti-symmetric flutter modes.

A simplified block diagram depicting the control laws for the maneuver load control (MLC) and gust alleviation (GA) systems is presented in figure 14. The low pass filter in the MLC system has unity steady state gain, whereas the band pass filter for the GA system has zero steady state gain.

The center of gravity acceleration feedback in the MLC control law provides load alleviation in maneuvers and in low frequency (below airplane short period) gusts. The wing acceleration feedback in the GA control law provides damping of the first wing bending vibrational mode, while the pitch rate feedback attenuates the airplane pitch response to gusts. Evaluations of the capability of the systems to alleviate maneuver and gust loads without exciting flutter modes are in progress. Results to date are encouraging.

Aileron Configuration Selection - Trade studies of various aileron/tab configurations ranging from a plain (untabbed) aileron to a 30 percent chord full span balance tab are being conducted. One of the considerations, illustrated in figures 15 and 16, is that the plain aileron is more effective in reducing bending moment but results in higher torsion levels than ailerons with balance tabs. The data shown reflect aileron lift and section pitching moment levels as estimated prior to the recently completed 747 EET wind tunnel testing. To account for the combined effects of bending moment and torsion, preliminary wing resizing studies using the wind tunnel aileron/tab aerodynamic data are in progress. Results to date have shown that the plain aileron is a possible candidate. Further evaluation is necessary before selecting the aileron/tab geometry for the 747 EET final configuration.

CONCLUDING REMARKS

The NASA/Boeing 747 EET program was initiated during May of 1977. Efforts to date have been directed principally at aerodynamic, structural, and WLA system configuration development. Detailed performance estimates and cost versus benefit evaluations are planned for later in the program. However, preliminary estimates indicate that wing tip modifications combined with wing load alleviation have the potential for providing trip fuel savings on the order of 2 to 4 percent, which is significant on a fleet-wide basis.

As the program progresses there will be an improved understanding of the benefits to be accrued when wing tip extensions and winglets are being applied to an existing airplane, and how these benefits may be different when these devices are being considered for a new airplane design. Criteria being developed during this study relating to structural design and flight control systems will be valuable for future and new advanced airplane designs.

The current program is directed toward determining the feasibility, costs and benefits of the application of wing tip extensions or winglets to the 747 airplane. At the conclusion of this study, a recommendation may be made to proceed into a flight test evaluation.

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TABLE I

CHARACTERISTICS OF 747-200B BASELINE MODEL FOR 747 EET STUDY PROGRAM*

Maximum Taxi Weight	3,580,000 N (808,000 lb.)
Operating Empty Weight	1,625,000 N (336,000 lb.)
Maximum Payload	712,000 N (160,500 lb.)
Fuel Capacity	1,530,000 N (344,480 lb.)
Wing Span	59.6 m (195.7 ft.)
Wing Aspect Ratio	6.96
Wing Sweep (1/4 Chord)	37.5°

*Note: JT9D-7FW Engines

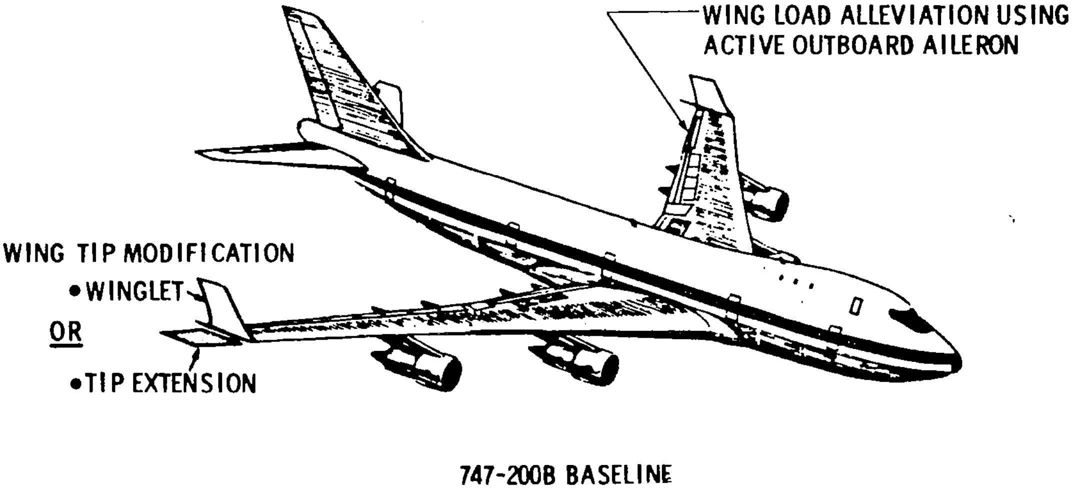


Figure 1.- 747 EET study configurations.

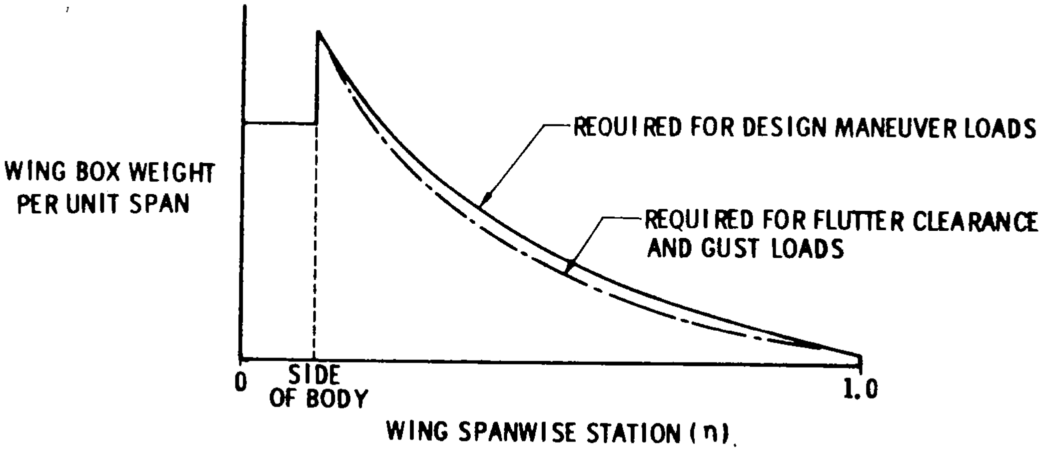


Figure 2.- Typical wing structural box weight distribution for maneuver critical wing.

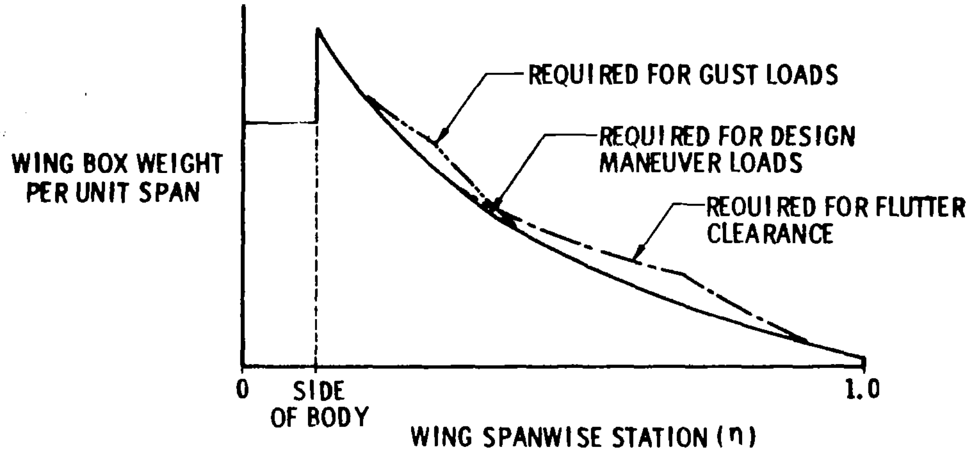


Figure 3.- Typical wing structural box weight distributions for flutter and gust critical wing.

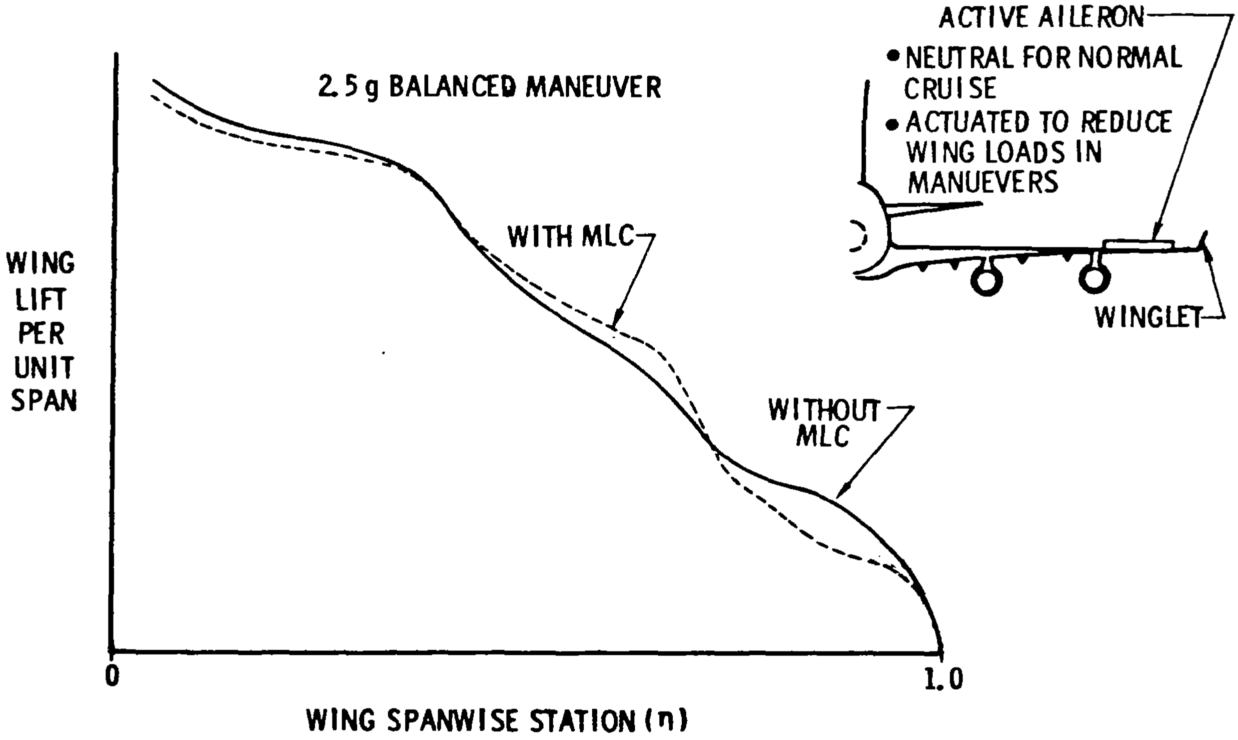


Figure 4.- Maneuver load control concept.

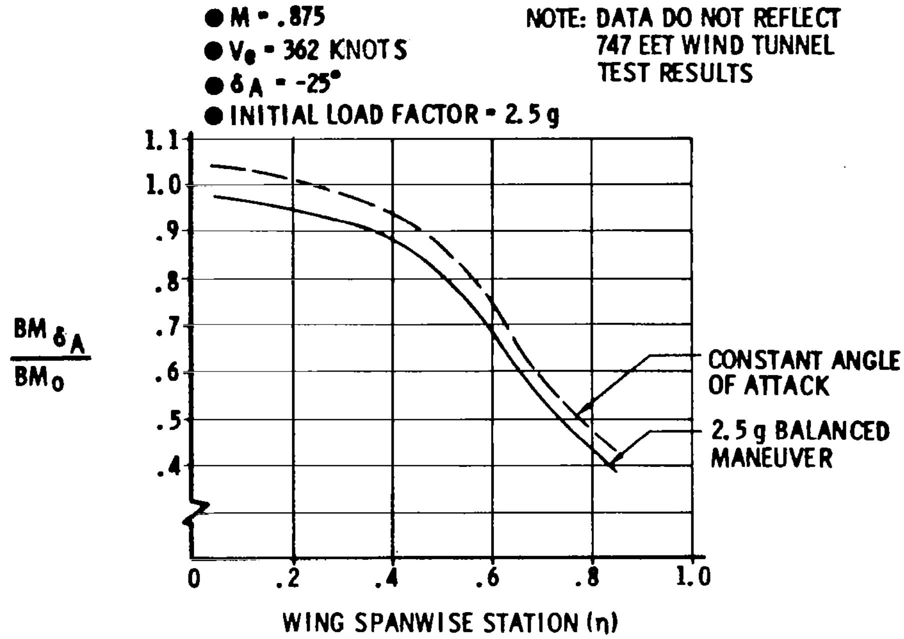


Figure 5.- Effect of plain aileron on wing moment.

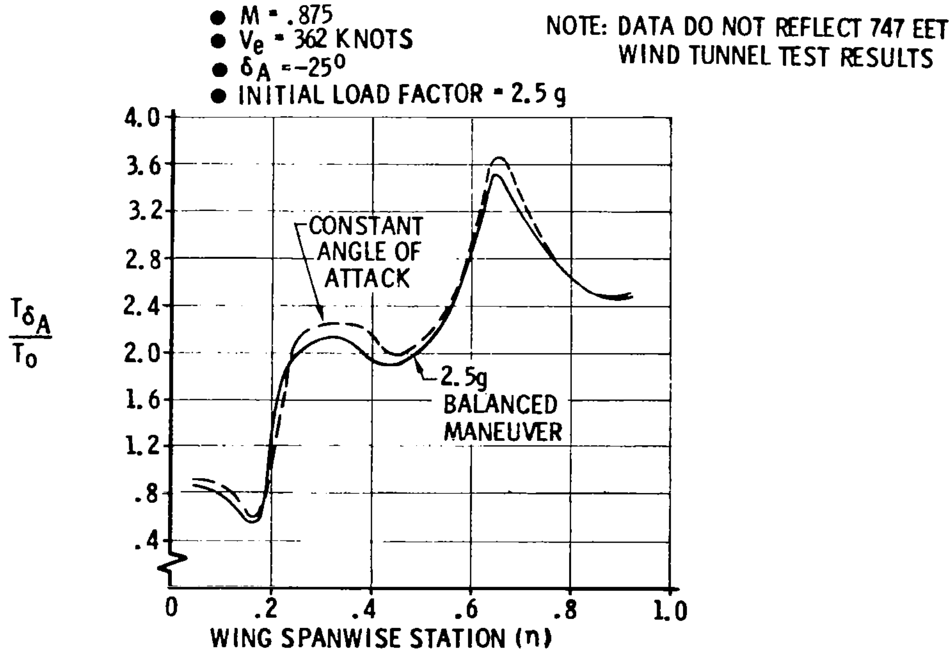


Figure 6.- Effect of plain aileron on wing torsion.

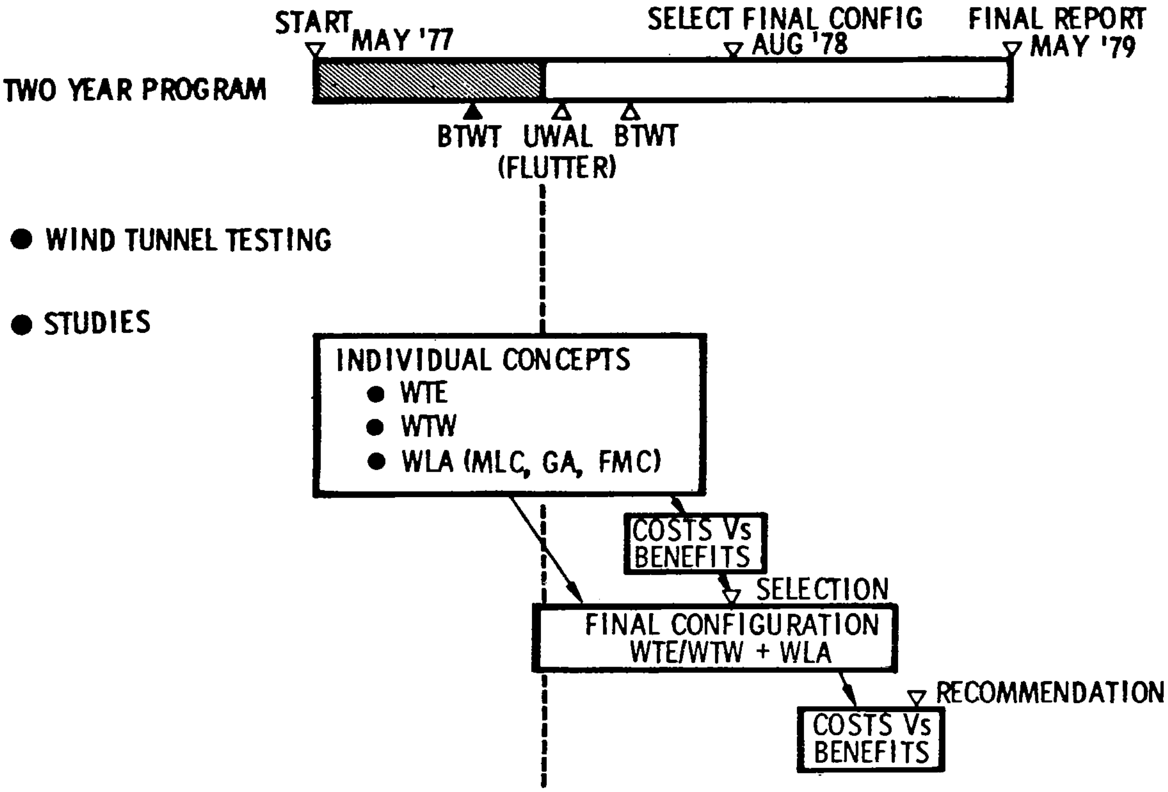


Figure 7.- 747 EET program outline.

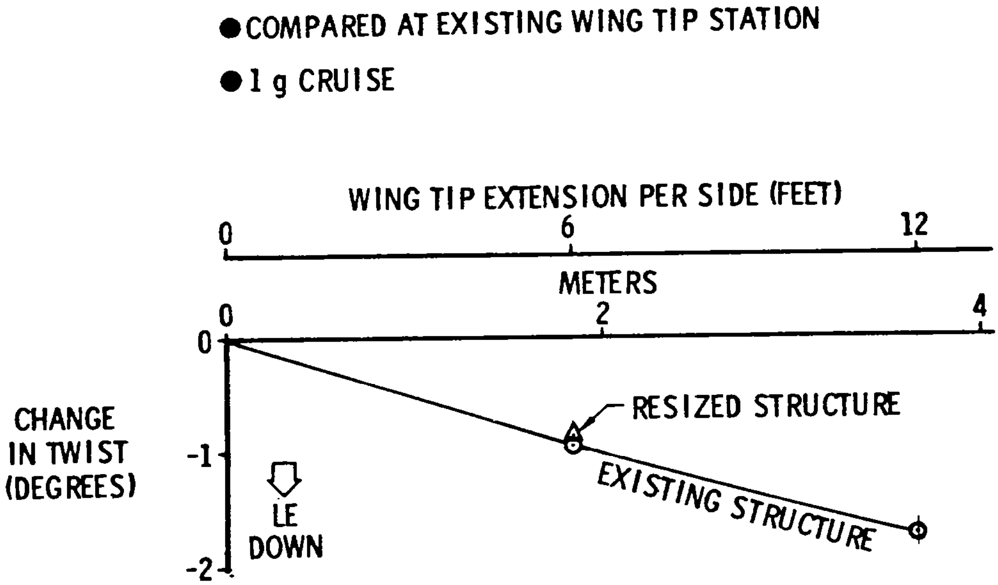


Figure 8.- Effect of tip extensions on aeroelastic twist.

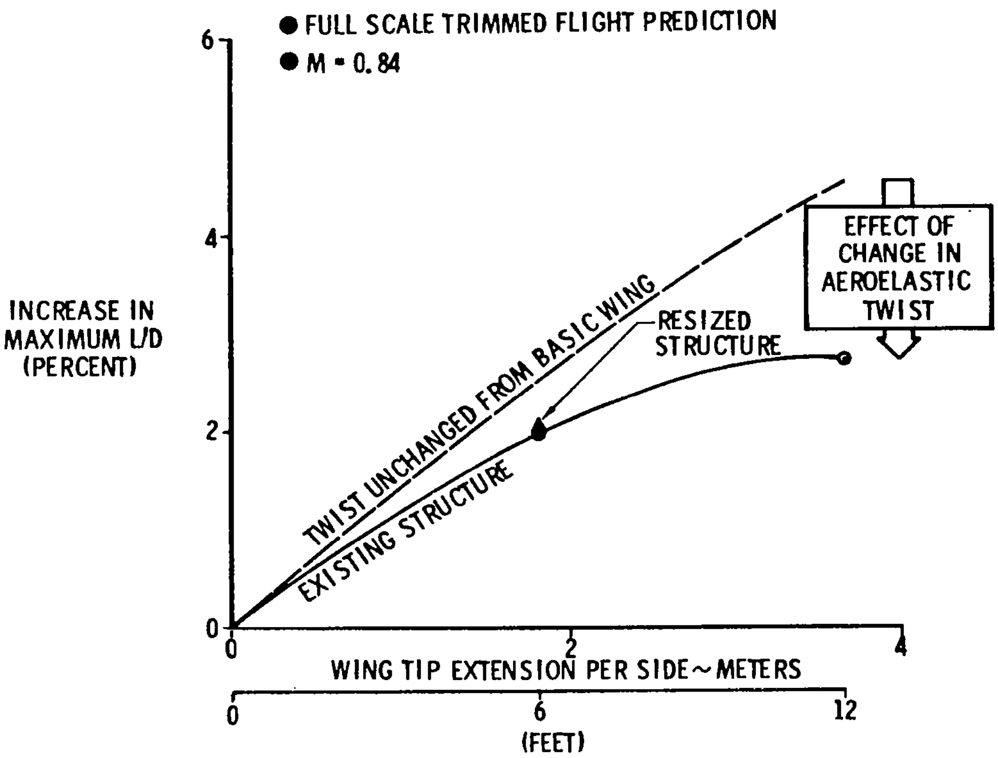
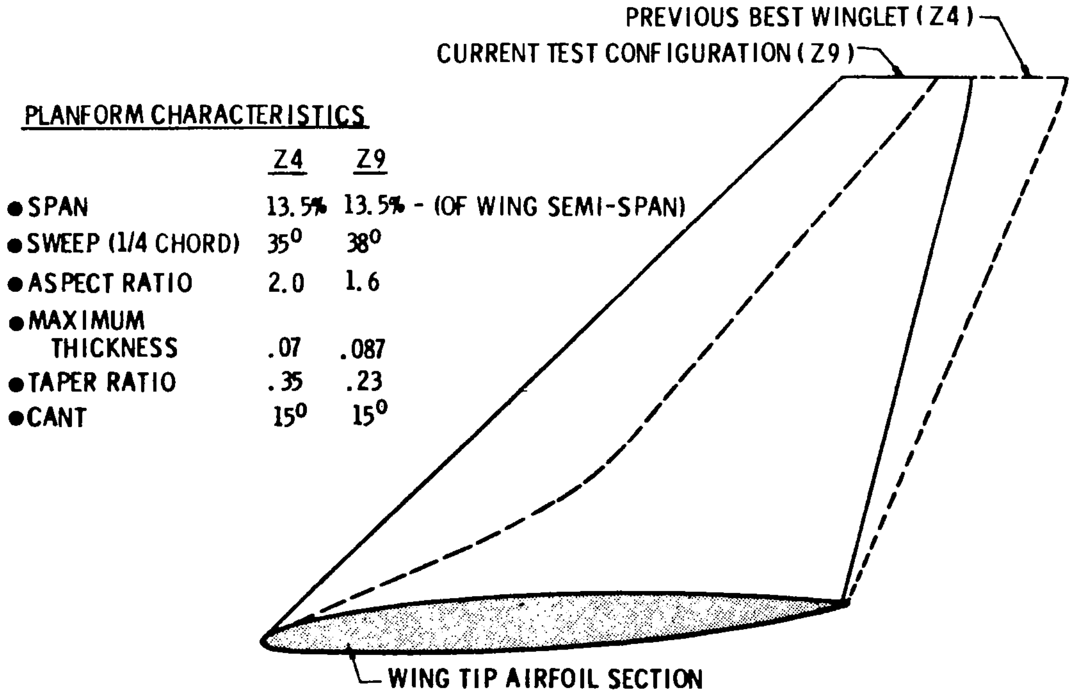


Figure 9.- L/D trends for wing tip extensions.



PLANFORM CHARACTERISTICS

	Z4	Z9	
● SPAN	13.5%	13.5%	- (OF WING SEMI-SPAN)
● SWEEP (1/4 CHORD)	35°	38°	
● ASPECT RATIO	2.0	1.6	
● MAXIMUM THICKNESS	.07	.087	
● TAPER RATIO	.35	.23	
● CANT	15°	15°	

Figure 10.- Winglet geometry comparisons.

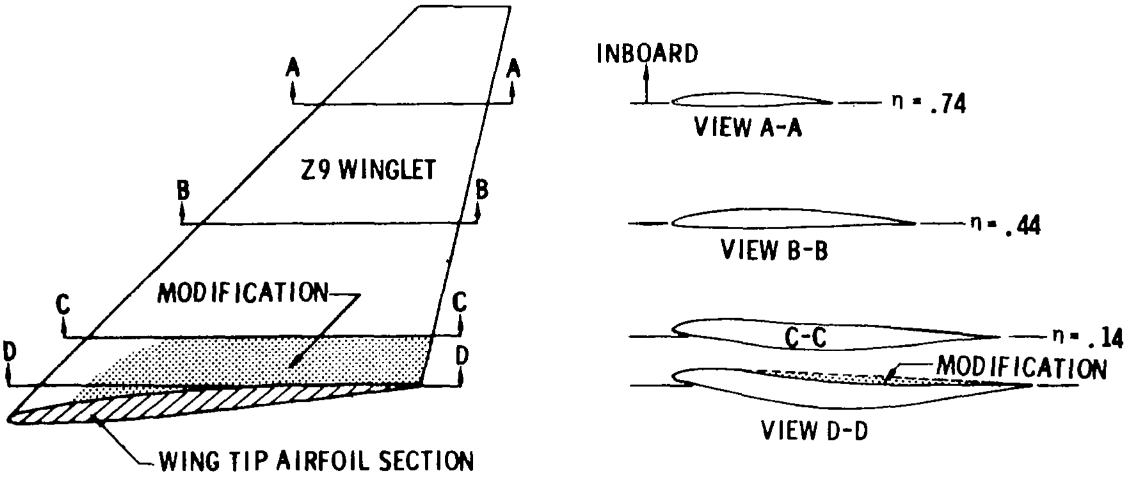


Figure 11.- Winglet cross sections for current test.

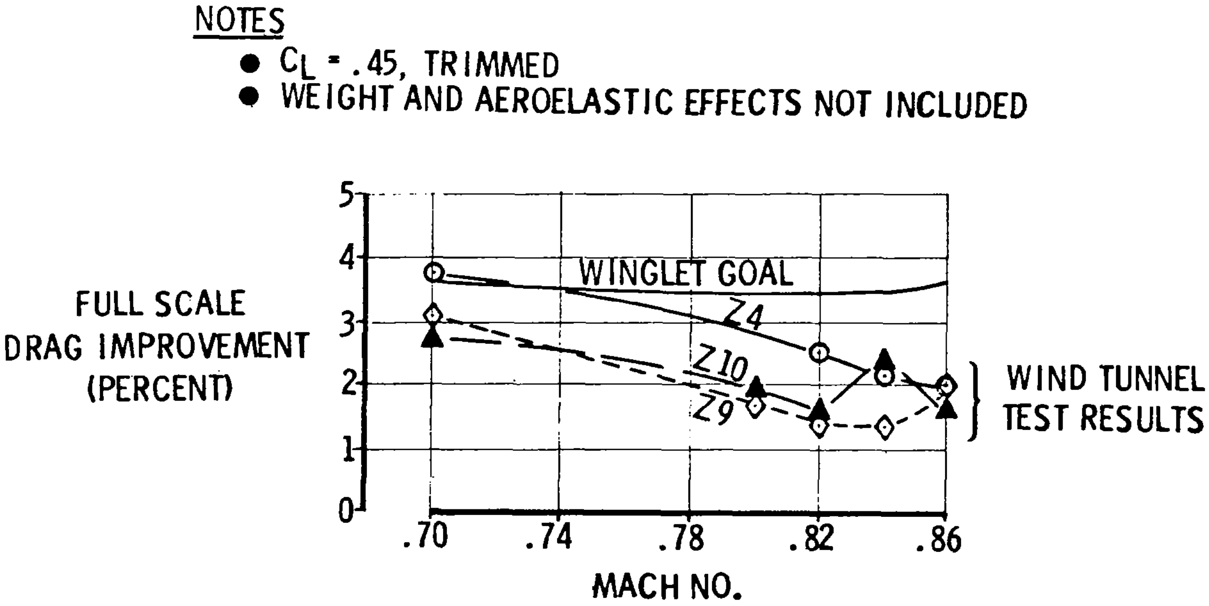
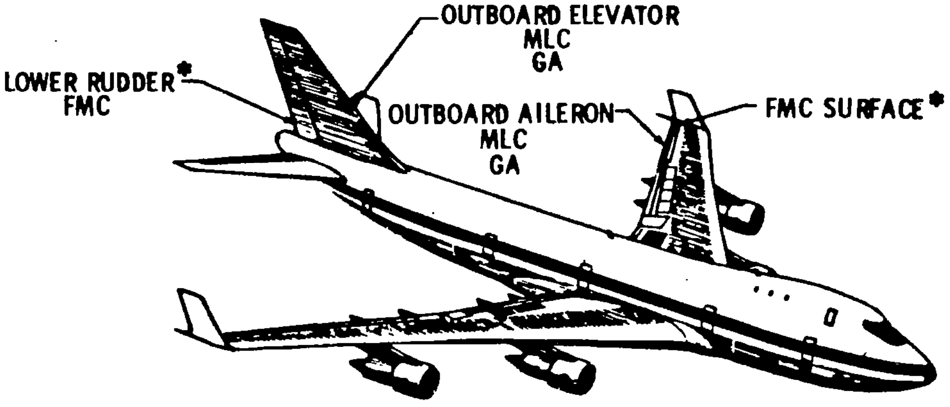


Figure 12.- Winglet drag comparisons.



*NOTE: CONTROL SURFACES TO BE USED FOR FMC NOT YET DEFINED

Figure 13.- WLA control surface locations for 747 EET.

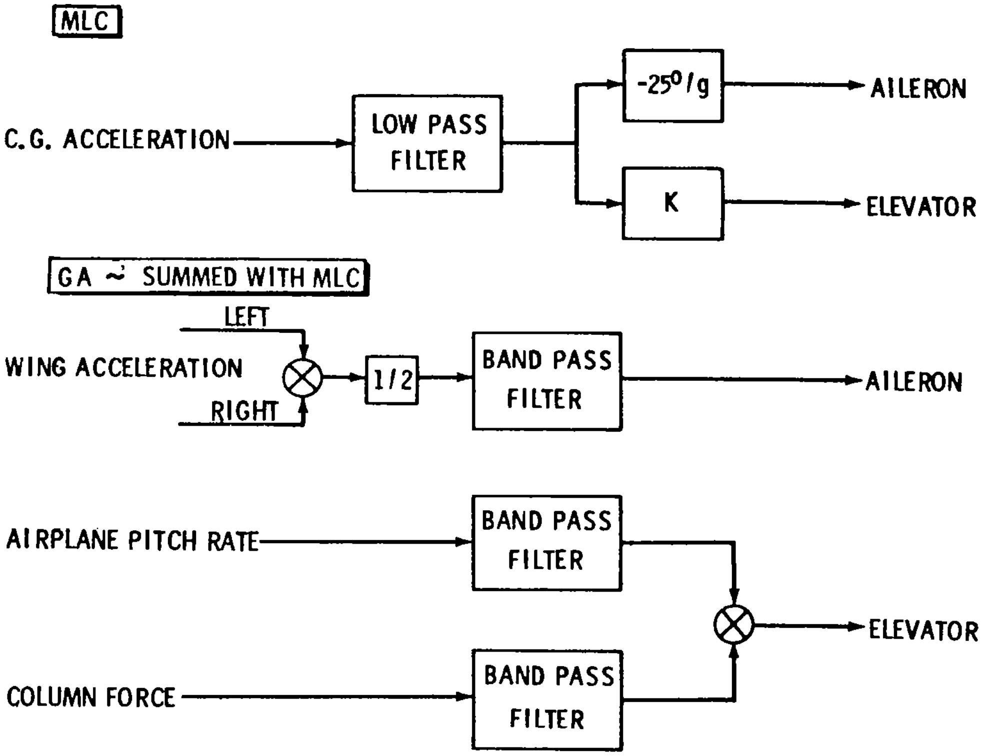


Figure 14.- MLC and GA system control laws.

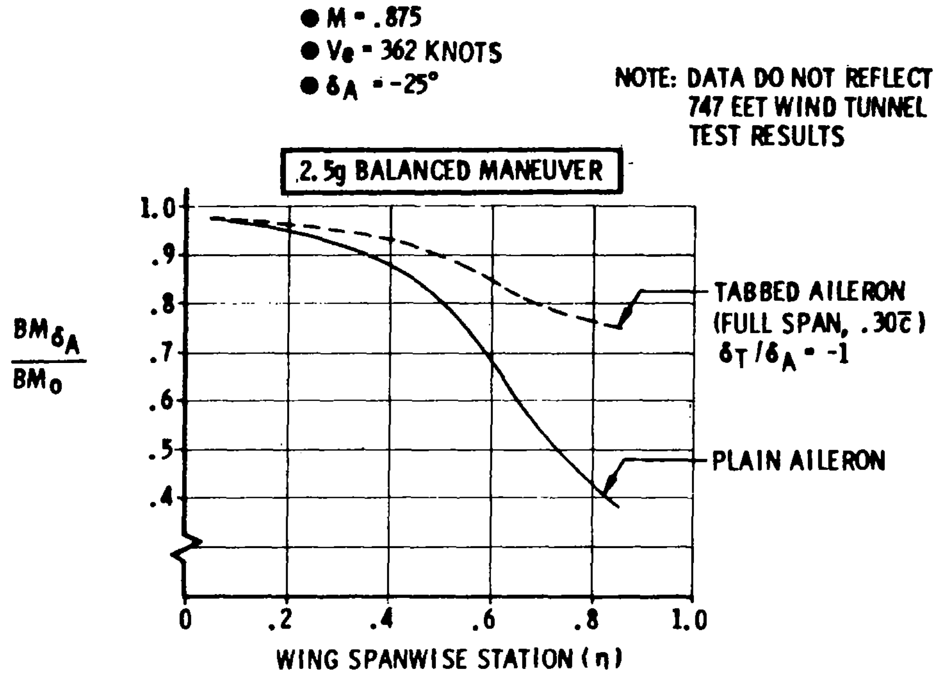


Figure 15.- Bending moment comparisons for plain and tabbed ailerons.

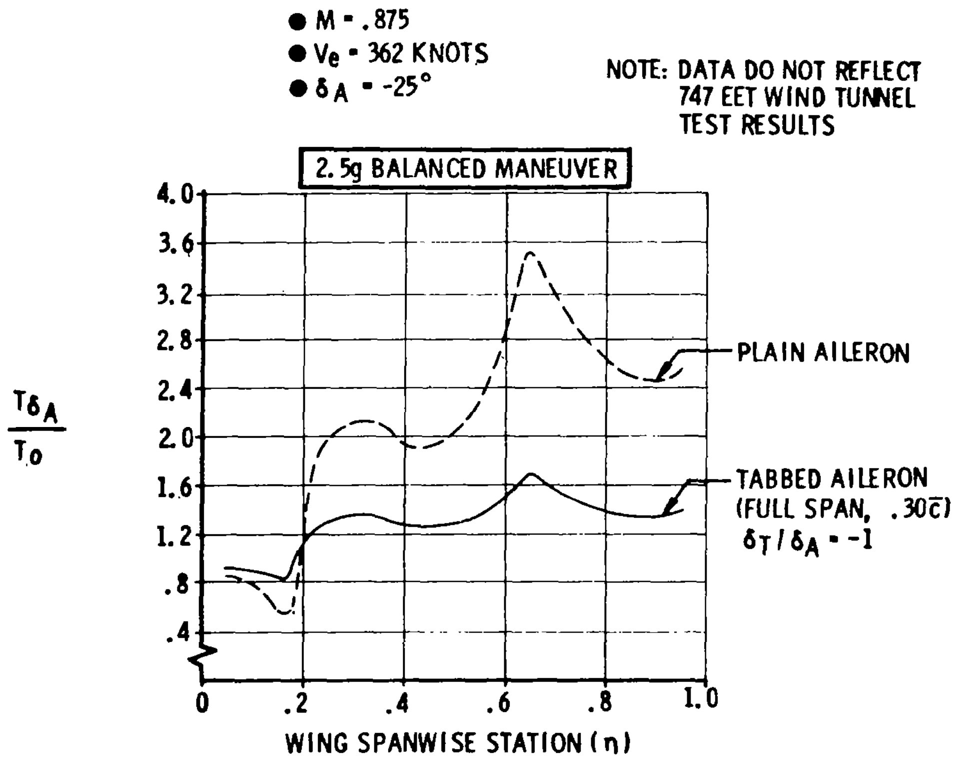


Figure 16.- Torsion comparisons for plain and tabbed ailerons.