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# DEVELOPMENT OF WEIGHT AND COST ESTIMATES FOR LIFTING SURFACES WITH ACTIVE CONTROLS

Final Report

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16. Abstract

Equations and methodology have been developed by the Boeing Commercial Airplane Company under contract NAS1-14064 for estimating the weight and cost incrementals due to active controls added to the wing and horizontal tail of a subsonic transport airplane. The methods are sufficiently generalized to be suitable for preliminary design. Supporting methodology and input specifications for the weight and cost equations are provided. The weight and cost equations are structured to be flexible in terms of the active control technology (ACT) flight control system specification. In order to present a self-contained package, methodology is also presented for generating ACT flight control system characteristics for the weight and cost equations. Use of the methodology is illustrated through a worked example.

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# DEVELOPMENT OF WEIGHT AND COST ESTIMATES FOR LIFTING SURFACES WITH ACTIVE CONTROLS

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## 1.0 SUMMARY

Equations and methodology have been developed for estimating the weight and cost incrementals due to active controls added to the wing and horizontal tail of a subsonic transport airplane. The methods are sufficiently generalized to be suitable for preliminary design.

The active control system functions considered include augmented stability (AS), maneuver load control (MLC), gust load alleviation (GLA), and flutter mode control (FMC).

Selections are made of the control surfaces used, surface size, deflection and rate, and level of redundancy for each of the preceding functions. The resulting surface hinge moments, actuator size, and power requirements are estimated. These quantities are the inputs to the equations for estimating control surface, control system, and power system weight increments.

Weight estimates are based on methods and equations developed in-house for preliminary design. The effects of the technologies expected to be available in 1990 have been applied (principally the use of composite materials in control surface structure) to derive a 1990 baseline weight. The additional control surface, actuation, etc., weight increments for active control technology (ACT) are then estimated with the same 1990 technology assumptions.

The costing methodology is similarly based on current methods, adjusted for 1990 weights, materials, and complexity factors, to which ACT costs based on engineering weight and complexity descriptions are added.

The scope of the work described in this report is restricted to estimation of the weight and cost *increments* due to incorporation of ACT functions in a baseline airplane. No estimate is made of the benefits accruing from ACT either to the baseline configuration or to a recycled design for a constant mission definition.

# 2.0 INTRODUCTION

## 2.1 BACKGROUND AND SCOPE

Active control technology (ACT) is defined as the use of automatic systems to provide stabilization, load reduction or redistribution, and structural mode damping in an airplane. Numerous studies, feasibility demonstrations, and military prototype airplanes have established the practicality and value of these systems in supersonic airplanes, STOL airplanes, and other aircraft with a difficult flight task or flight envelope. References 1 and 2 are excellent bibliographies.

The benefits of ACT to a conventional subsonic transport airplane configuration are more difficult to establish. Airplanes that have satisfactory mission performance, flying qualities, and structural characteristics can be and demonstrably have been designed without ACT. It is necessary to prove that the structural weight and drag reductions through the addition of ACT provide mission performance and economic benefits that are sufficient to offset the inevitable increase in complexity, weight, and cost of the added systems. Because of the sensitivity of these trades, design studies must be carried out to a significant level of detail to establish credible answers. Significant application of ACT to commercial airplanes is unlikely to occur unless substantial overall economic benefits can be shown.

The purpose of this report is to present methods for estimating weight and cost increments due to the addition of ACT functions to the lifting surfaces of a subsonic transport airplane. The methods are generalized and in a form usable in the type of design study described previously.

Previous work done by Boeing Commercial Airplane Company (BCAC) and the Boeing Wichita Division (BWD) has been extensively used in this study. As described in section 4.2, the baseline weight equations are those used by BCAC preliminary design and developed by in-house IR&D activity. BWD has done extensive analysis and flight demonstration of ACT systems in a B-52 airplane under a series of USAF contracts. This work (ref. 2) forms the background for the ACT functions, control surface selection and sizing, and control surface rate and bandwidth specifications developed in section 4.1. See figure 1 for the study flow plan.

## 2.2 AIRPLANE MISSION AND SIZE

The weight and cost estimating methodology developed in this report is valid for subsonic conventional takeoff and landing (CTOL) aircraft with design range from approximately 1000 to 10 000 km (540 to 5400 nmi) and maximum takeoff gross weights from 45 000 to 320 000 kg (100 000 to 700 000 lb). The baseline weight equations, shown in section 4.2.1, were developed from a statistical base covering aircraft with this size and design range.

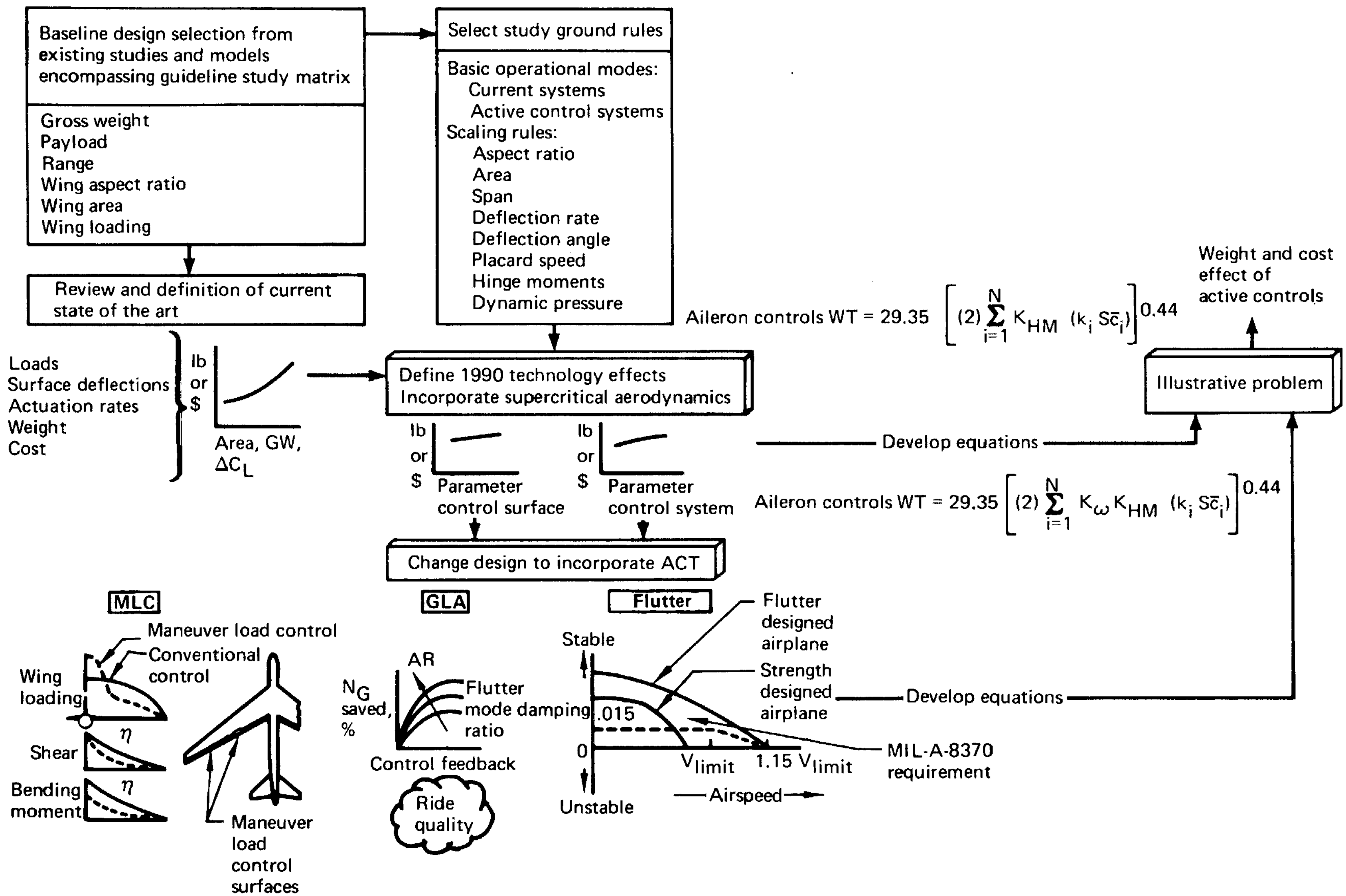



*Figure 1.—Study Plan*

## 2.3 DESCRIPTION OF ACT CONCEPTS

Active control technology is an airplane design concept in which vehicle performance, weight, and economic characteristics are optimized through a reliance on the flight control system to augment the airplane's stability, to reduce designing loads, and to manage the airplane's configuration for aerodynamic efficiency. The study aircraft incorporate maneuver and gust load control, flutter mode control, and augmented stability ACT functions. A good description of these ACT concepts is given in reference 3 and is repeated here for clarity.

*Maneuver load control (MLC)* is any method of redistributing wing lift during maneuvering flight. Incremental stresses may be reduced by symmetrically deflecting wing control surfaces in response to load factor commands in a manner that shifts the wing center of lift inboard, thus reducing wing-root bending moments.

*Gust load alleviation (GLA)* is any technique for reducing airframe peak transient loads resulting from gust disturbances. GLA encompasses control of rigid body and/or structural flexibility components of the airplane gust response. Gust load alleviation systems can also reduce fatigue rate damage and improve the ride qualities.

*Flutter mode control (FMC)* is any technique for actively damping flutter modes using aerodynamic surfaces. FMC provides potential for weight savings and/or extending flutter placard speeds.

*Augmented stability (AS)* is any technique used to eliminate the requirement for inherent airplane static or dynamic stability. This will typically mean introducing an augmentation system that provides the required safety and/or handling qualities. The AS concept will often mean that the final design can use a smaller empennage and more favorable balance with the corollary improvement of a generally smaller airplane. In a broad sense, this category includes concepts such as envelope limiting, which is considered either in lieu of high alpha (angle-of-attack) stability or as a means of reducing design load factor. AS provides better control response, which improves maneuvering performance. Relaxed static stability (RSS) is another name that has been applied to this concept.

For the class of aircraft being considered in this study, the requirement for active control technology functions is restricted to critical design areas of the operating envelopes. The aircraft will have "get-home" capability with the ACT function inoperative, since the ACT functions are used to expand the aircraft's operational envelopes. Figure 2 shows the aspects of envelope expansion due to ACT functions. Shaded areas represent the envelope expansion resulting from ACT incorporation. Specific features of envelope expansion due to ACT are the following:

- Augmented stability (longitudinal).-The airplane is balanced at or slightly aft of the neutral point for the landing approach flight condition. The handling qualities at the design condition must be rated at least adequate-pilot rating (PR) = 6.5.

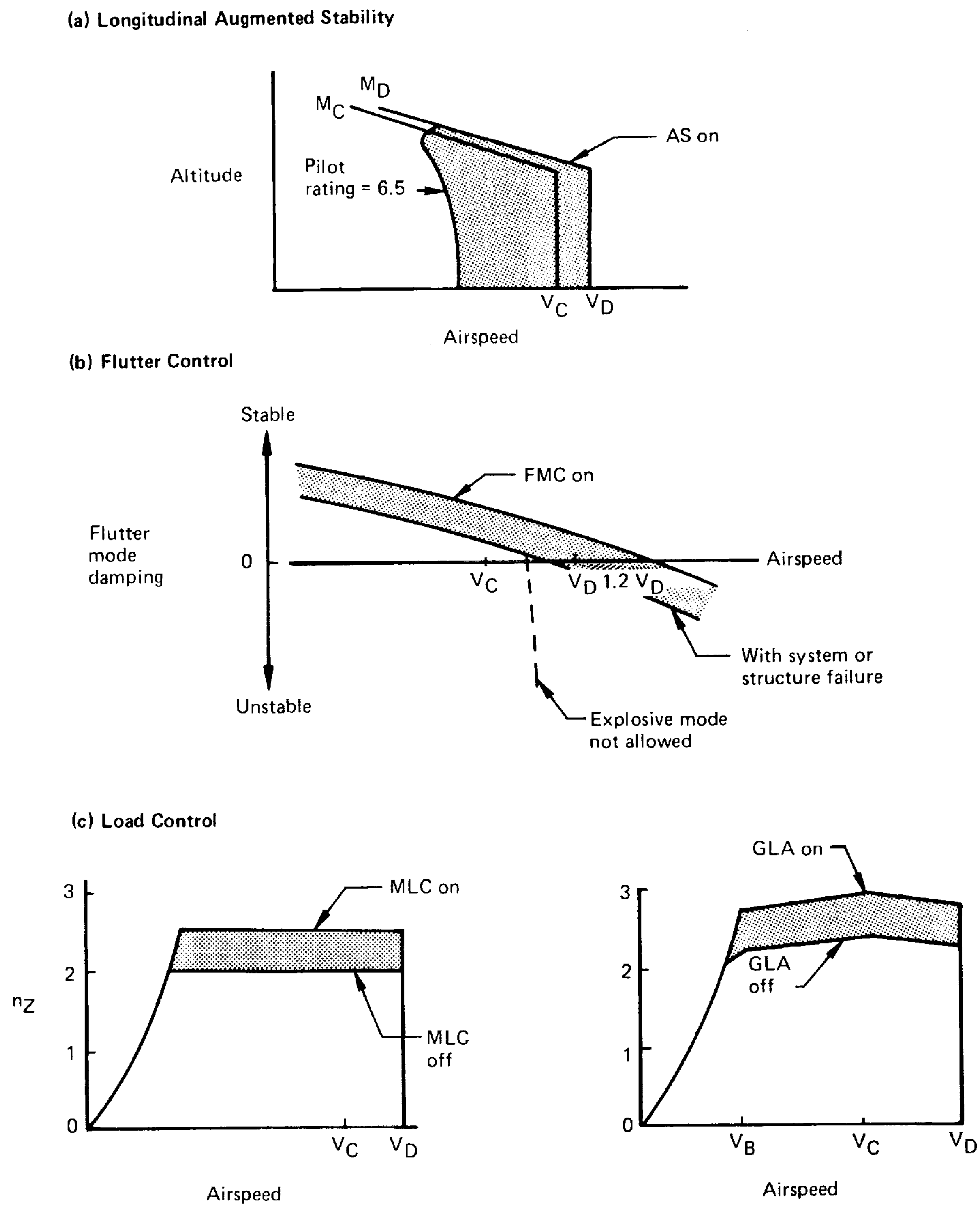



*Figure 2.—Operating Envelope Expansion Due to Active Controls*

- Flutter mode control.–The airplane is designed to have stable flutter modes for airspeeds less than the design cruising speed for normal operation ($V_C$). At speeds greater than $V_C$ but less than 1.2 $V_D$ (design dive speed), predicted flutter modes are nonexplosive (e.g., change in damping with airspeed is not abrupt).

- Maneuver and gust load control.–Airplane structure is designed to FAR Part 25 fail-safe strength boundaries for maneuvering and gust loads (section 25.571.C), and to normal boundaries with the system operative.

# 3.0 ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| ACT | active control technology |
| AIA | inboard aileron area, $m^2$ ($ft^2$) |
| AIF | inboard trailing-edge flap area, $m^2$ ($ft^2$) |
| AISP | inboard spoiler area, $m^2$ ($ft^2$) |
| ANET | fixed trailing-edge net area, $m^2$ ($ft^2$) |
| AOA | outboard aileron area, $m^2$ ($ft^2$) |
| AOF | outboard trailing-edge flap area, $m^2$ ($ft^2$) |
| AOSP | outboard spoiler area, $m^2$ ($ft^2$) |
| A/P | airplane |
| AR | aspect ratio |
| AS | augmented stability |
| $\bar{c}$ | mean chord |
| CCV | control configured vehicle |
| c.g. | center of gravity |
| $C_H$ | hinge moment coefficient |
| $C_{H_0}$ | hinge moment coefficient for Whitcomb airfoil for $c_s/c_W$ = 0.25 and $\delta = 0$ |
| $C_\ell$ | section lift |
| $C_{L_{buffet}}$ | lift coefficient for buffet onset |
| $C_{L_\delta}$ | change in lift coefficient for a unit change in deflection angle |
| $C_p$ | local pressure coefficient |
| $c_s$ | control surface local chord, m (in.) |
| CTOL | conventional takeoff and landing |

| | |
|---|---|
| $\bar{c}_w$ | wing mean aerodynamic chord, m (in.) |
| $c_w$ | local wing chord, m (in.) |
| FBW | fly by wire |
| FCS | flight control system |
| FMC | flutter mode control |
| GLA | gust load alleviation |
| GW | gross weight, kg (lb) |
| h | altitude |
| HM | surface hinge moment, N·m (lb-in.) |
| $HM_a$ | hinge moment per actuator, N·m (lb-in.) |
| HL | hinge line |
| inbd | inboard |
| KEAS | knots estimated airspeed |
| $K_{HM}$ | correction factor for supercritical aerodynamic effects on hinge moment |
| $K_{load}$ | function of tail unit loading |
| $K_{\alpha}$ | changes in hinge moment coefficient due to changes in surface chord ratio (angle of attack) |
| $K_{\delta}$ | changes in hinge moment coefficient due to changes in surface chord ratio (control surface deflection) |
| $K_{\lambda}$ | function of tail surface taper ratio; theoretical tip chord/theoretical root chord |
| $K_{\omega}$ | correction factor for nonstandard actuation rate |
| $K_{\%}$ | function of elevator planform chord/planform tail surface chord |
| LE | leading edge |
| M | Mach number |
| M.G. | main landing gear |

| | |
|---|---|
| MLC | maneuver load control |
| $N_G$ | ultimate gust load factor |
| $n_{max}$ | maximum limit load factor |
| $n_Z$ | load factor |
| OEW | operating empty weight |
| outbd | outboard |
| P | actuator power, kW (hp) |
| PBW | power by wire |
| PFC | primary flight control |
| PR | Cooper Harper pilot rating |
| PTU | power transfer unit |
| q | dynamic pressure, $N/m^2$ ($lb/ft^2$) |
| RSS | relaxed static stability |
| $S\bar{c}_i$ | aileron area moment about hinge line for the individual aileron panel, $m^3$ ($ft^3$) per side |
| $S_s$ | control surface area, $m^2$ ($ft^2$) |
| $S_w$ | wing area, $m^2$ ($ft^2$) |
| t | time |
| t/c | wing maximum thickness ratio |
| TE | trailing edge |
| $V_B$ | design speed for maximum gust intensity, km/hr (kn) |
| $V_C(M_C)$ | design cruising speed (Mach) |
| $V_D(M_D)$ | design dive speed (Mach) |
| $V_e$ | equivalent airspeed, km/hr (kn) |
| W/S | wing loading, $N/m^2$ ($lb/ft^2$) |

| | |
|---|---|
| $x/c$ | normalized wing chord location, percent |
| $y/c$ | normalized wing thickness, percent |
| $\delta$ | surface deflection, rad (deg) |
| $\dot{\delta}$ | surface deflection rate, rad/s (deg/s) |
| $\delta_a$ | aileron deflection, rad (deg) |
| $\delta_{max}$ | maximum surface deflection, rad (deg) |
| $\dot{\delta}_{max}$ | maximum surface deflection rate, rad/s (deg/s) |
| $\Delta C_{H_{airfoil}}$ | incremental change in hinge moment coefficient due to airfoil type |
| $\Delta C_{H_{\delta}}$ | incremental change in hinge moment coefficient due to control deflection |
| $\Delta C_L$ | change in lift coefficient |
| $\Delta C_{L_{ail}}$ | change in lift due to deflecting one aileron panel |
| $\Delta P_a$ | differential pressure across the actuator piston, $MN/m^2$ ($lb/in^2$) |
| $\Delta W$ | weight increment, lb |
| $\eta$ | spanwise location (percent span) |
| $\lambda$ | taper ratio |
| $\Lambda_{HL}$ | hinge line sweep angle, rad (deg) |
| $\Lambda_{0.5\bar{c}}$ | midspan wing sweep, rad (deg) |
| $\dot{\omega}$ | pitch acceleration, $rad/s^2$ ($deg/s^2$) |
| $\omega_{ACT}$ | actuator bandwidth, rad/s (deg/s) |

# 4.0 DISCUSSION

Equations have been developed for calculating control surface and actuation weights and costs for implementing active control technology functions. These equations are generalized for the aircraft missions and sizes defined in section 2.2. Supporting methodology and input specifications are provided for the weight and cost equations, which are structured to be flexible in terms of the ACT flight control system specification. In order to present a self-contained package, methodology is also presented for generating ACT flight control system characteristics for the weight and cost equations.

## 4.1 FLIGHT CONTROL SYSTEM (FCS)

This section describes a set of inputs that define the active control technology features of the flight control system for the control surface and actuation weight and cost equations. The contract statement of work (ref. 4) states that the weight and cost equations shall account separately for the control surface itself, for actuating electrical and hydraulic systems, and for the impact on wing structure due to the addition of ACT features. This description is limited to only those aspects of the FCS that are directly affected by the addition of ACT, including (1) those parts of the primary FCS that are used for ACT, (2) dedicated ACT control surfaces, (3) actuator modifications or additions for ACT, and (4) hydraulic and electrical system modifications for ACT. Thus, the description accounts only for the addition of ACT functions to an FCS, not for the total FCS.

In order to quantitize the weight and cost of incorporating active control technology features, the 747 flight control system was defined as the study baseline. All 747 primary control surfaces are powered by irreversible hydraulic actuators and are signaled mechanically. The actuators are supplied by four independent hydraulic systems. All primary control surfaces, except for the spoilers, use dual-tandem actuators. Each cylinder of the dual-tandem actuator can drive its control surface at full rate and achieve adequate authority. Each spoiler panel is actuated by a single linear actuator. The lateral control system (i.e., ailerons and spoilers) has a central secondary electrohydraulic actuator for electrical autopilot commands. The rudders also have secondary electrohydraulic actuators for series lateral-directional stability augmentation signals. Specific characteristics of the baseline flight control system are presented in table 1.

Major elements of the flight control system description include a definition of control system requirements, redundancy considerations, hinge moment prediction, actuator requirements, and hydraulic and electrical system sizing. These elements are described in the following paragraphs, and the relationship between each element and the weight and cost equations is shown in figure 3.

*Table 1.—Baseline Primary Flight Control System Properties*

| Control surface | Number per airplane | $\frac{S_s}{S_w}$ | $\frac{\bar{c}_s}{\bar{c}_w}$ | $\dot{\delta}_{max}$, deg/s | $\delta_{max}$, deg | Actuator type | Hydraulic supply (number per surface) |
|---|---|---|---|---|---|---|---|
| Inboard aileron | 2 | 0.0065 | 0.23 | 47 | ±20 | Dual tandem | 2 |
| Outboard aileron | 2 | 0.0139 | 0.11 | 54 | -25/15 | Dual tandem | 2 |
| Inboard spoilers | 2 | 0.0063 | 0.17 | 75 | 45 | Single cylinder | 1 |
| Outboard spoilers | 8 | 0.0038 | 0.12 | 75 | 45 | Single cylinder | 1 |
| Elevator | | | | | | | |
| Outboard | 2 | 0.0141 | 0.16 | 45 | -23/17 | Dual tandem | 2 |
| Inboard | 2 | 0.0156 | 0.27 | 38 | -23/17 | Dual tandem | 2 |

Note: Baseline = B747.

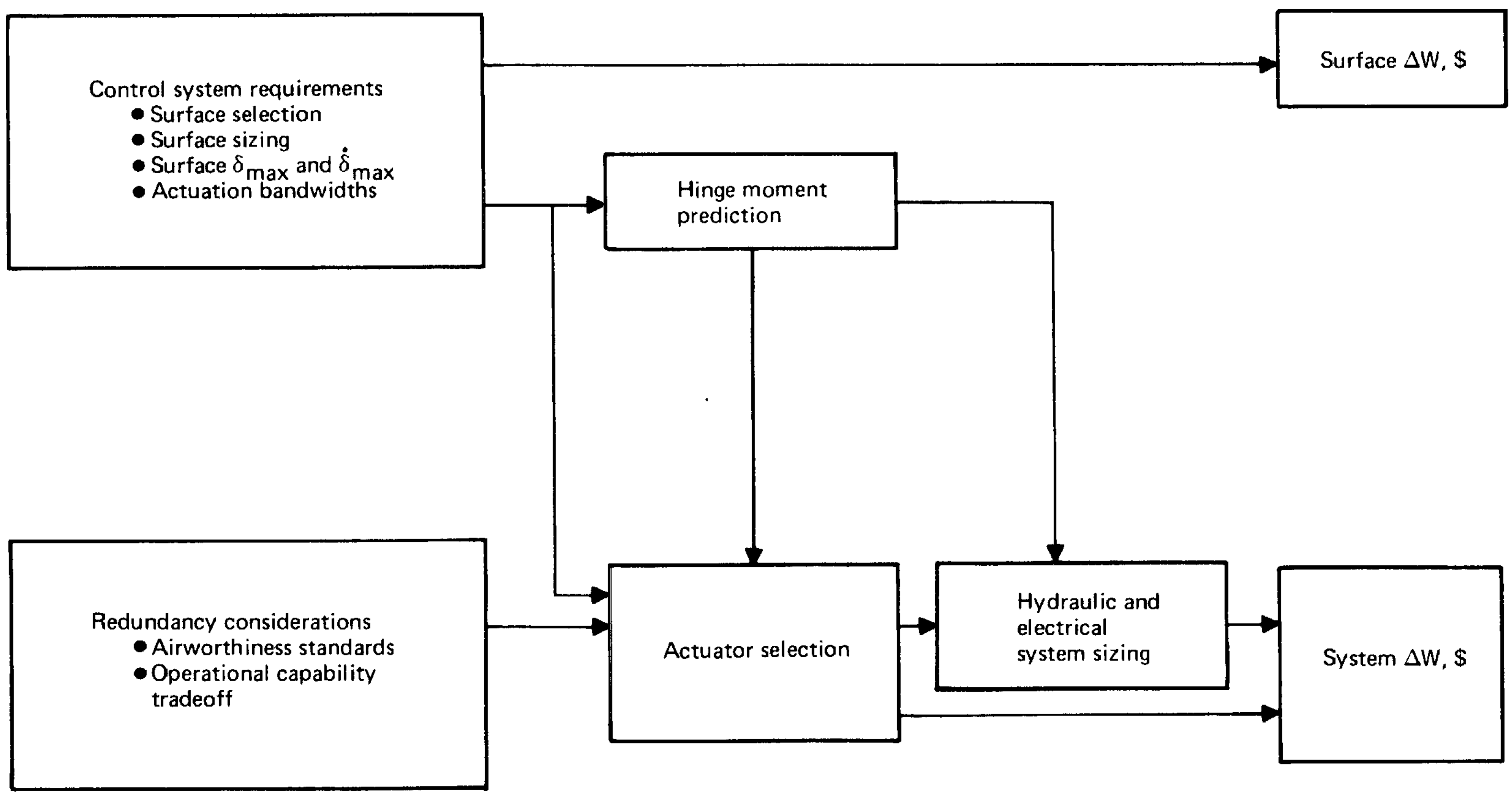



*Figure 3.—Flight Control System Analysis Flow Chart*

### 4.1.1 CONTROL SYSTEM REQUIREMENTS

The specification of control system requirements includes control surface selection, sizing, authority and rate limits, and actuation bandwidths. The specification is made for four ACT concepts: viz, augmented stability, gust load alleviation, maneuver load control, and flutter mode control. Generalized ACT control system characteristics are presented in table 2.

**Control Surface Selection**

Recommended ACT control surfaces are shown in figure 4 with the function of each surface defined by the inset table. The ACT control system uses some primary control surfaces (e.g., horizontal tail) and some new surfaces (e.g., load control flap), but it does not use wing leading-edge devices.

Leading-edge (LE) flap/slats on high-aspect-ratio wings, which are designed for low-speed stall protection, are poor devices for ACT from both an aerodynamic and a mechanization standpoint. Aerodynamically, these devices are very nonlinear ($c_\ell \not\propto \delta$), and they do not generate significant lift at constant angle of attack. Current LE devices are designed for down-motion with only one or two positions (i.e., takeoff and landing), and they have slow extension/retraction rates. Any attempt to add up-motion and rapid deflection rates would greatly penalize the low-speed aerodynamic performance of the wing.

The assumption has been made that each wing panel has at least one engine and that any flutter mode (fig. 2) can be handled through proper engine location and with an outboard control surface. A section of the outboard aileron is used for flutter control. The flutter control surface is sized to have the same control effectiveness (i.e., $C_{L_\delta}$) as the B-52 control configured vehicle (CCV) outboard flutter control surface. The inboard section of the outboard aileron is used since it is the stiffest part of the aileron.

Trailing-edge (TE) segments of the high-lift flaps and the outboard spoilers are used for load control. The maneuver load control system reduces wing bending moments by loading the inboard wing section with the inboard load control flap and unloading the outboard section of the wing with either the outboard spoilers or the outboard load control flap. A detailed structural analysis is required in order to make a selection between spoiler and flaps for MLC. Reference 5 points out that care must be taken in selecting the MLC control surface since adverse sectional pitching moments increase the requirement for torsional stiffness material. The gust load alleviation system uses the outboard load control flaps for suppressing loads due to continuous turbulence and the spoilers for dumping loads that result from discrete winds. In addition to the wing control surfaces, the horizontal tail is also used for gust load alleviation, reducing gust loads by providing pitch attitude stiffness.

The design requirements for the load control flaps have a major impact on the high lift and the load control actuation system. The design requirements for the load control flaps are:

*Table 2.—Active Control Technology System Features*

| ACT control surface | Number of panels/airplane | $\frac{S_s}{S_w}$ | $\frac{\bar{c}_s}{\bar{c}_w}$ | $\dot{\delta}_{max}$, deg/s | $\delta_{max}$, deg | $\omega_{ACT}$, rad/s |
|---|---|---|---|---|---|---|
| Inboard load control flap | 2 | 0.0157 | 0.112 | 5→10 | ±10 | 5 |
| Outboard load control flap | 2 | 0.0151 | 0.078 | 30→50 | ±10 | 15 |
| Outboard spoiler | 10 | 0.0037 | 0.114 | 30→50 | 45 | 15 |
| Flutter mode control flap | 2 | 0.0057 | 0.119 | 80→100 | ±10 | 40 |
| Slab horizontal tail | 1 | 0.191 | 0.541 | 9.6 | ±10 | 15 |
| or | | | | | | |
| Elevator | | | | | | |
| Inboard | 2 | 0.0135 | 0.178 | 30→50 | ±25 | 15 |
| Outboard | 2 | 0.0120 | 0.154 | 30→50 | ±25 | 15 |

| Control surface | AS | MLC | GLA | FMC |
|---|---|---|---|---|
| Flutter flap | | | | X |
| Outbd load flap | | X | X | |
| Inbd load flap | | X | | |
| Horizontal tail | X | | X | |
| Outbd spoiler | | X | X | |

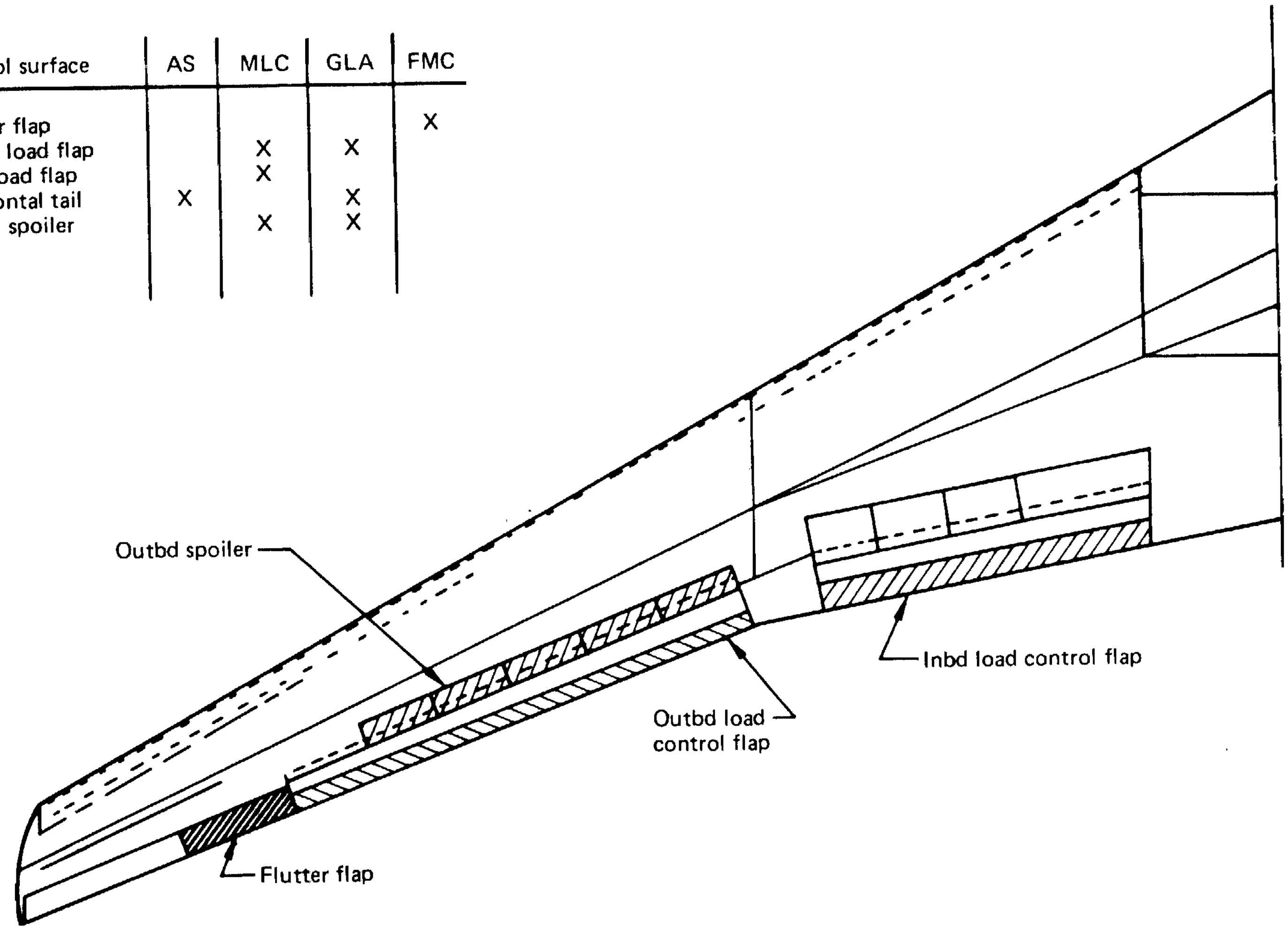



*Figure 4.—ACT Control Surfaces*

1. Up and down motion

2. Flaps retracted and extended operation

3. Rigid flap structure for good frequency response (i.e., minimal phase lag and good gain margin) for MLC and GLA

These requirements are satisfied with an externally hinged, double-slotted flap. (See sec. 4.1.3 for detailed background information pertaining to this section.) The double-slotted flap is designed to have a large aft segment to house a power-by-wire (PBW) actuator. The PBW actuator has a self-contained hydraulic pump and reservoir and is signaled electrically. These actuators are selected for the load control flaps to avoid carrying hydraulic supply lines across the hinge of the high-lift flap. Figure 5 shows the integration of the load control surface with a double-hinged flap and the PBW actuation scheme. The size of the load control flap is dependent on the size of the PBW actuator since both must fit within the geometry of the aft flap segment.

The horizontal tail is used for augmented stability and gust load control, as discussed previously. A slab tail and the aft airplane balancing philosophy of augmented stability yield the minimum horizontal tail size.

### Control Surface Sizing

The wing control surface configuration shown in figure 4 is representative of most subsonic CTOL aircraft. The inboard aileron is placed behind an engine and at the break in the TE, and the outboard aileron runs from the edge of the outboard flap to the wingtip. The percentage of the wing devoted to high-lift devices and ailerons is fairly constant since most CTOL aircraft have similar high-lift requirements for takeoff and landing. Spoilers in addition to the ailerons are sized for roll control power. Again, a fixed relationship exists between control surface size and airplane size (i.e., bigger airplanes need larger control surfaces for a specified response). Because of this similarity in control surface configuration for different sized airplanes, control surface volume (area times chord) is assumed to be proportional to the product of wing area and chord.

### Control Surface Authority

Control surface authority for the flutter and load control flaps is set at 10°. This limit is selected to provide linear control effectiveness for FMC and GLA commands. Supercritical airfoils, which have been assumed for this study, are designed with trailing-edge camber. Because of the aft camber, these airfoils are heavily loaded for no control deflection and stall early for downward control deflections. This characteristic is highlighted in figure 6, which shows the change in aileron effectiveness with aileron deflection for a supercritical airfoil.

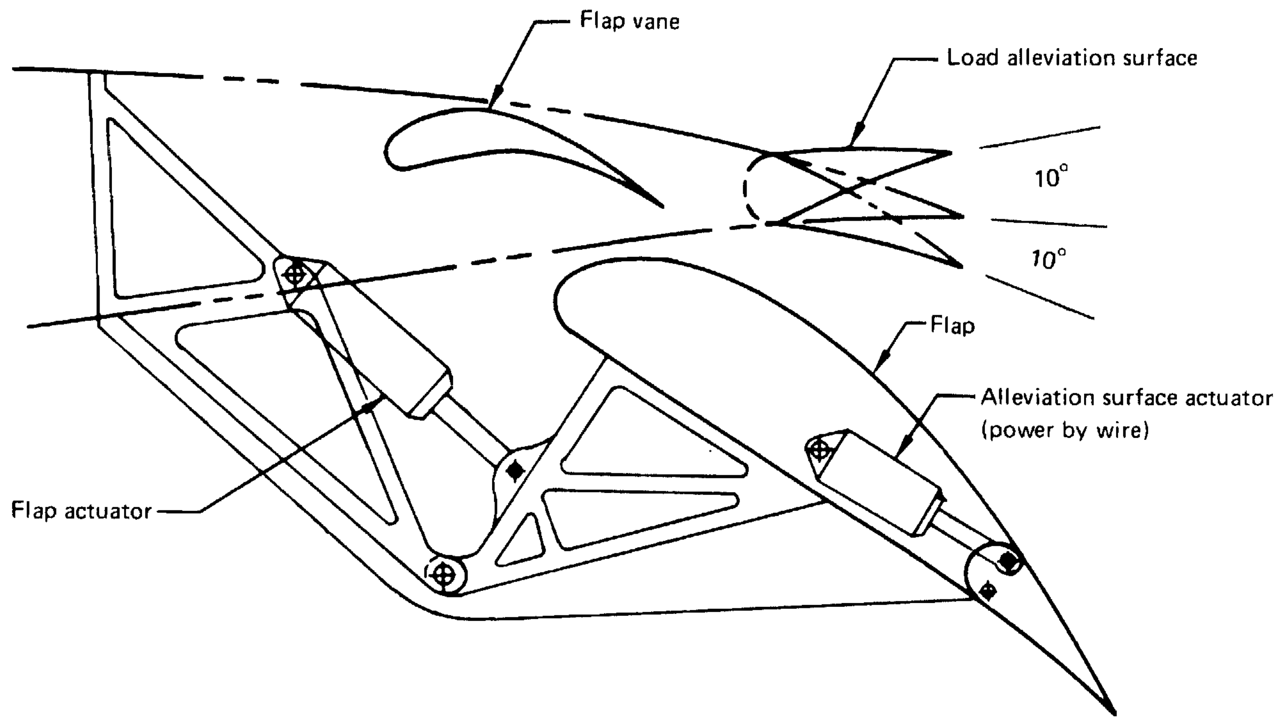



*Figure 5.—Externally Hinged Flap With Load Alleviation Surface Driven by an Actuator in the Translating Flap*

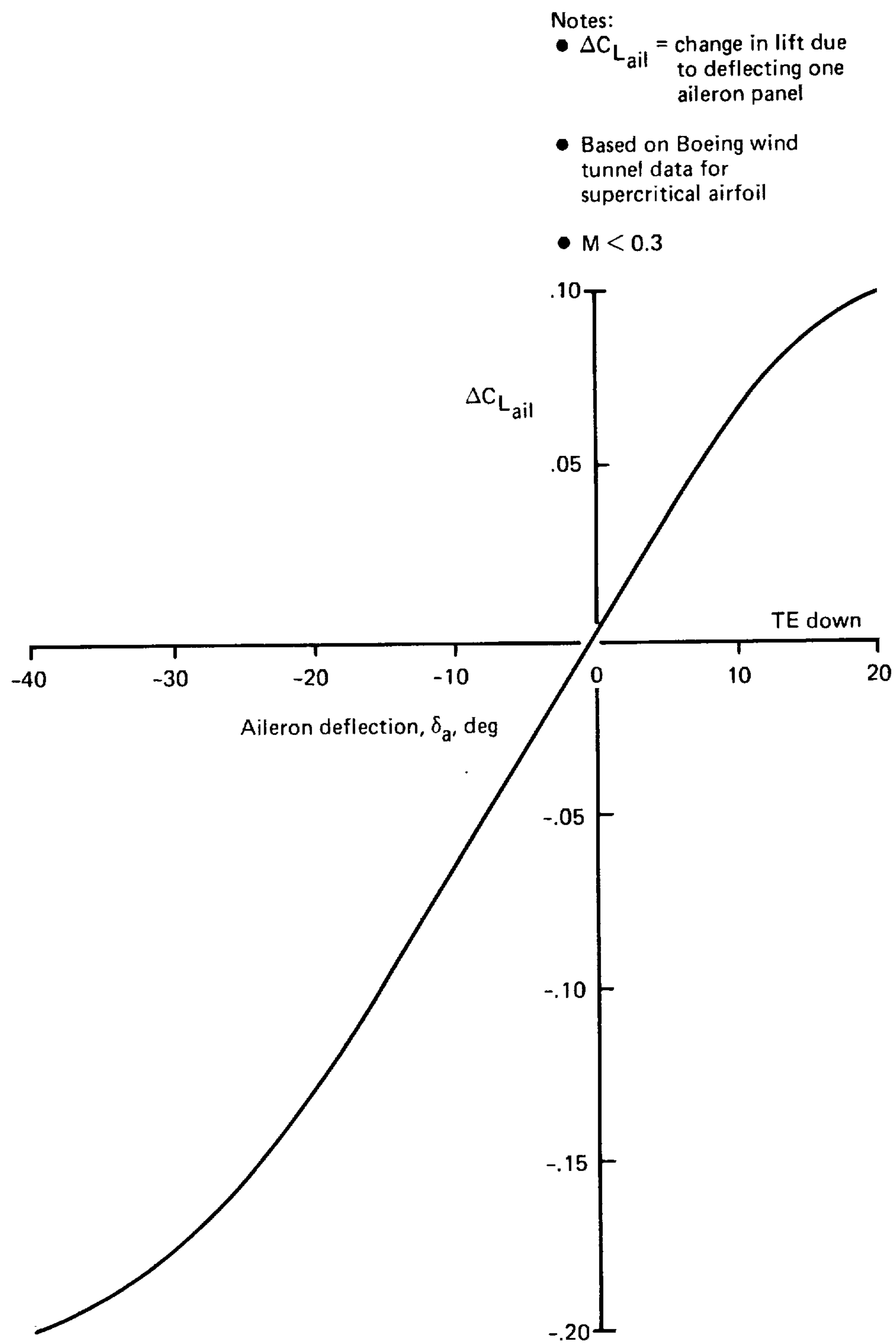



*Figure 6.—Effect of Control Deflection on Lift Linearity for Supercritical Airfoil*

### Control Surface Rate

The required control surface rate is a function of the mode being controlled and the size of the control surface. Since the significant parameter is the generated acceleration per unit of time (e.g., $\Delta n_Z/\Delta t$), an acceptable large surface would have a lower surface actuation rate than a smaller one. Since gust load and fatigue rate reduction dominant frequencies are similar to the basic maneuvering frequencies, normal control surface rates will be adequate for these modes (e.g., 30-50°/s). Since the maneuver load control is a retrimming function, slower surface rates are acceptable (e.g., 5-10°/s). Flutter mode suppression requires rapid surface actuation (e.g., 80-100°/s).

### Actuation Bandwidth

Actuation bandwidth requirements are related to dominant airplane frequencies. In general, actuator bandwidths should be one decade faster than the dominant frequency. With this separation between the dominant frequency and the actuator bandwidth, the phase lag due to the actuator at the dominant frequency is minimized. Typical dominant frequencies and actuator bandwidths are given in the following list:

| Mode | Dominant frequency, rad/s | Actuator bandwidth, rad/s | (Hz) |
|---|---|---|---|
| Pitch and roll maneuvering | 1.5 | 15 | (2.39) |
| Maneuver load control | 0.5 | 5 | (0.80) |
| Gust load alleviation | 1.5 | 15 | (2.39) |
| Flutter mode suppression | 25 | 40 | (6.37) |

## 4.1.2 REDUNDANCY CONSIDERATIONS

System redundancy for active control technology functions is addressed to define the required number of actuators and the hydraulic system distribution. Flight control system computer and sensor redundancies are not included. The approach taken relates redundancy level to operational mission requirements and to the extent of flight envelope expansion due to ACT for a given set of safety rules.

Operational mission requirements pertain to dispatch capability with failed system(s) and the ability to sustain full flight envelope operation after system failure(s). The development of redundancy requirements is based on the assumption that the airplane has an operable channel for retreating to a safe regime of the flight envelope.

The recommended redundancy requirements satisfy the system failure paragraphs of FAR Part 25, sections 25.671 and 25.672. Section 25.671 defines types of failure states, and section 25.672 defines flying qualities with failed automatic systems. Pertinent paragraphs from sections 25.671 and 25.672 that directly relate to the formulation of redundancy requirements are paraphrased as follows:

- Section 25.671c: The airplane must be shown to be capable of continued safe flight and landing after any of the following failures or jamming in the flight control system and surfaces (including trim, lift, drag, and fuel systems):

1. Any single failure, excluding jamming (for example, disconnection or failure of mechanical or electrical elements)

2. Any combination of failures not shown to be extremely improbable, excluding jamming (for example, dual electrical or hydraulic system failures, or any single failure in combination with any probable hydraulic or electrical failure)

3. Any jamming in a control position unless the jamming is shown to be extremely improbable or can be alleviated (A runaway of a flight control to an adverse position and jamming must be accounted for if such runaway and subsequent jamming are not extremely improbable.)

- Section 25.672: It must be shown that the following conditions exist after any single failure of the stability augmentation system or any other automatic or power-operated system:

  1. The airplane is safely controllable when the failure or malfunction occurs at any speed or altitude that is within the approved operating limitations and critical for the type of failure being considered.

  2. The controllability and maneuverability requirements of this Part are met within a practical operational flight envelope.

  3. The trim, stability, and stall characteristics are not impaired below a level needed to permit continued safe flight and landing.

Redundancy configurations for augmented stability, flutter mode control, maneuver load control, and gust load alleviation are shown in figure 7. Each channel is assumed to have an actuator, a hydraulic supply, and an electrical input resulting from sensor signals that have been processed by a flight control system computer.

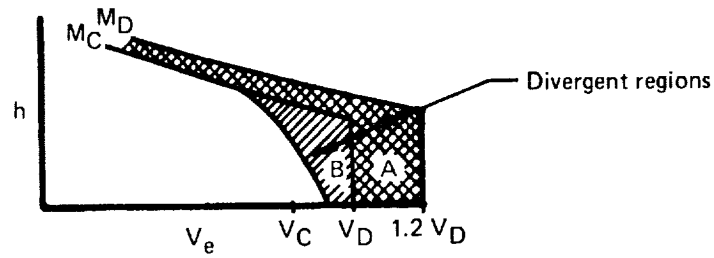
### 4.1.3 ACTUATOR SELECTION

Hydraulic actuation is considered the only practical means to provide the load capability, response, and accuracy required for active controls. Multiple actuators consistent with the selected redundancy level are required for all ACT surfaces except the spoilers, and they must be sized to provide sufficient authority that the airplane can be flown to a safe flight regime on the remaining active channel(s) during partial failure conditions.

ACT commands will undoubtably be electric, and a number of electrically commanded hydraulic servoactuator types can be considered for the various ACT surfaces. Final choices will depend on a number of factors, including how much space is available for installation and whether or not they will also be used for basic flight control functions.

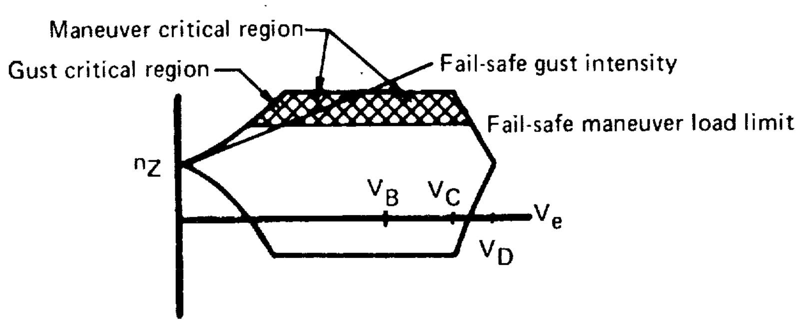
Possible types for the various active control surfaces likely to be considered are described in the following paragraphs.

**(a) Flutter and Augmented Stability**




| Reliability conf. number | Dispatch capability with failed system | Flight envelope operational capability | Required redundancy |
|---|---|---|---|
| R1 (region A) | Permitted with restricted flight envelope | $V_C/M_C$ must be reduced after failure | 1 |
| R2 (regions A and B) | Permitted with restricted flight envelope | $V_C/M_C$ must be reduced after first failure | 2 |
| R3 (regions A and B) | Permitted with no restriction for first failure; restricted after second failure· | Flight envelope must be restricted after second failure | 3 |

**(b) Maneuver Load Control and Gust Load Alleviation**




| Reliability conf. number | Dispatch capability with failed system | Flight envelope operational capability | Required redundancy |
|---|---|---|---|
| R4 | Permitted with restricted flight envelope (GLA) or maneuvering (MLC) | Flight envelope (GLA) or maneuvering (MLC) restricted after first failure | 2 |
| R5 | Permitted with no restriction for first failure; restricted after second failure | Flight envelope (GLA) or maneuvering (MLC) must be restricted after second failure | 3 |

*Figure 7.—Flight Envelope-Redundancy Level Requirements*

## Trailing-Edge Flap Load Control Surface Actuation

Actuation of the trailing-edge load control flaps poses a difficult design problem and will probably influence the basic design of the high-lift flap itself. Although actuation will likely be required only when the flaps are fully retracted, the actuator installation must accommodate the flap motion during extension. Two or more actuators located along the span of each surface will be required, depending on the degree of redundancy selected.

Actuation of the aft flap of a conventional double- or triple-slotted flap with large Fowler motion would probably require that the actuators be attached to the wing rear spar. This would require a means of providing a relatively large amount of overtravel in the output linkage to accommodate the Fowler motion. One possible mechanism is shown in figure 8 where actuator output motion is transmitted to the aft segment load control surface through a spline shaft to a universal coupling connected to bell crank linkage and to a push rod to the control surface. However, this scheme is subject to excessive backlash in the translating spline shaft couplings, which could produce undesirable deadband in the control system.

The latter problem could be avoided by mounting the actuators in the aft flap directly connected to the load control surface. If the aft-flap surface is large enough, such as in the double-slotted externally hinged arrangement shown in figure 5, the load control surface actuators can be buried completely within the flap envelope.

Although this obviates the need to provide overtravel in the output linkage, it introduces a problem for the hydraulic lines to the actuators. Consideration could be given to the use of flexible hose, swivel joints, or hydraulic linear extension units to accommodate the translation during flap extension. However, concern that leaks could develop that could completely bleed down the affected hydraulic system, because of failure of a hose or a seal in a swivel joint or extension unit, is justified considering the load and vibration environment and the exposure to mechanical damage that would exist.

Hydraulic lines can be avoided by use of integrated power-by-wire servoactuator packages. These PBW actuators incorporate an electric-motor-driven hydraulic pump, fluid reservoir, servovalve, and actuator in the same assembly. Such units have been used on three British production aircraft: the VC-10 airliner, the Vulcan bomber, and the Belfast cargo carrier. Continued development and refinement of the concept are expected in order to meet survivability requirements for U.S. military aircraft.

Electric power from the aircraft system will be required for these units, and it is expected that flexible electric cables, electrical swivel joints, or extension units should prove satisfactory. Similarly, electric command signaling would be simpler than a mechanical input system designed to accommodate translation of the flap.

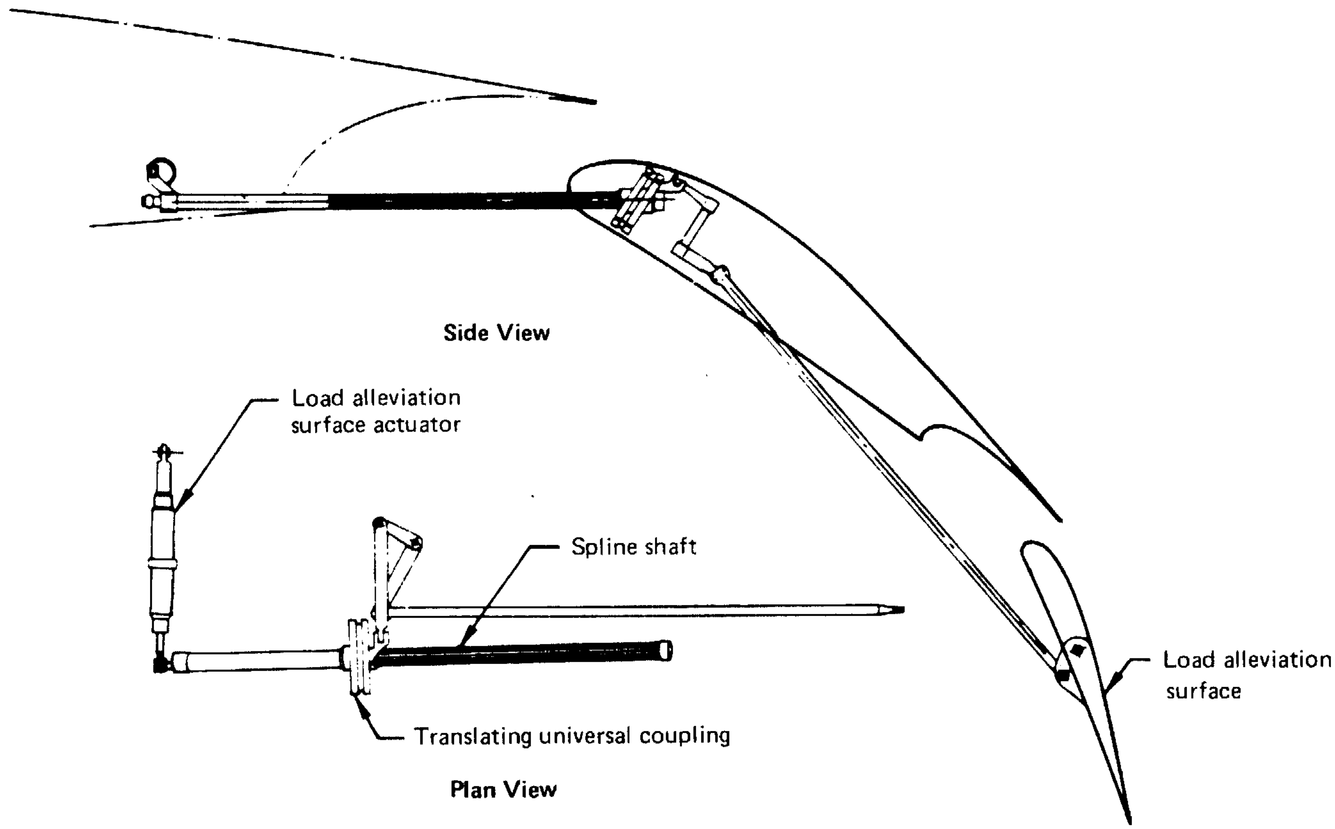



*Figure 8.— Double-Slotted Flap With Load Alleviation Surface Driven by a Fixed Actuator Through a Translating Coupling*

### Spoiler Actuators

Actuation of the basic outboard flight spoilers for maneuver load control and gust load alleviation, in addition to their normal lateral control and speed-brake functions, requires that electric command provisions be added if not already provided. Full fly-by-wire (FBW) spoiler actuators have been used on a number of advanced U.S. military aircraft, and they are being considered for future commercial airliners. A decision to employ active load alleviation controls will undoubtedly prompt such a choice. In accordance with current practice, probably no more than one actuator per spoiler panel will be required.

### Flutter Suppression Flap Actuators

Actuation of an outboard aileron for flutter mode control requires an actuation system that responds to both the primary lateral control and the high-rate flutter suppression commands. Both segments of the outboard aileron are actuated separately. For low-speed lateral control, the low-speed aileron and flutter mode control actuators work together. For high-speed flight, the low-speed aileron actuator is used to hold the aileron in contour while the flutter mode control surface operates.

The choice of flutter mode control actuator will probably be one of the following types and will be made on the basis of which type offers the best compromise between meeting the redundancy requirements and fitting into the available installation space:

- Dual-tandem actuators
- Dual side-by-side actuators
- Triple-tandem actuators
- Triple side-by-side actuators

The actuators could be either the type that can accept both mechanical input commands for normal control and electric commands for flutter mode control or the full electric-command (fly-by-wire) type. Integrated power-by-wire actuators might also be considered but, as indicated for the illustrative example airplane system in section 5.2, the power requirements are apt to be too high for practicality.

### Augmented Pitch Stability Actuators

Augmented pitch stability control may be achieved either by actuation of the elevators on a trimming horizontal stabilizer or by direct actuation of a flying stabilizer.

On airplanes with fully powered flight controls without manual reversion, the elevators are often divided into two segments on each side for redundancy. Likewise, where the elevators are used for critical functions (such as autoland) in addition to normal pitch control where stabilizer trim provides the backup mode, dual actuators are used on at least the inboard segments.

Where a trimming-stabilizer powered-elevator pitch control is also used to restore basic relaxed stability, dual-tandem or dual side-by-side actuators would probably be required on each elevator surface. In a full fly-by-wire system, the actuators would be controlled by integrated electrical commands. If mechanical control is retained for the normal pitch mode, stability augmentation would be provided by electric commands to an electrohydraulic servovalve incorporated within each elevator servoactuator.

Where a flying stabilizer is used, the choice of actuators would be the same, and the minimum number would be dependent on the redundancy requirements. In some cases, three actuators might meet the redundancy requirements; in others, four might be required, particularly if more than one hydraulic system is exposed to failure from a single event such as an engine rotor burst.

Even where three actuators might meet the requirement, four might be selected to save weight. If three actuators are used, each would have to meet the minimum hinge moment requirement, and the total capacity would be three times the minimum. When four actuators are used, it may be possible to size each to satisfy only half the minimum requirement, thereby reducing the total capacity to two times the minimum. In addition, four actuators lend themselves more easily to a four-channel stability augmentation network to provide operational capability after two failures.

### 4.1.4 HINGE MOMENTS

The required load capability and size of the ACT actuators are directly dependent on the predicted aerodynamic hinge moments on the control surfaces and on the chosen level of redundancy. The required hydraulic flow rates are, in turn, dependent on actuator piston areas and required surface deflection rates.

A generalized method is presented for predicting hinge moments for trailing-edge control surfaces. The hinge moment prediction accounts for the size of the wing ACT control surface and the airfoil type, which has a profound impact on hinge moments. Hinge moments are very large for supercritical airfoils due to the aft surface loading. For example, the hinge moment at zero deflection for an aileron on a Whitcomb airfoil is more than six times the hinge moment for the same aileron on a nonsupercritical airfoil wing. This difference in hinge moments is shown in figure 9, which shows the pressure distribution, airfoil shape, and hinge moment for a Boeing-designed supercritical airfoil (slightly less aft camber than the Whitcomb airfoil) and a current technology airfoil.

The following set of equations is used to predict hinge moment, N·m (lb-in.):

$$
\begin{aligned}
HM &= q\, S_S\, \bar{c}_S\, C_H \\
&= q\, \frac{S_S\, \bar{c}_S}{S_W\, \bar{c}_W} (S_W\, \bar{c}_W)\, C_H
\end{aligned}
$$

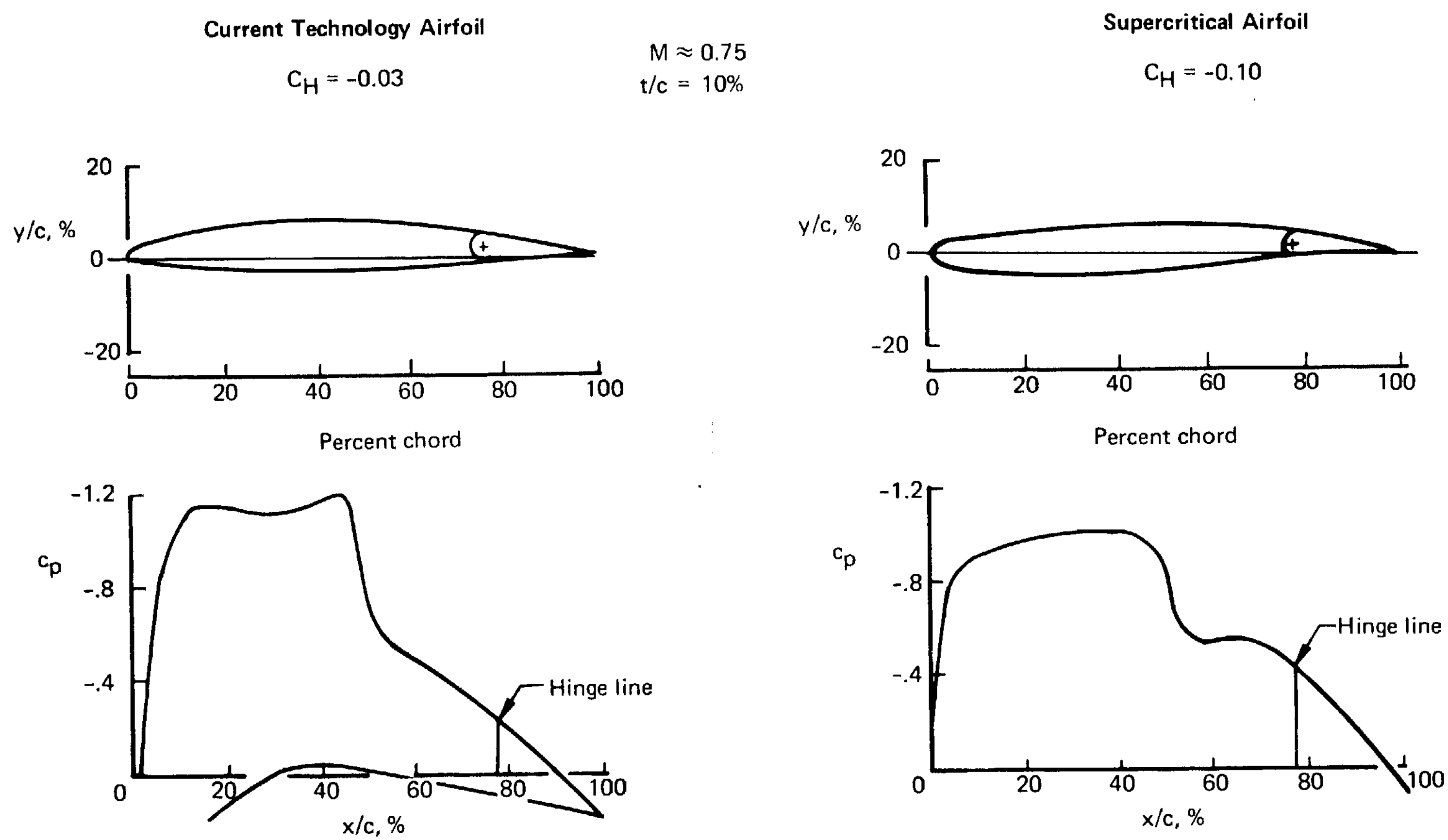



Figure 9.—Impact of Airfoil on Chordwise Pressure Distributions and $C_H$

where

$q$ = dynamic pressure, $N/m^2$ ($lb/ft^2$) (See table 3 for design condition.)

$\frac{S_s \bar{c}_s}{S_w \bar{c}_w}$ = control surface area volume ratio (from table 2)

$S_w$ = reference wing area, $m^2$ ($ft^2$)

$\bar{c}_w$ = wing mean aerodynamic chord, m (in.)

$C_H$ = hinge moment coefficient (See the following equation.)

$$C_H = K_\alpha \left( C_{H_0} + \Delta C_{H_{airfoil}} \right) + K_\delta \, \Delta C_{H\delta}$$

where

$C_{H_0}$ = hinge moment coefficient for Whitcomb airfoil for $\bar{c}_s/c_w = 0.25$ and $\delta = 0$ (See fig. 10.)

$\Delta C_{H_{airfoil}}$ = incremental change in hinge moment coefficient due to changes in airfoil aft loading relative to Whitcomb airfoil (Typical values for $\Delta C_{H_{airfoil}}$ are
0.16 conventional airfoil (no aft loading) and
0.14 Whitcomb airfoil with filled cusp.)

$\Delta C_{H_\delta}$ = incremental change in hinge moment coefficient due to 10° surface deflection down (See fig. 10.)

$K_\alpha$, $K_\delta$ = changes in hinge moment coefficient due to changes in chord ratio (See fig. 10.

### 4.1.5 HYDRAULIC AND ELECTRIC SYSTEM SIZING

**Hydraulic System**

For subsonic commercial jet aircraft, the flight control system requirements normally have very little impact on the flow capacity of the hydraulic system. Landing gear and flap actuation demand large flow rates at takeoff and landing, and the flow demands for flight control are small in comparison to those requirements.

Whether or not the increased flow demands for active controls can be met with the excess capacity available will have to be determined by an accurate load analysis for each particular system. Even if it at first appears that additional flow capacity may be required, a number of load and flow reducing options can be considered. It is therefore reasonably safe to assume, for preliminary design purposes, that incorporation of an active control system will not require increased hydraulic flow capacity.

*Table 3.—Design Flight Conditions*

**Maneuver Load Control:** buffet/$n_{max}$ corner

$$q_{MLC} = \frac{(n_{max})\,(W/S)}{C_{L_{buffet}}};\ (M \approx 0.60)$$

Typical values:

$q_{MLC}$ = 250 → 312 lb/ft$^2$ for

$n_{max}$ = 2.5

W/S = 100 → 125 lb/ft$^2$

$C_{L_{buffet}}$ = 1.0

**Gust Load Alleviation:** $V_C/M_C$ corner

Typical value:

$q_{GLC}$ = 415 lb/ft$^2$ ($V_{MO}$ = 350 kn, M = 0.9)

**Flutter Mode Control:** 1.2 $V_D$

Typical value:

$q_{FMC}$ = 781 lb/ft$^2$ (1.2 $V_D$ = 480 kn)

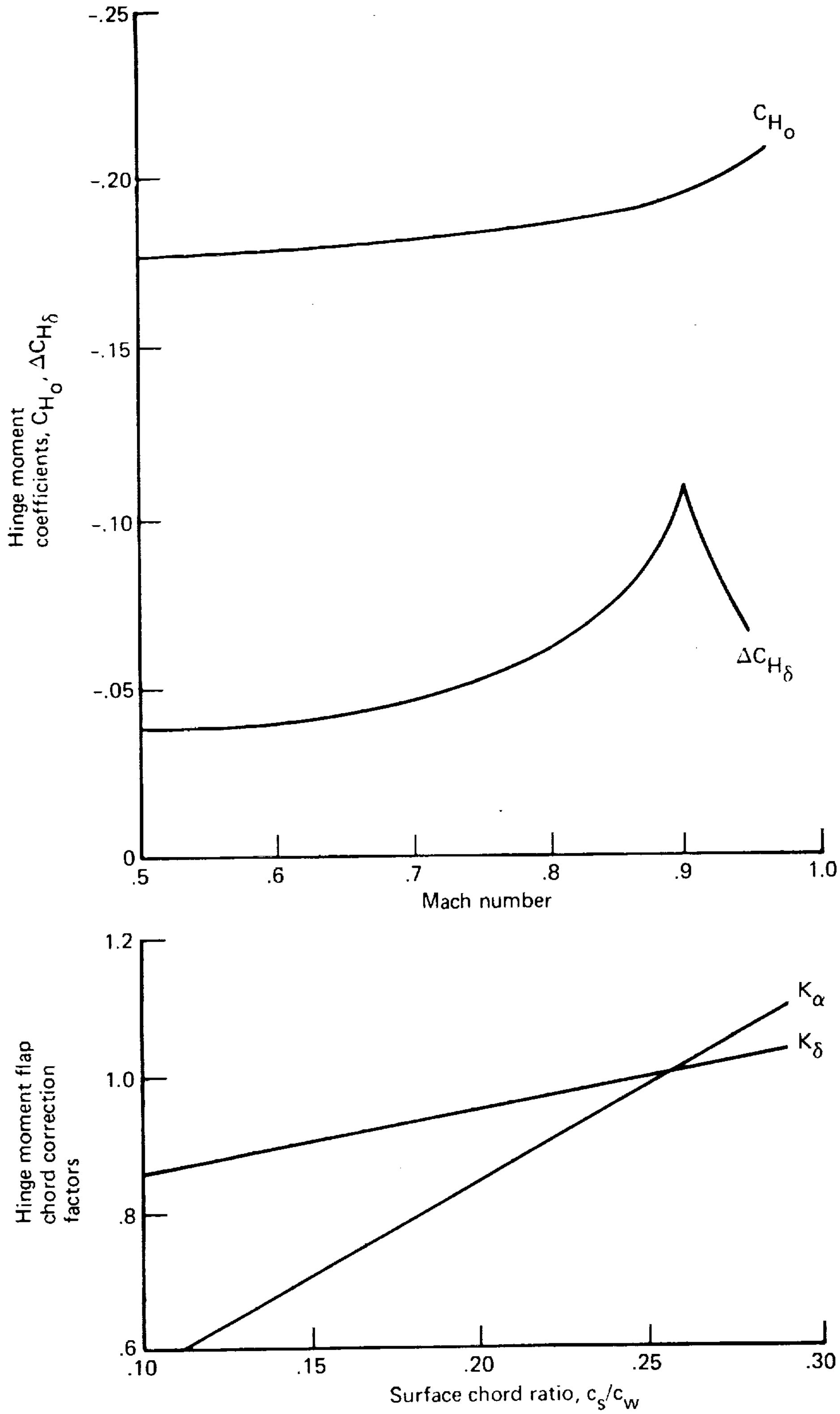



*Figure 10.—Hinge Moment Data*

Preliminary design estimates of the hydraulic flow rates required for flight control actuation can be made with the following equations once the maximum design hinge moment requirement for the control surface is known, the redundancy levels are established, and the desired surface rate is determined.

$$P = \frac{HM_a \cdot \dot{\delta}}{C_1}$$

where:

$P$ = actuator power output, kW (hp)

$HM_a$ = required hinge moment capability per actuator, N·m (lb-in.)

$\dot{\delta}$ = surface rate, rad/s (deg/s)

$C_1$ = calculation constant = 1000 (377 000)

After the power requirement is determined, the required flow rate can be calculated from:

$$Q = \frac{C_2 \cdot P}{\Delta P_a}$$

where

$Q$ = hydraulic flow rate, $cm^3/s$ (gal/min)

$P$ = actuator power output, kW (hp)

$\Delta P_a$ = available differential pressure across the actuator piston, $MN/m^2$ ($lb/in^2$)

$C_2$ = calculation constant = 1000 (1714)

In a 3000-$lb/in^2$ system, the available differential pressure used for sizing flight control actuators is usually assumed to be on the order of 2800 $lb/in^2$ (2900 $lb/in^2$ at the pump when it is delivering high flow, less 100 $lb/in^2$ pressure in the system return line). When the surface is first displaced from the neutral (faired) position, the actual hinge moment load is relatively low, and only a low pressure is required to react the load, leaving the remaining pressure available to accelerate the surface, the actuator, and hydraulic fluid in the lines. As the rate increases, some of the available pressure is consumed in fluid friction losses in the tubing and the actuator servovalve. However, since the surface is not loaded to its maximum hinge moment until it reaches full displacement, where it stalls to zero rate, it is valid to assume zero pressure loss in determining the required actuator piston area.

For the active control actuators, however, where a number of rapid high-rate full-reversing actuation cycles are expected whenever a control demand occurs, full flow rate builds up and is sustained until the control demand is completed. Therefore, for sizing those actuators, continuous loss of available pressure in the tubing and servovalves must be assumed.

For preliminary design estimates where the actuators' attachment dimensions and operating moment arms are not yet established, the required flow rate is estimated by equating the expression for hydraulic power $(Q \cdot \Delta P_a)/C_2$ to the mechanical power required at the surface $(HM_a \cdot \dot{\delta})/C_1$ without going through the step of determining the required actuator piston areas. This procedure was followed for the illustrative example investigated in this study, and the flow rate estimates for the normal flight control surface actuators are based on 19.3 MN/m$^2$ (2800 lb/in$^2$) of differential pressure available. For the active control surface actuators, a 25% pressure loss was assumed, and the flow rate estimates are based on 14.5 MN/m$^2$ (2100 lb/in$^2$) of differential pressure available.

It should be noted that the flow rate requirements quoted herein are all based on use of a 3000-lb/in$^2$ system such as used on current jet transports. For a 1990-technology airplane, it is possible that a higher system pressure level, such as 27.6 MN/m$^2$ (4000 lb/in$^2$), might be selected if the need to reduce weight is sufficient to warrant the additional development costs and logistic problems for stocking new component parts. However, there will undoubtedly be considerable resistance from the user airlines.

**Electrical System**

Power requirements for flight controls are a small factor in sizing airplane electrical systems. The principal requirements are assurance of essential power and freedom from large switching transients. It is expected that this will also hold true for active flight control systems.

The major exception could be in the use of power-by-wire servoactuator packages that incorporate an electric-motor-driven hydraulic pump in each unit. It is possible that their total power requirements could exceed the available installed electrical generating capacity above that required for other electrical loads, or that their inrush current demands for startup could require larger generators. This would have to be determined by an accurate load analysis for each particular system.

## 4.2 WEIGHT METHODOLOGY

### 4.2.1 BASELINE WEIGHT SENSITIVITIES

Weight estimating methodology for current technology lifting surface control systems and related surfaces has been fully developed through independent research. These methods for subsonic commercial aircraft have been developed primarily around the Boeing family of airplanes, as a statistical base, and include the consideration of geometry, load, redundancy, and function requirements in the analysis. The basic format of the equations is such that modifications to the weight sensitivities can be accomplished with ease to reflect differences in technology level, materials, geometry, function, etc.

Table 4 shows an example of estimated weights versus actual weights from the family of airplanes from which the baseline equations were constructed (fixed trailing-edge structure). Control systems weight correlations are shown in figures 11 through 16. The weight equations were developed in the customary English units and are presented as developed. Tables of results are shown in SI units as well as in English units.

These weight equations are, of necessity, design oriented and require a minimum level of geometric and functional definition in order to evaluate systems and structures weights. The equations have been developed with the intent of providing functional weight trade capability with parametric sensitivities limited to provide the simplicity required in a preliminary design situation. Diagrams are included to clarify definitions and standardize assumptions. Where appropriate, default values of parameters are suggested.

**Ailerons**

$$\text{Weight} = 1.3 \sin \delta_{max} \left[\frac{V_D}{100} \cos \Lambda_{HL}\right]^2 (A_p)^{0.845} + 3(A_p)^{0.87}$$

where

$A_p$ = aileron surface area, ft$^2$

$V_D$ = design speed, kn

$\delta_{max}$ = maximum surface deflection, deg

$\Lambda_{HL}$ = hinge line sweep angle

**Trailing-Edge Flaps**

Surfaces

$$\text{Weight (single-slotted)} = 2.850 \left[\frac{(\text{FLPCHD})\ (\text{FLPSPN})}{144}\right]^{1.000}$$

$$\text{Weight (double-slotted)} = 3.738 \left[\frac{(\text{FLPCHD})\ (\text{FLPSPN})}{144}\right]^{0.974}$$

$$\text{Weight (triple-slotted)} = 5.397 \left[\frac{(\text{FLPCHD})\ (\text{FLPSPN})}{144}\right]^{0.974}$$

*Table 4.—Fixed Trailing-Edge Structure*

| | Units | 747-21P | 737-200 | 727-200 | 707-320B | ACT example |
|---|---|---|---|---|---|---|
| Gross TE area | $m^2$ ($ft^2$) | 74.5 (801.4) | 15.5 (167.0) | 26.6 (285.8) | 51.5 (554.1) | 112.8 (1214.4) |
| AIA | $m^2$ ($ft^2$) | 3.3 (35.9) | 0 | 1.0 (10.6) | 2.1 (22.1) | 4.4 (47.7) |
| AOA | $m^2$ ($ft^2$) | 7.1 (76.7) | 1.3 (13.5) | 1.7 (18.6) | 3.5 (37.7) | 8.1 (87.3) |
| AIF | $m^2$ ($ft^2$) | 12.1 (130.0) | 1.6 (17.2) | 3.5 (37.6) | 6.1 (66.1) | 21.7 (233.8) |
| AOF | $m^2$ ($ft^2$) | 7.7 (82.5) | 2.6 (28.5) | 3.3 (35.6) | 6.3 (67.9) | 23.7 (255.1) |
| AISP | $m^2$ ($ft^2$) | 6.4 (68.7) | 0.9 (9.9) | 2.4 (26.0) | 2.4 (26.0) | 10.9 (116.8) |
| AOSP | $m^2$ ($ft^2$) | 7.7 (83.3) | 2.0 (21.7) | 2.9 (31.2) | 2.6 (28.2) | 10.8 (116.2) |
| ANET | $m^2$ ($ft^2$) | 30.1 (324.2) | 8.5 (92.0) | 14.4 (154.7) | 31.0 (333.2) | 44.0 (474.0) |
| Estimated TE weight | kg (lb) | 329.7 (726.8) | 83.6 (184.4) | 147.3 (324.7) | 339.6 (748.7) | 498.5 (1099) |
| Estimated TE unit weight | $kg/m^2$ ($lb/ft^2$) | 11.0 (2.242) | 9.8 (2.004) | 10.2 (2.099) | 11.0 (2.247) | 11.3 (2.319) |
| Actual TE weight | kg (lb) | 415.7 (916.5) | 83.9 (185.0) | 147.0 (324.0) | 359.5 (792.5) | — — |
| Actual TE unit weight | $kg/m^2$ ($lb/ft^2$) | 13.8 (2.827) | 9.8 (2.011) | 10.2 (2.094) | 11.6 (2.379) | — — |

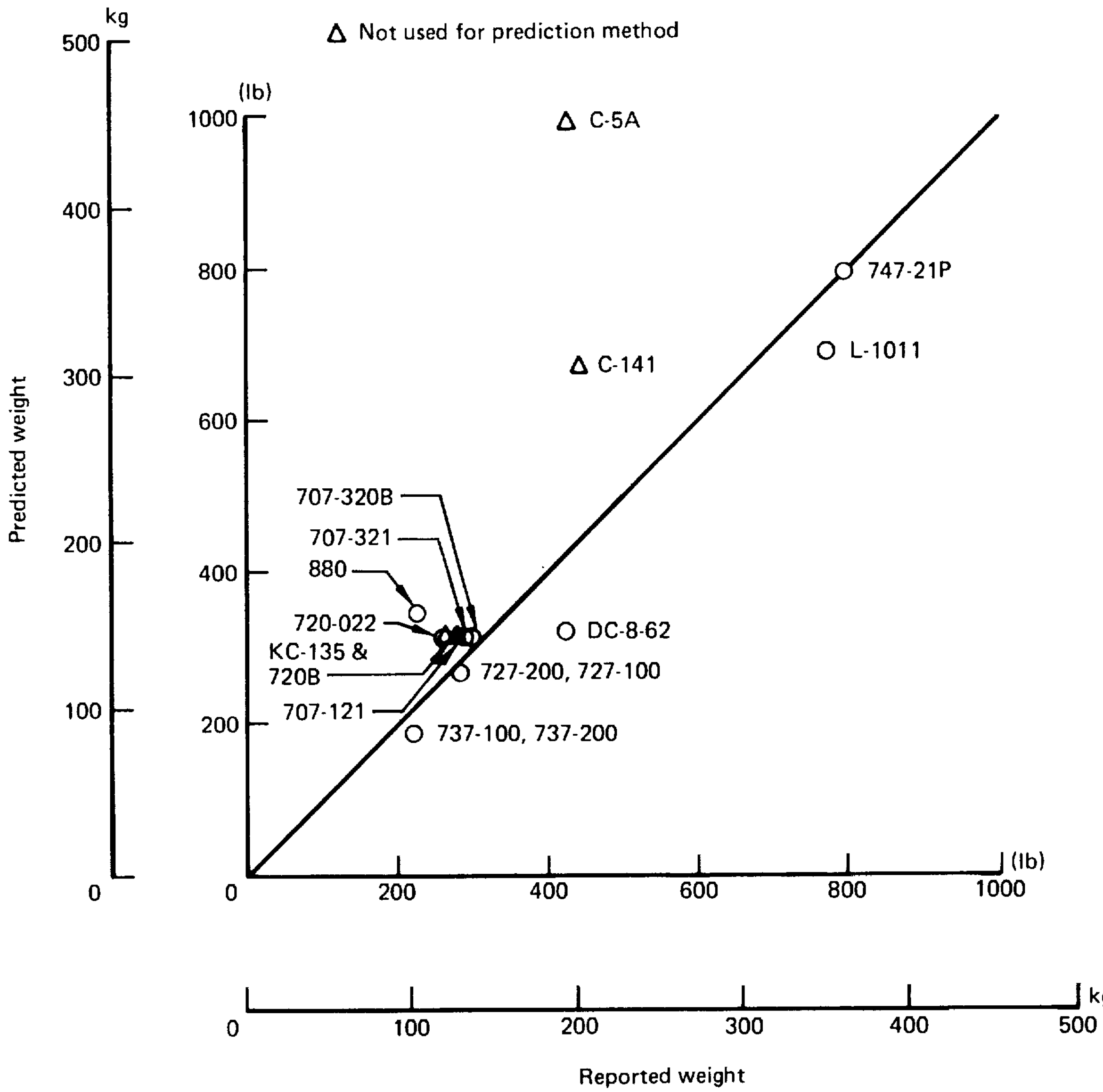



*Figure 11.—Aileron Controls Predicted Versus Actual Weights*

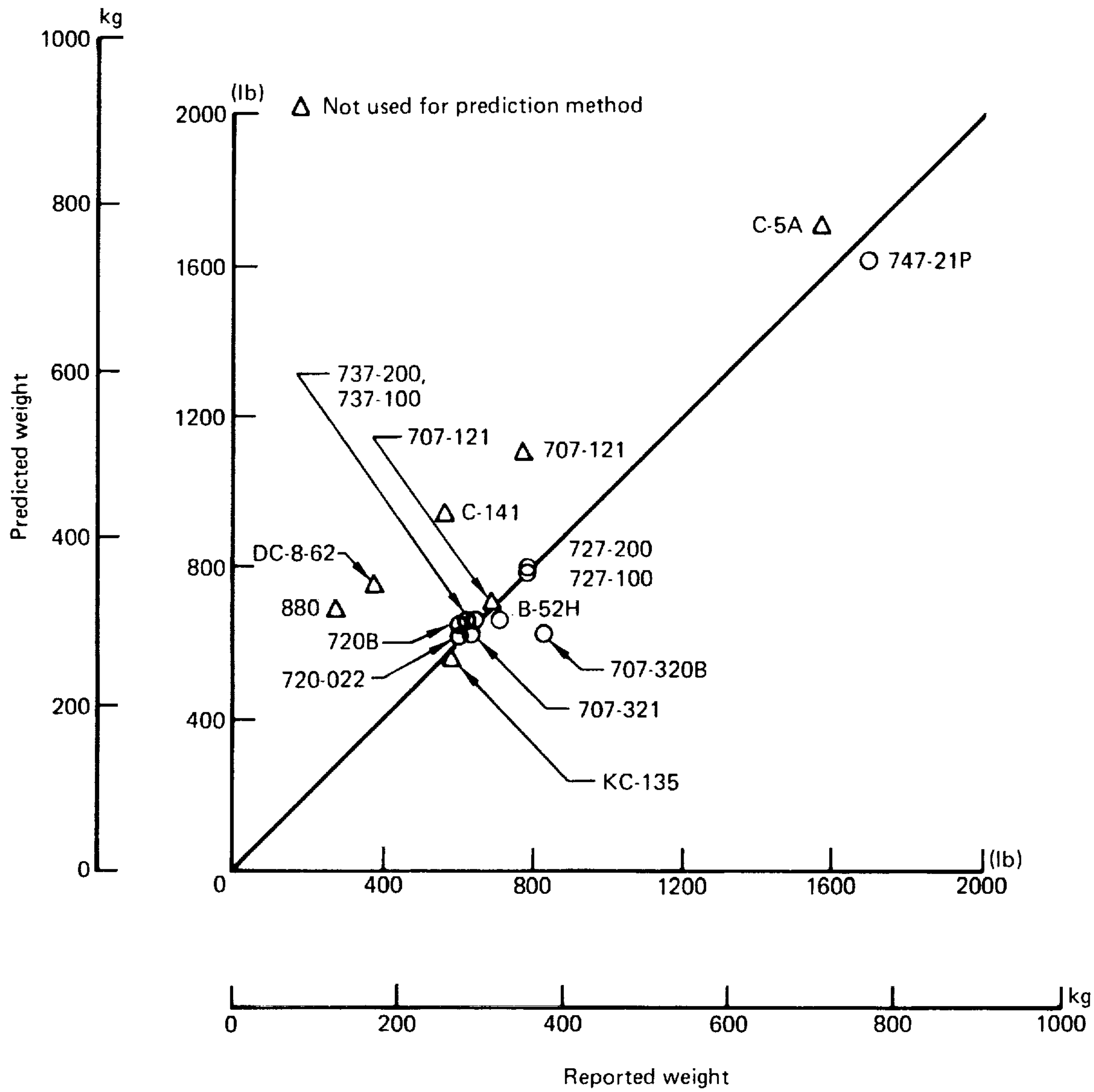



*Figure 12.—Trailing-Edge Flap Controls Predicted Versus Actual Weights*

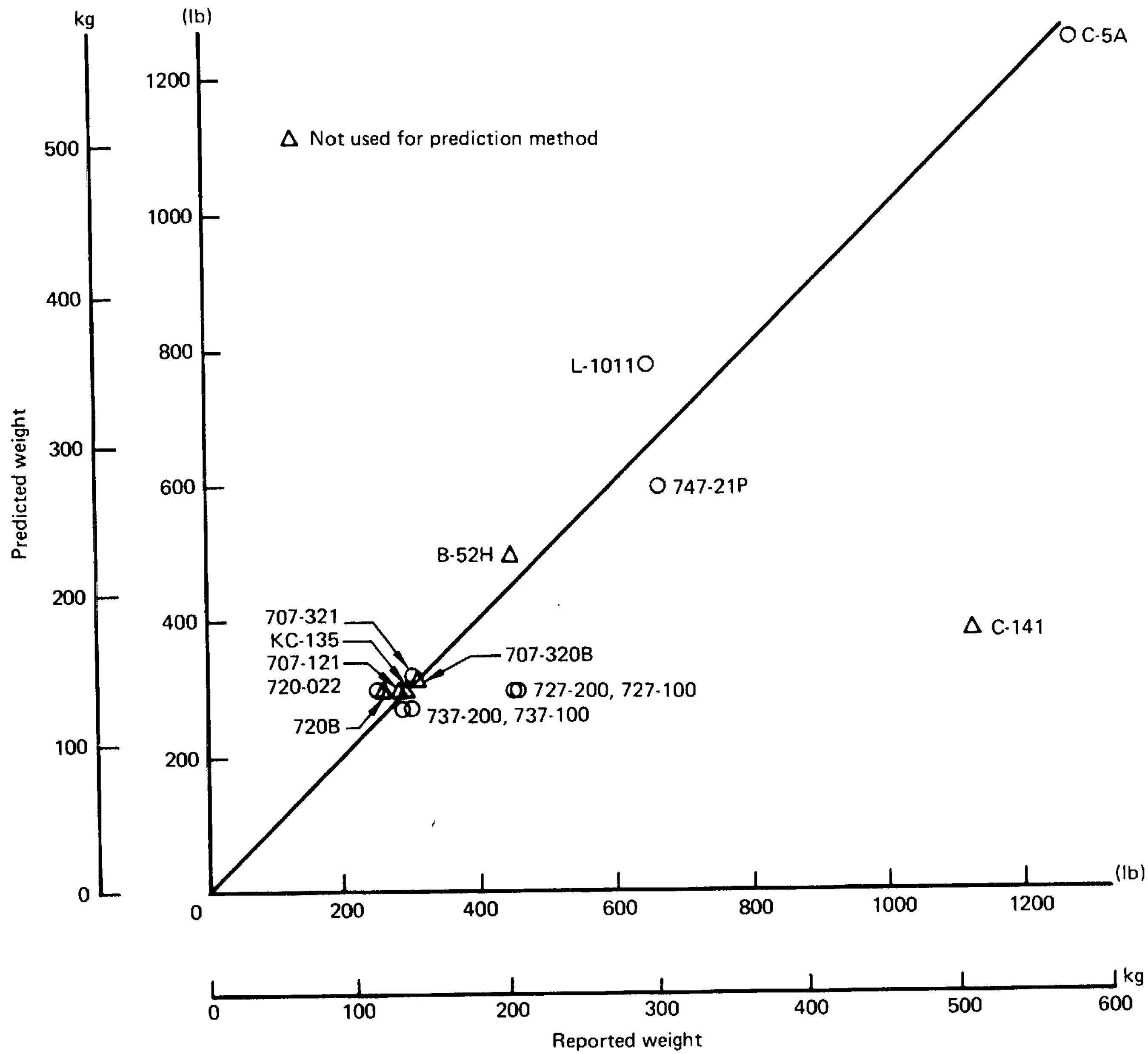



*Figure 13.—Spoiler and Speed Brake Controls Predicted Versus Actual Weights*

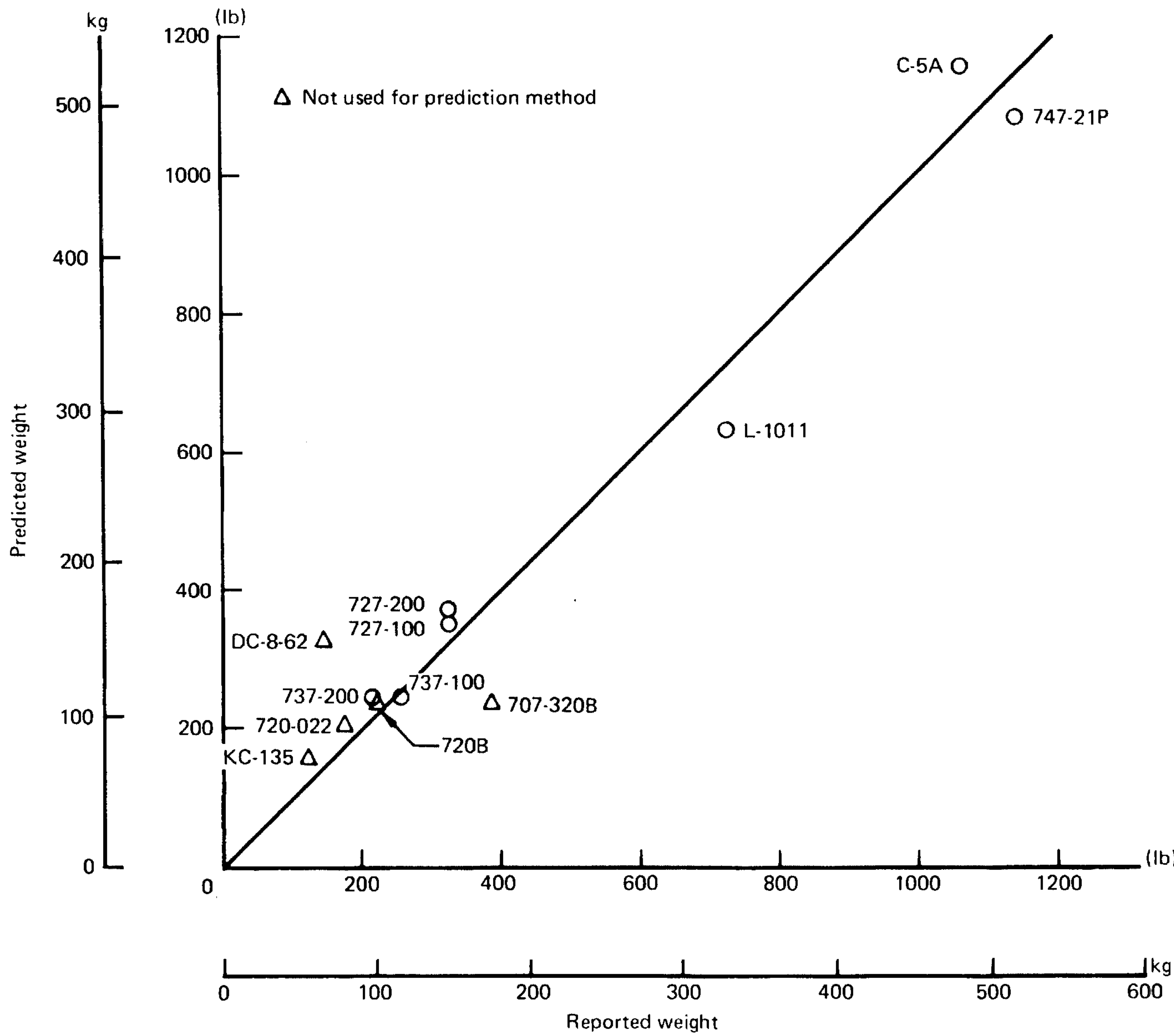



Figure 14.—Leading-Edge Flap and Slat Controls Predicted Versus Actual Weights

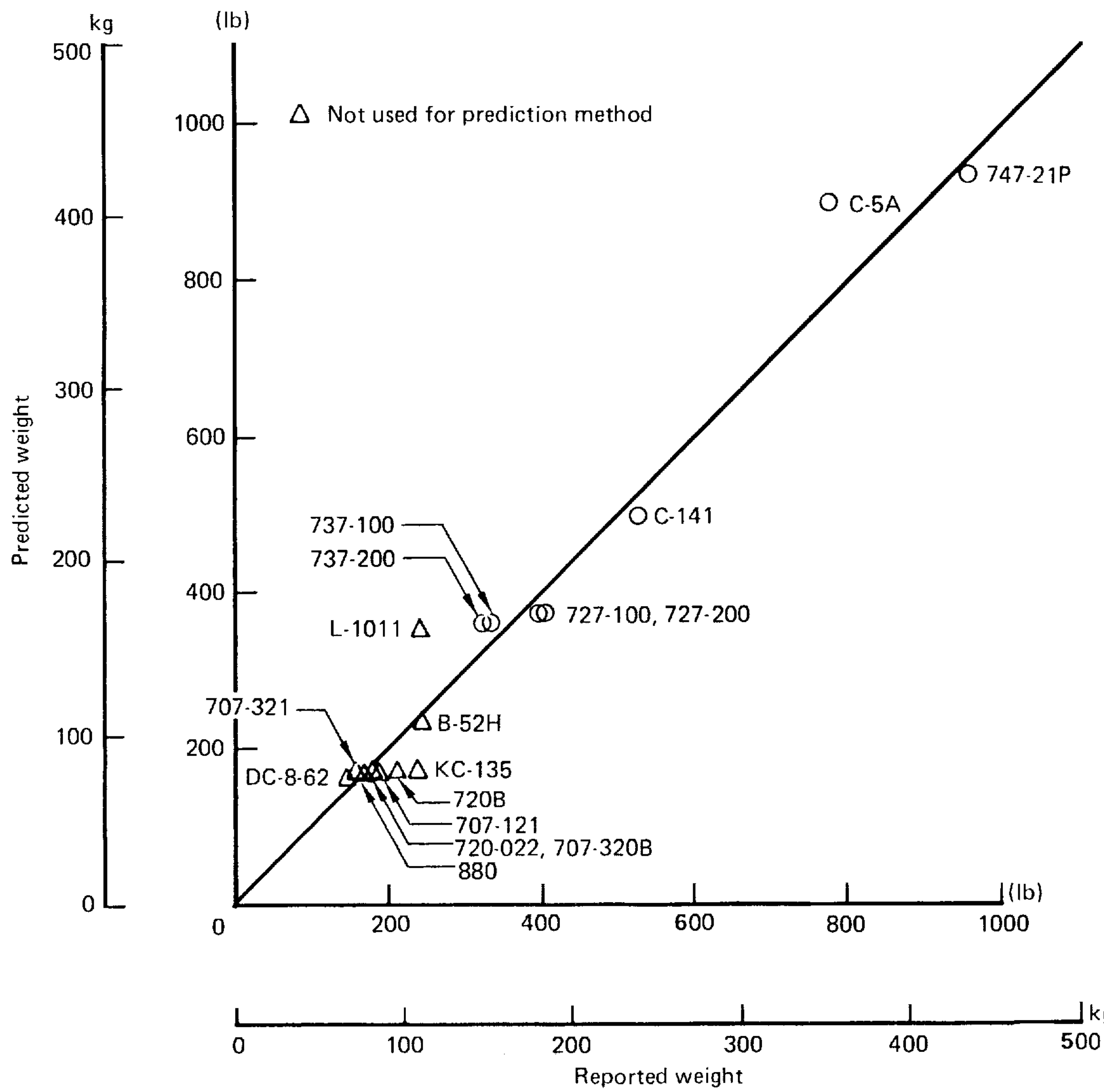



*Figure 15.—Elevator Controls Predicted Versus Actual Weights*

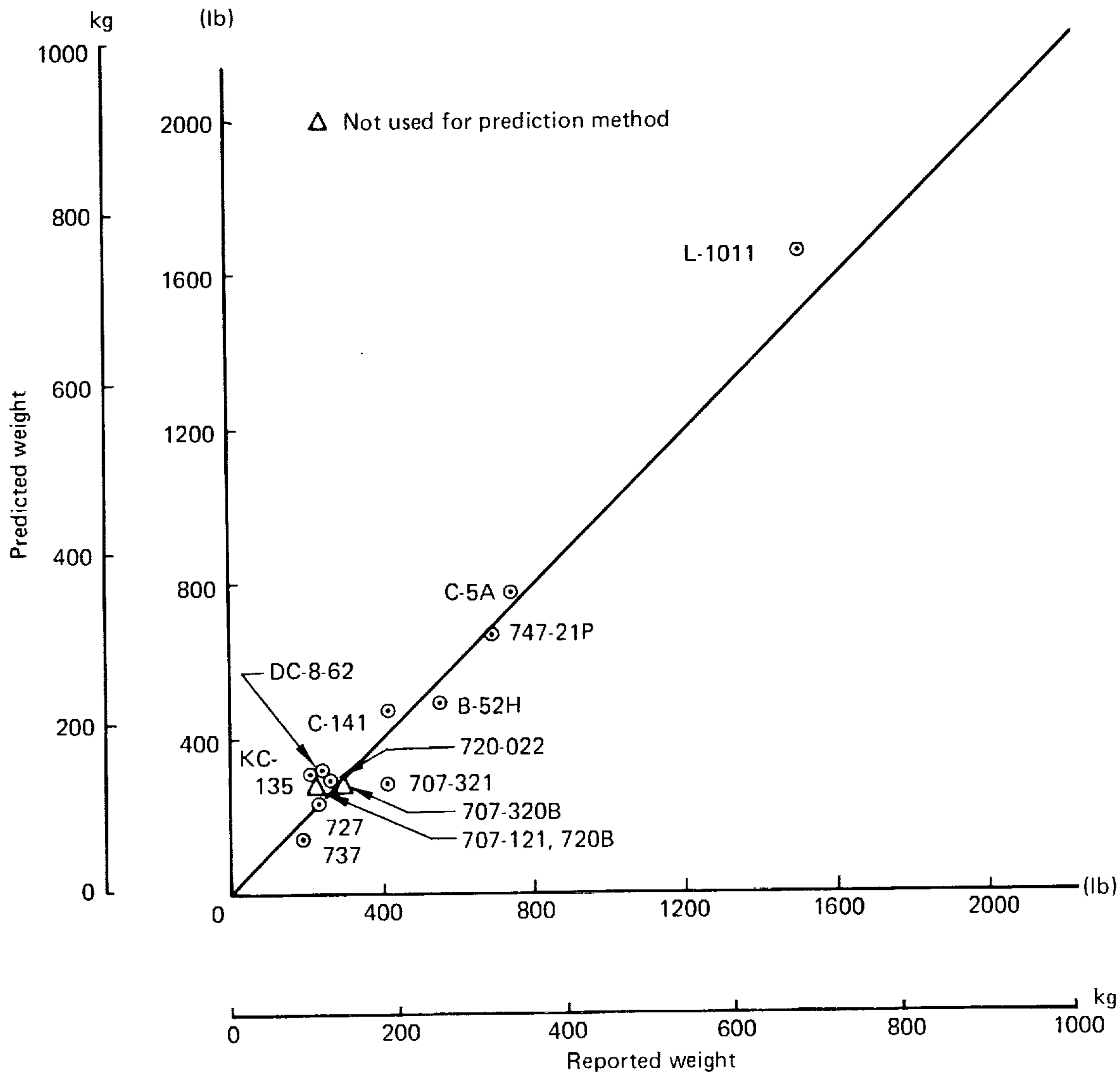



*Figure 16.—Stabilizer Adjustment Controls Predicted Versus Actual Weights*

Support Structure

$$\text{Weight (single-slotted)} = 3.772 \left[(\text{DISTCANT})(\text{ASUM})\right]^{0.769}$$

$$\text{Weight (double-slotted)} = 3.772 \left[(\text{DISTCANT})(\text{ASUM})\right]^{0.769}$$

$$\text{Weight (triple-slotted)} = 5.382 \left[(\text{DISTCANT})(\text{ASUM})\right]^{0.769}$$

Support Fairings

$$\text{Weight} = 2.45\ (\text{AF})$$

Trailing-Edge Flaps Installation = Surfaces + Support Structure + Fairings

where

FLPCHD = streamwise flap chord in the retracted, nested position, in.

FLPSPN = aerodynamic flap span, in.

DISTCANT = cantilevered distance for flap load from wing rear spar at outboard track, ft

ASUM = summation of all individual flap segment areas (fore, mid, aft), $ft^2$

AF = fairing wetted area, $ft^2$

**Spoilers**

$$\text{Weight} = 0.125\ (\text{ASP})^{1.143}\ (\text{SPLFDN})^{0.666}$$

where

ASP = spoiler area per surface, $ft^2$

SPLFDN = maximum spoiler deflection, deg

**Fixed Trailing-Edge Structure**

$$\text{Weight} = 1.340\ (\text{ANET})^{1.089} \geqslant 2.0\ (\text{ANET})$$

where

ANET = fixed trailing-edge net area, $ft^2$

$$\text{ANET} = \text{AGROSS} - (\text{AIA} + \text{AOA} + \text{AIF} + 0.5\ \text{AISP} + 0.5\ \text{AOSP})$$

where

AGROSS = gross trailing-edge area, $ft^2$

AIA = inboard aileron area, $ft^2$

AOA = outboard aileron area, $ft^2$

AIF = inboard trailing-edge area, $ft^2$

AOF = outboard trailing-edge flap area, $ft^2$

AISP = inboard spoiler area, $ft^2$

AOSP = outboard spoiler area, $ft^2$

**Fixed Leading-Edge Structure**

$$\text{Weight} = 1.24\ (\text{SFXLE})^{1.191}$$

where

SFXLE = planform area of leading edge

**Leading-Edge Flaps**

$$\text{Weight} = 4.83\ \left[(2)\ (\text{SVCFL})\ (\text{AEXT})\right]^{0.884}\ \text{(variable camber Krueger)}$$

$$\text{Weight} = 3.05\ \left[(2)\ (\text{SFCFL})\ (\text{AEXT})\right]^{0.884}\ \text{(fixed camber Krueger)}$$

where

SVCFL = planform area of variable camber flaps, $ft^2$

SFCFL = planform area of fixed camber flaps, $ft^2$

AEXT = area extension ratio

= 1.35 for variable camber Krueger flaps

= 1.55 for fixed camber Krueger flaps

**Aileron Controls**

$$\text{Weight} = 29.35 \left[(2) \sum_{i=1}^{N} (k_i\ S\bar{c}_i)\right]^{0.44}$$

where

$S\bar{c}_i$ = (2) (aileron area moment about hinge line for the individual aileron panel), $ft^3$ per side

N = number of aileron panels per side

$k_i$ = $k_s N_s + k_t N_t$

$k_s$ = $\frac{xb - ya}{xb}$ (0.80)

$k_s$ = 1.00 if no tabs are used

x = aileron panel span, in.

b = aileron panel chord, in.

y = aileron tab span, in.

a = aileron tab chord, in.
(See fig. 17 for illustrations of chord and span definitions.)

$N_s$ = number of manual actuation systems driving the individual aileron panel

$N_t$ = number of powered actuation systems driving the individual aileron panel

$k_t$ = power reduction factor for the individual aileron panel

$k_t$ = 1.00, unless tabs are used to reduce control loads in powered mode (as on C-141), in which case $k_t = k_s$. (Generally, the tabs function only during manual operation and are locked to the main aileron panels when powered operation is available.)

Suggested default values:

$N_s$ = 0

$N_t$ = 2

$k_t$ = 1.00

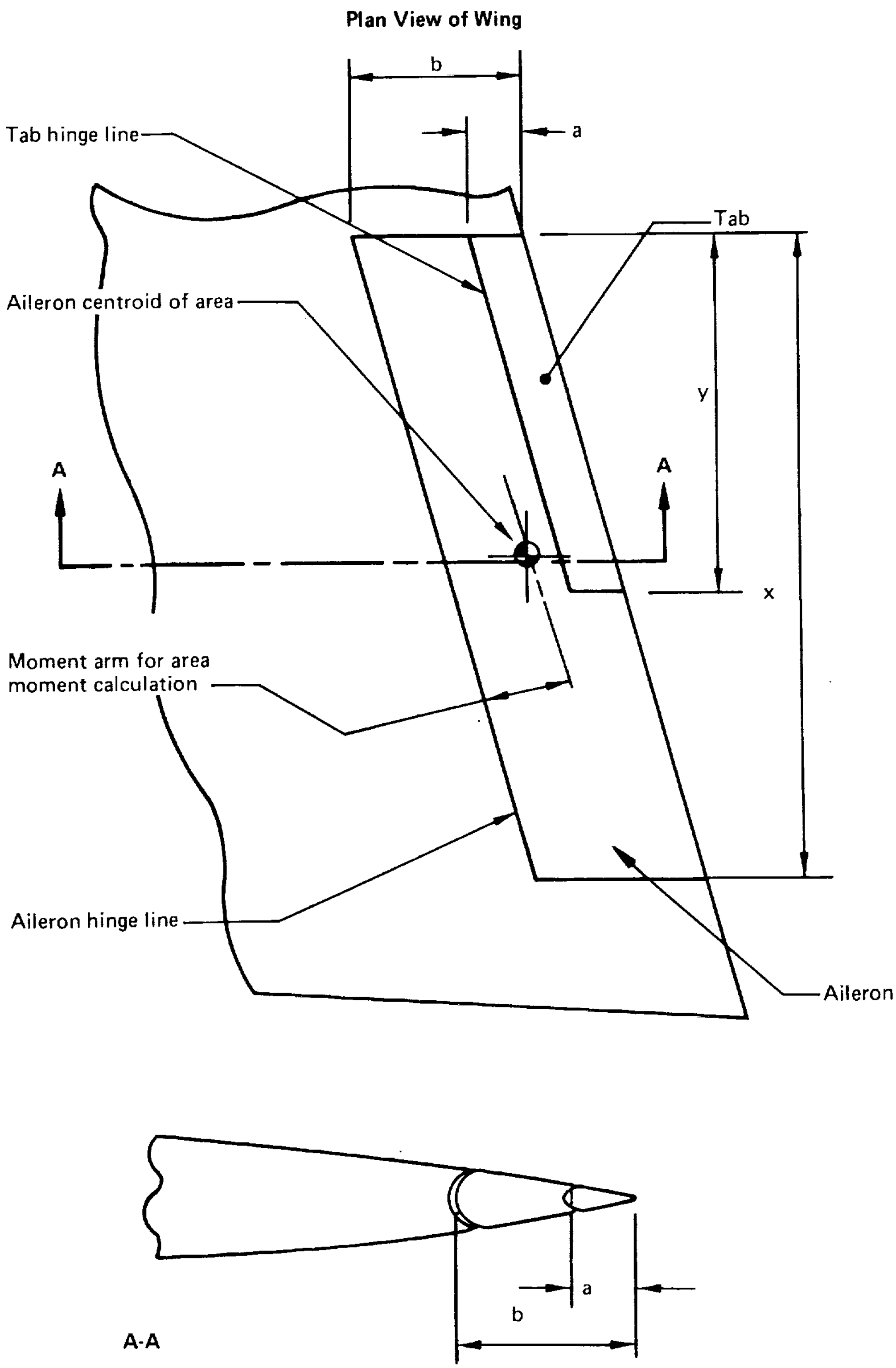



*Figure 17.—Aileron Chord and Span Definitions*

### Trailing-Edge Flap Controls

The current weight equation is

$$\text{Predicted weight} = 392 + 145\left[\frac{(\Delta C_L)(W_{GR})}{100\ 000}\right]$$

where

$W_{GR}$ = airplane maximum flight gross weight, flaps up, lb

$\Delta C_L$ $= \dfrac{295}{S}\left[\dfrac{W_{L1}}{(V_{L1})^2} - \dfrac{W_{GR}}{(V_{S1})^2}\right]$

S = aerodynamic reference wing area, $ft^2$

$W_{L1}$ = airplane maximum landing weight, lb

$V_{L1}$ = stall speed with full flaps at $W_{L1}$ with power off, KEAS

$V_{S1}$ = stall speed with flaps retracted at $W_{GR}$ with power off, KEAS

Suggested default values:

$V_{L1}$ = 95 kn at $W_{GR} < 200\ 000$ lb

$V_{L1}$ = 102 kn at $200\ 000 < W_{GR} < 300\ 000$ lb

$V_{L1}$ = 109 kn at $W_{GR} > 300\ 000$ lb

$V_{S1}$ = 166 kn

### Leading-Edge Flap Controls

Leading-edge flap and slat controls weight is predicted as follows:

$$\text{Weight} = 2.5 + 127.9\left[\frac{(\Delta C_L)(W_{GR})}{100\ 000}\right]$$

where

$W_{GR}$ = airplane maximum flight gross weight, flaps up, lb

$\Delta C_L$ $= \dfrac{295}{S}\left[\dfrac{W_{L1}}{(V_{L1})^2} - \dfrac{W_{GR}}{(V_{S1})^2}\right]$

S = aerodynamic reference wing area, $ft^2$

$W_{L1}$ = airplane maximum landing weight, lb

$V_{L1}$ = stall speed with flaps extended at $W_{L1}$ with power off, KEAS

$V_{S1}$ = stall speed with flaps retracted at $W_{GR}$ with power off, KEAS

Suggested default values:

$V_{L1}$ = 95 KEAS at $W_{GR} < 200\,000$ lb

$V_{L1}$ = 102 KEAS at $200\,000 \leq W_{GR} \leq 300\,000$ lb

$V_{L1}$ = 109 KEAS at $W_{GR} > 300\,000$ lb

$V_{S1}$ = 166 KEAS

**Spoiler Controls**

$$\text{Weight} = 89 + G_{SP} + 76.8 \sum_{i+1}^{N} F_{SPi}$$

where

N = number of spoiler and speed brake panels per side

$F_{SPi} = \left(\frac{\varphi_{SP}}{100}\right)(K_{SP})^{0.75}$

$\varphi_{SP}$ = maximum spoiler deflection, deg

$K_{SP} = \dfrac{(V_{BD})^2 (\cos \lambda_{SP}) (S\bar{c}_{SP}) (\sin \varphi_{SP})}{10^6}$

$V_{BD}$ = spoiler panel blowdown-start velocity for spoilers used in flight, or maximum refused takeoff speed for panels used only as groundspeed brakes, kn

$\lambda_{SP}$ = sweep angle of spoiler panel hinge line, deg

$S\bar{c}_{SP}$ = 2 times area moment about the hinge line of the individual spoiler or speed brake panel, $ft^3$

$G_{SP}$ = 20 if groundspeed brakes are used

$G_{SP}$ = 0 if no groundspeed brakes are used

Suggested default values:

$\varphi_{SP}$ = 50°

$V_{BD}$ = 295 kn

**Stabilizer Adjustment Control**

$$\text{Weight} = (W_{bsa})\left[N_{bsa} + N_{psa}\left(\frac{B_p}{B_{bsa}}\right)^{1/2}\right]$$

where

$W_{bsa}$ = weight of basic stabilizer adjustment control system

$W_{bsa}$ = $63.6 + (4.1)(K_{sa})$

$K_{sa}$ = $\dfrac{\text{Max } T_{spa}}{(\ell_{sta})\,(10)^3}$

Max $T_{spa}$ = ultimate design total moment about stabilizer trim pivot axis, in-lb

$\ell_{sta}$ = stabilizer trim mechanism lever arm length, in.

$N_{bsa}$ = number of power drive systems that are capable of driving stabilizer at partial trim rate

$N_{psa}$ = number of power drive systems that are capable of driving stabilizer at full trim rate

$B_p$ = trim rate capability of partial power systems with flaps down, deg/s

$B_{bsa}$ = trim rate of full capability power systems with flaps down, deg/s

Suggested default values:

Max $T_{spa}$ = $(1.33)\,(L_T)\,(\ell_{PA})$

$L_T$ = design ultimate tail load, lb

$L_T$ = 0.35 (maximum flight gross weight), lb

$\ell_{PA}$ = perpendicular distance from stabilizer exposed area centroid to stabilizer pivot axis, in.

$N_{bsa}$ = 1.0

$N_{psa}$ = 0

**Elevator Controls**

$$\text{Weight} = (2) \sum_{i=1}^{N} \left[ (119) \left( \frac{S\bar{c}_i}{S\bar{c}_{total}} + 0.03\, P_{eci} \right) (N_{pi}\, K_{pi} + N_{mi}\, K_{mi}) \right]$$

where

$S\bar{c}_i$ = 2 times elevator area moment about the hinge line for the individual elevator panel, $ft^3$ per side

$S\bar{c}_{total}$ = $(2) \sum_{i=1}^{N} S\bar{c}_i$

N = number of elevator panels per side

$P_{eci}$ = elevator controls equivalent load factor for the individual elevator panel

$P_{eci}$ = $(\sin \Lambda_e) \left( \frac{V_D}{100} \right)^2 (\cos \delta_e)\, (S\bar{c}_i)$

$\delta_e$ = maximum deflection angle for the individual elevator panel, deg

$V_D$ = airplane design dive speed, kn

$\Lambda_e$ = sweep angle of elevator hinge line for the individual elevator panel, deg

$N_{pi}$ = number of powered actuation systems driving the individual elevator panels

$K_{pi}$ = tab factor applicable to powered systems

$K_{pi}$ = 1.00 unless tabs function also in the powered mode, in which case $K_{pi} = K_{mi}$

$N_{mi}$ = number of manual actuation systems driving the individual elevator panels

$K_{mi}$ = elevator tab factor for the individual elevator panel

$K_{mi}$ = $\left( \frac{xb - ya}{xb} \right) (0.80)$ = 1.00 if no tabs are used (see fig. 17.)

Suggested default values:

$\delta_e$ = 20°

$V_D$ = 445 kn

$N_{pi}$ = 2

$N_{mi}$ = 0

**Horizontal Tail**

$$\text{Weight} = (\text{basic weight})\,(K_{load})\,(K_{\lambda})\,(K_{elevator\ chord})\,(K_{TT})\,(K_S)$$

where

Basic weight = function of (structural span)$^2$, planform area, and mean depth (See fig. 18.)

The parameter definitions required to develop the basic weight influence factors are as follows:

$b_{0.5c}$ = structural span of the tail surface measured along the elastic axis, ft (Use exposed area structural span for slab tails, ft.)

$S_{HT}$ = planform area of conventional horizontal tail, ft$^2$, including the section blanked out by the body (Use exposed planform area for slab tails, ft$^2$.)

d = mean structural depth of tail, ft, computed as 80% of the maximum root chord depth plus 20% of the tip chord depth (Use exposed root chord depth for slab horizontal tails.)

$K_{load}$ = function of tail unit loading (fig. 19) (Use fig. 20 for horizontal tail load calculation.)

The horizontal tail unit loading is the figure 20 value divided by gross tail area measured to body centerline.

$K_{\lambda}$ = function of tail surface taper ratio; theoretical tip chord/theoretical root chord (See fig. 21.) (Use exposed surface geometry for slab tails.)

$K_{\%}$ = function of elevator planform chord/planform tail surface chord (See fig. 21.)

$K_{TT}$ = correction for installing a torque tube required for horizontal tail body carry-through structure = 1.5

$K_S$ = correction for installing a spindle in the root section of a horizontal slab tail = 1.25

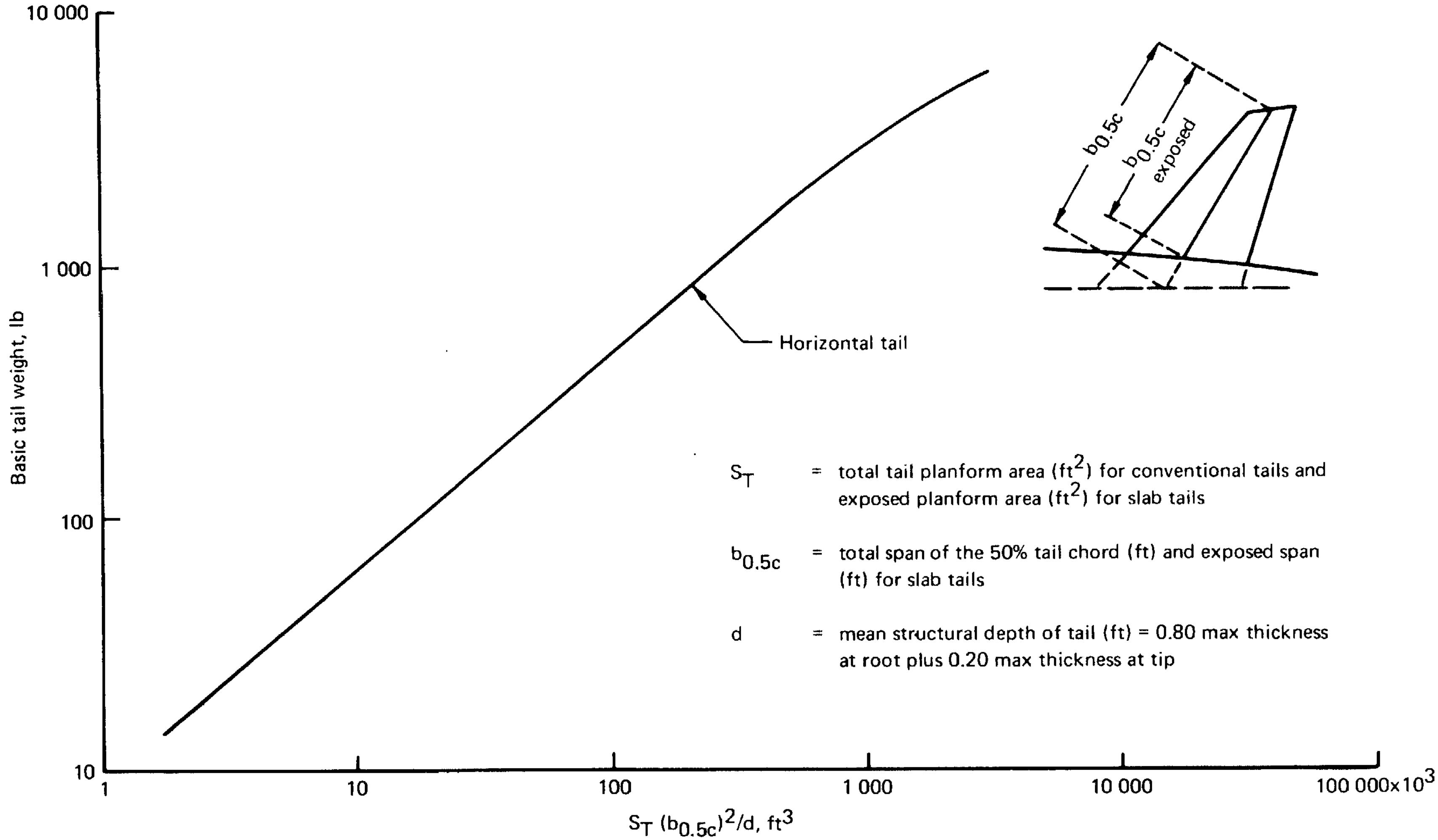



*Figure 18.—Horizontal Tail—Basic Weight*

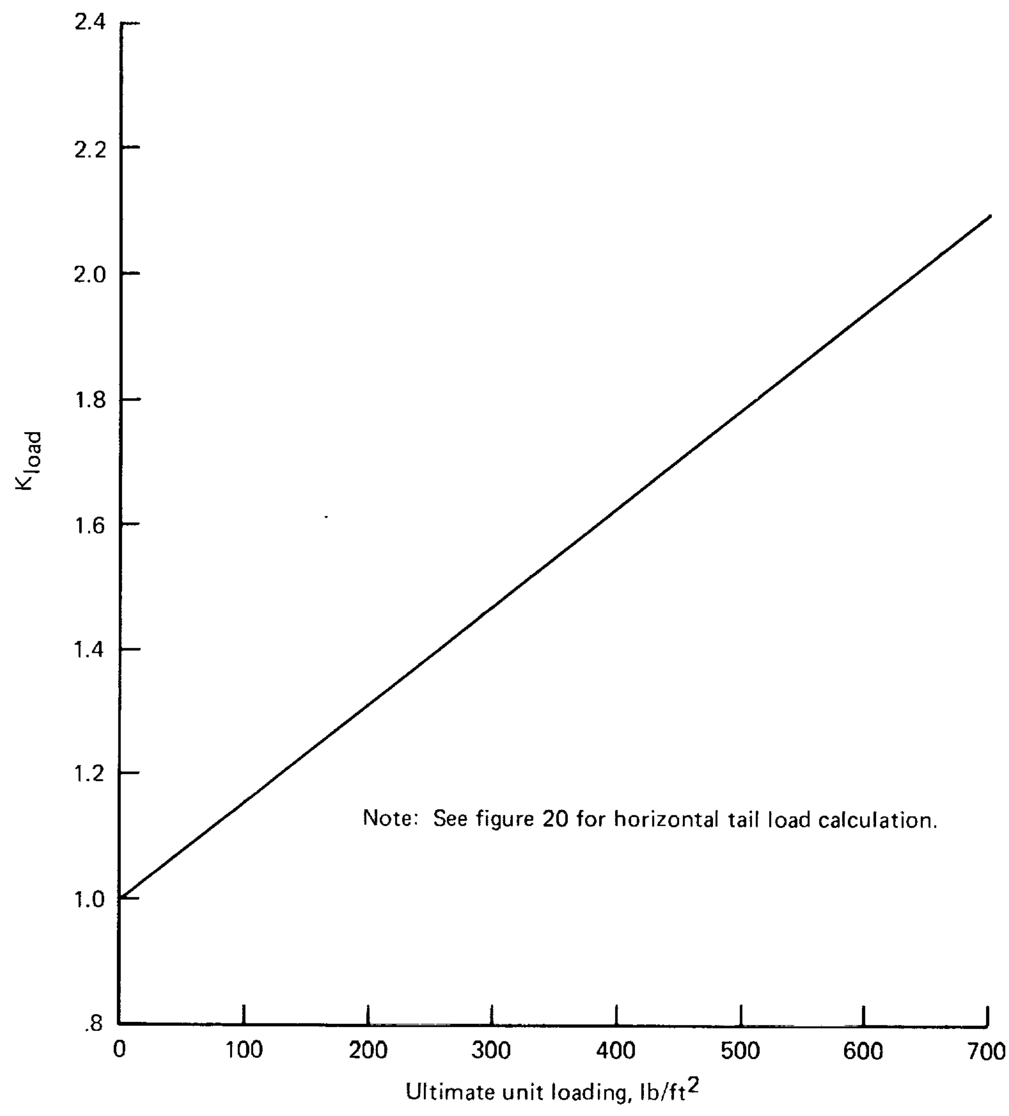



*Figure 19.—Ultimate Unit Loading Versus $K_{load}$*

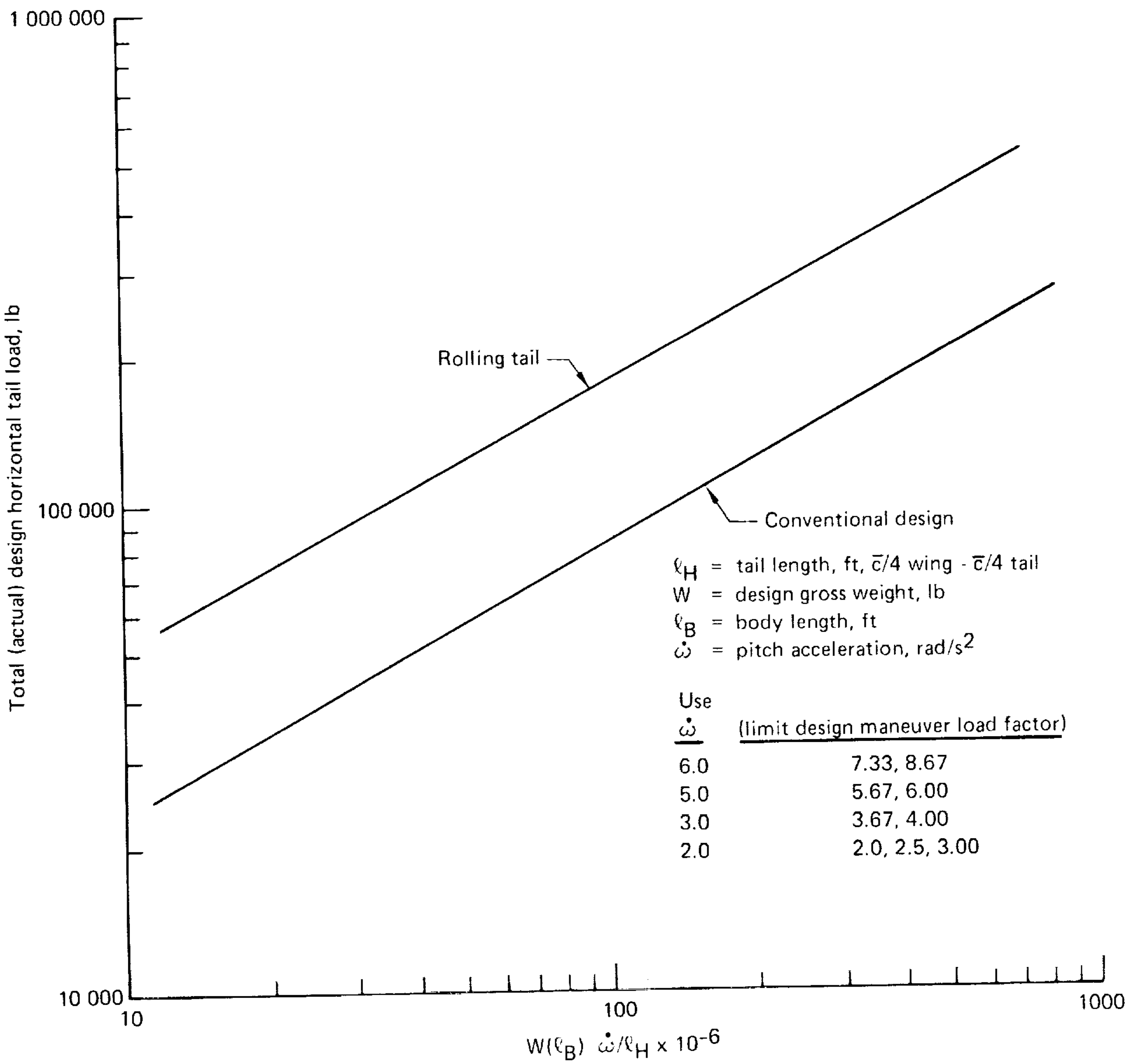
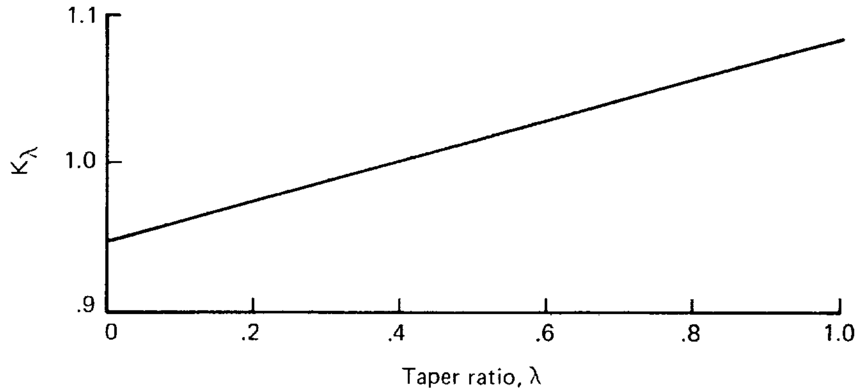



*Figure 20.—Design Horizontal Tail Load Versus Tail Load Parameter*



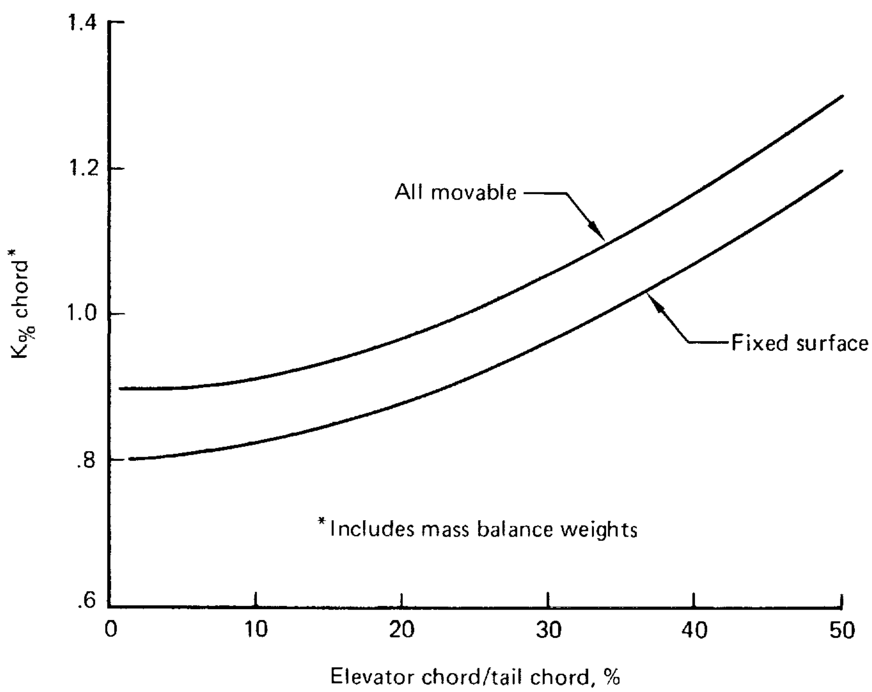




*Figure 21.—Taper Ratio Versus $K_\lambda$—Percent Chord Versus $K_{\%}$ Chord*

Use the following weight formulas for other empennage surfaces:

$$\text{Dorsal fin} = 3.5 \text{ lb/ft}^2 \text{ of planform area}$$

$$\text{Ventral fin} = 4.0 \text{ lb/ft}^2 \text{ of planform area}$$

Canard weight is computed the same as horizontal tail, except that maximum load is estimated from a static balance diagram using the most forward c.g. location.

Note that tail unit weights should not be less than 3.5 lb/ft$^2$.

### 4.2.2 1990 WEIGHT TECHNOLOGY SENSITIVITIES

Current research and development work is advancing technology levels available for future aircraft. To make the baseline weight sensitivities responsive to these technology improvements, the equations were modified to reflect advanced composite structure and supercritical aerodynamic effects. Composite structure weight benefits shown for 1990 available technology are consistent with weight benefits shown for similar structures in reference 6. The weight effects of supercritical aerodynamics are the result of higher control surface hinge moments that prevail due to the aft-loaded chordwise pressure distributions. The effects of these higher hinge moments are shown to be in surface control systems with little or no structural weight effect on the surface structures due to higher loads.

High-pressure hydraulics (4000 to 10 000 lb/in$^2$) were considered for 1990 technology effects, but past studies have shown that the current 3000-lb/in$^2$ systems are near optimum weights, and very little weight benefit is available by increasing hydraulic supply pressures (ref. 7). The higher pressure systems would be considered for applications with severe space restrictions.

Fly-by-wire electronic control technology is anticipated for the 1990 period and would be almost a requirement for realization of effective active control functions. However, fly-by-wire reliability-redundancy requirements and concepts of mechanization vary widely among the several studies conducted at Boeing for applications to commercial transports. Fly-by-wire control systems that have been studied for application to the 747 have resulted in control system weight reductions of only about 5%. The following weight equations for the 1990 technology level will therefore not reflect a major weight benefit to control systems due to fly by wire.

**Ailerons**

$$\text{Weight} = 0.94 \sin \delta_{max} \left[\frac{V_D}{100} \cos \Lambda_{HL}\right]^2 (A_p)^{0.845} + 2.16\,(A_p)^{0.87}$$

Coefficients reflect 28% weight benefit due to advanced composite structure. Parameters are defined in section 4.2.1.

**Trailing-Edge Flaps**

Surfaces

$$\text{Weight (single-slotted)} = 2.138 \left[\frac{\text{(FLPCHD) (FLPSPN)}}{144}\right]^{1.000}$$

$$\text{Weight (double-slotted)} = 2.804 \left[\frac{\text{(FLPCHD) (FLPSPN)}}{144}\right]^{0.974}$$

$$\text{Weight (triple-slotted)} = 4.048 \left[\frac{\text{(FLPCHD) (FLPSPN)}}{144}\right]^{0.974}$$

Coefficients reflect 25% weight benefit due to advanced composite structure.

Support Structure

$$\text{Weight (single-slotted)} = 2.640 \left[\text{(DISTCANT) (ASUM)}\right]^{0.769}$$

$$\text{Weight (double-slotted)} = 2.640 \left[\text{(DISTCANT) (ASUM)}\right]^{0.769}$$

$$\text{Weight (triple-slotted)} = 3.767 \left[\text{(DISTCANT) (ASUM)}\right]^{0.769}$$

Coefficients reflect 30% weight benefit due to advanced composite structure.

Support Fairings

$$\text{Weight} = 1.72 \text{ (AF)}$$

The equation reflects 30% weight benefit due to advanced composite structure.

Trailing-Edge Flaps Installation = Surfaces + Support Structure + Fairings

Parameters are defined in section 4.2.1.

**Spoilers**

$$\text{Weight} = 0.100 \text{ (ASP)}^{1.143} \text{ (SPLFDN)}^{0.666}$$

The equation reflects 20% weight benefit due to advanced composite structure. Parameters are defined in section 4.2.1.

**Fixed Trailing-Edge Structure**

$$\text{Weight} = 1.005 \text{ (ANET)}^{1.089} \geq 1.50 \text{ ANET}$$

The equation reflects 25% weight benefit due to advanced composite structure. Parameters are defined in section 4.2.1.

**Fixed Leading-Edge Structure**

$$\text{Weight} = 0.93\ (\text{SFXLE})^{1.191}$$

The equation reflects 25% weight benefit due to advanced composite structure.

**Leading-Edge Flaps**

$$\text{Weight} = 3.62\ \left[(2)\ (\text{SVCFL})\ (\text{AEXT})\right]^{0.884} \text{ (variable camber Krueger)}$$

$$\text{Weight} = 3.05\ \left[(2)\ (\text{SFCFL})\ (\text{AEXT})\right]^{0.884} \text{ (fixed camber Krueger)}$$

The equations reflect 25% weight benefit due to advanced composite structure. Parameters are defined in section 4.2.1.

**Aileron Controls**

$$\text{Weight} = 29.35 \left[ (2) \sum_{i=1}^{N} K_{HM}\ (k_i\ S\bar{c}_i) \right]^{0.44}$$

where

$K_{HM}$ = correction factor for supercritical aerodynamic effects on hinge moment

$$= \frac{C_{H_{\text{supercritical airfoil}}}}{C_{H_{747\ \text{airfoil}}}}$$

See figure 22. Other parameters and suggested default values are defined in section 4.2.1.

**Trailing-Edge Flap Controls**

$$\text{Weight} = 392 + 145 \left[ \frac{(\Delta C_L)\ (W_{GR})}{100\ 000} \right]$$

Parameters and suggested default values are defined in section 4.2.1.

**Leading-Edge Flap Controls**

$$\text{Weight} = 2.5 + 127.9 \left[ \frac{(\Delta C_L)\ (W_{GR})}{100\ 000} \right]$$

Parameters and suggested default values are defined in section 4.2.1.

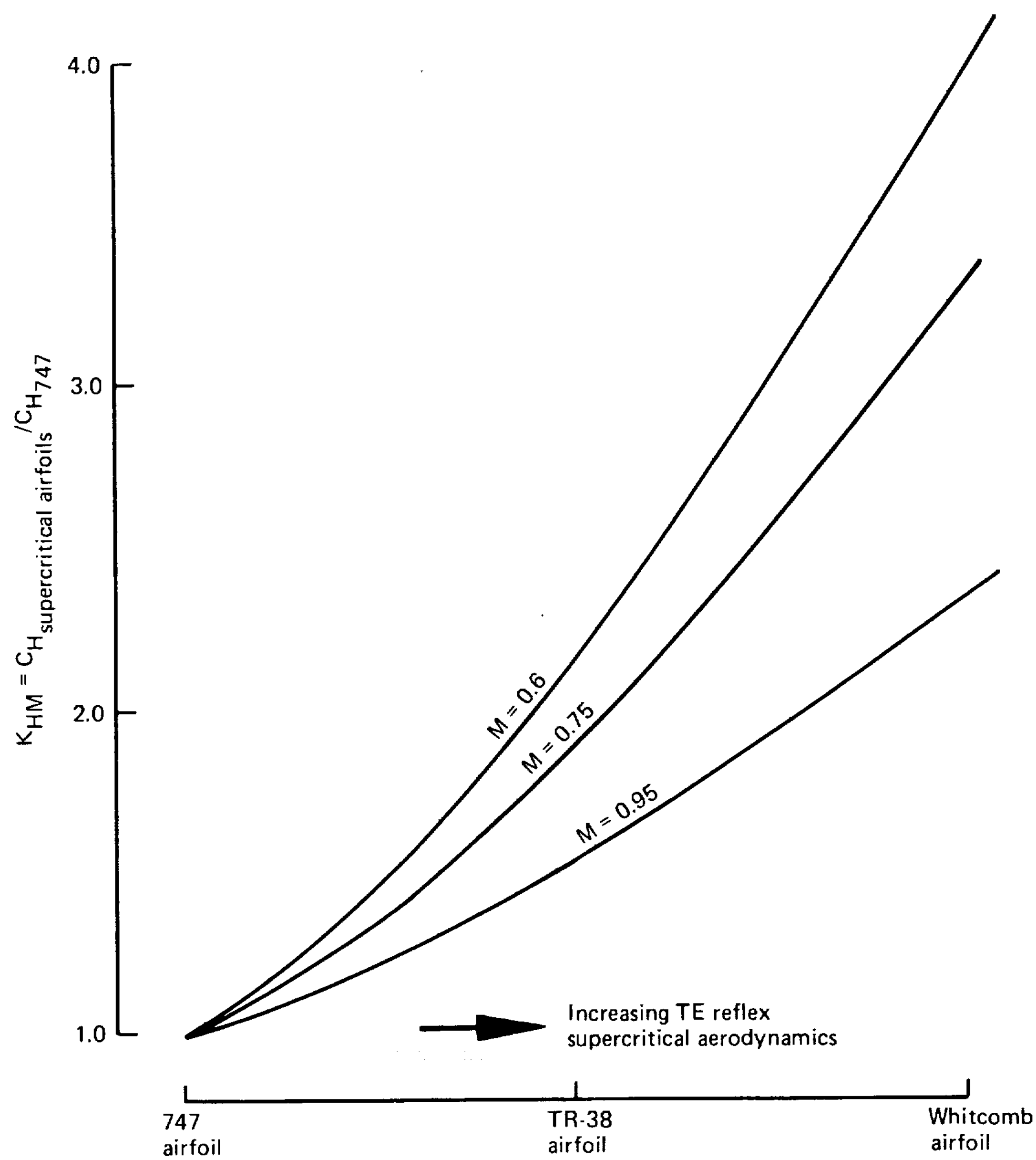



*Figure 22.—Hinge Moment Correction Factor Versus Airfoil Types*

**Spoiler Controls**

$$\text{Weight} = 89 + G_{SP} + 76.8 \sum_{i=1}^{N} F_{SPi}$$

Parameters and suggested default values are defined in section 4.2.1.

**Stabilizer Adjustment Control**

$$\text{Weight} = (W_{bsa}) \left[ N_{bsa} + N_{psa} \left( \frac{B_p}{B_{bsa}} \right)^{1/2} \right]$$

Parameters and suggested default values are defined in section 4.2.1.

**Elevator Controls**

$$\text{Weight} = (2) \sum_{i=1}^{N} \left[ (119) \left( \frac{S\bar{c}_i}{S\bar{c}_{total}} + 0.03\, P_{eci} \right) (N_{pi}\, K_{pi} + N_{mi}\, K_{mi}) \right]$$

Parameters and suggested default values are defined in section 4.2.1.

**Horizontal Tail**

The weight equation is the same as given in section 4.2.1 but with 25% structural weight benefit due to advanced composite structure.

### 4.2.3 ACTIVE CONTROL TECHNOLOGY WEIGHT SENSITIVITIES

Active control functions may impose weight penalties to existing control surfaces due to geometric interruptions (split surfaces), increased deflection rates, or new surfaces dedicated to active functions. Control surface structures of the 1990 projected technology level, however, will be constructed of advanced composite materials and should be able to withstand the predicted loads of active functions with relatively little weight penalty. The 1990 technology weight equations have therefore been modified to recognize geometry interruptions of split surfaces. In the case of load alleviation functions added to the trailing-edge flaps, the split surface effect includes the addition of an aileron-like function to the aft segment of the flaps. In this case, the aileron equation is added to the flap equation with the appropriate geometry inputs.

The surface controls system weights, however, are quite responsive to load changes, and these equations have been modified to include hinge moment and actuation rate requirements. Redundancy requirements are considered in the baseline equations, and no modifications to the equations were required in this respect.

**Ailerons**

$$\text{Weight} = 0.94 \sin \delta_{max} \left[ \frac{V_D}{100} \cos \Lambda_{HL} \right]^2 (A_p)^{0.845} + 2.16\, (A_p)^{0.87}$$

Parameters are defined in section 4.2.1.

**Trailing-Edge Flaps Installation**

Surfaces

$$\text{Weight (single-slotted)} = 2.138 \left[\frac{(\text{FLPCHD})\ (\text{FLPSPN})}{144}\right]^{1.00}$$

$$+ 0.94 \sin \delta_{max} \left[\frac{V_D}{100} \cos \Lambda_{HL}\right]^2 \ (A_p)^{0.845}$$

$$+ 2.16\ (A_p)^{0.87}$$

$$\text{Weight (double-slotted)} = 2.804 \left[\frac{(\text{FLPCHD})\ (\text{FLPSPN})}{144}\right]^{0.974}$$

$$+ 0.94 \sin \delta_{max} \left[\frac{V_D}{100} \cos \Lambda_{HL}\right]^2 \ (A_p)^{0.845}$$

$$+ 2.16\ (A_p)^{0.87}$$

$$\text{Weight (triple-slotted)} = 4.048 \left[\frac{(\text{FLPCHD})\ (\text{FLPSPN})}{144}\right]^{0.974}$$

$$+ 0.94 \sin \delta_{max} \left[\frac{V_D}{100} \cos \Lambda_{HL}\right]^2 \ (A_p)^{0.845}$$

$$+ 2.16\ (A_p)^{0.87}$$

Support Structure

$$\text{Weight (single-slotted)} = 2.640\ [(\text{DISTCANT})\ (\text{ASUM})]^{0.769}$$

$$\text{Weight (double-slotted)} = 2.640\ [(\text{DISTCANT})\ (\text{ASUM})]^{0.769}$$

$$\text{Weight (triple-slotted)} = 3.767\ [(\text{DISTCANT})\ (\text{ASUM})]^{0.769}$$

Support Fairings

$$\text{Weight} = 1.72\ (\text{AF})$$

Parameters are as defined in section 4.2.1, with the following exceptions:

FLPCHD = streamwise flap chord in the retracted, nested position minus the chord of that portion activated for load control functions

$A_p$ = surface planform area of that portion activated for load control functions

**Spoilers**

$$\text{Weight} = 0.100\ (\text{ASP})^{1.143}\ (\text{SPLFDN})^{0.666}$$

Parameters are defined in section 4.2.1.

**Fixed Trailing-Edge Structure**

$$\text{Weight} = 1.005\ (\text{ANET})^{1.089}$$

Parameters are defined in section 4.2.1.

**Fixed Leading-Edge Structure**

$$\text{Weight} = 0.93\ (\text{SFXLE})^{1.191}$$

Parameters are defined in section 4.2.1.

**Leading-Edge Flaps**

$$\text{Weight} = 3.62\ \left[(2)\ (\text{SVCFL})\ (\text{AEXT})\right]^{0.884} \text{ (variable camber Krueger flaps)}$$

$$\text{Weight} = 2.29\ \left[(2)\ (\text{SFCFL})\ (\text{AEXT})\right]^{0.884} \text{ (fixed camber Krueger flaps)}$$

Parameters are defined in section 4.2.1.

**Aileron Controls**

$$\text{Weight} = 29.35 \left[(2) \sum_{i=1}^{N} (K_{\omega} K_{HM})\ (k_i\ S\bar{c}_i)\right]^{0.44}$$

Parameters are as defined in sections 4.2.1 and 4.2.2, with the following exceptions:

$K_{\omega}$ = correction factor for nonstandard actuation rate

$$K_{\omega} = \frac{\omega_{\text{active control function}}}{\omega_{\text{normal function}}} \geqslant 1.00$$

$\omega_{\text{normal function}}$ = 60°/s (default value)

$\omega_{\text{active control function}}$ = 100°/s (flutter suppression default value)

The GLA or MLC function applied to ailerons would not impact power requirements, since the actuation rates are below normal aileron design rates.

**Trailing-Edge Flap Controls**

$$\text{Weight} = 392 + 145\left[\frac{(\Delta C_L)\ (W_{GR})}{100\ 000}\right] + 29.35\left[(2) \sum_{i=1}^{N} (K_{\omega} K_{HM})\ (k_i\ S\bar{c}_i)\right]^{0.44}$$

Parameters are defined in sections 4.2.1 and 4.2.2, and in the preceding aileron controls equation in this section.

**Leading-Edge Flap Controls**

$$\text{Weight} = 2.5 + 127.9 \left[\frac{(\Delta C_L)\,(W_{GR})}{100\,000}\right]$$

Parameters are defined in section 4.2.1.

**Spoiler Controls**

$$\text{Weight} = 89 + G_{SP} + 76.8 \sum_{i=1}^{N} F_{SP_i}$$

Parameters are defined in section 4.2.1.

**Stabilizer Adjustment Controls**

$$\text{Weight} = (W_{bsa}) \left[ N_{bsa} + N_{psa} \left( \frac{B_p}{B_{bsa}} \right)^{1/2} \right]$$

Parameters are defined in section 4.2.1.

**Elevator Controls**

$$\text{Weight} = (2) \sum_{i+1}^{N} \left[ \left( 119 \frac{S\bar{c}_i}{S\bar{c}_{total}} + 0.03\, P_{eci} \right) \left( N_{pi}\, K_{pi} + N_{mi}\, K_{mi} \right) \right]$$

Parameters are defined in section 4.2.1.

**Horizontal Tail**

The weight equation is the same as given in section 4.2.1, but using the slab tail option.

## 4.3 COST METHODOLOGY

This section includes the baseline costs, the 1990 technology cost sensitivities, and the active control technology cost sensitivities. It describes the cost data used as a baseline for the control systems and control surfaces and the relationships of new technology as defined by Engineering to the baseline cost. The Engineering definition includes the work statement, the system complexity, and the weight differences between the baseline and the new technology flight control system.

The broad objective is to determine the incremental flyaway cost in 1975 dollars between current technology and advanced technology programs. The flyaway cost estimates include the nonrecurring and recurring costs for 200 airplanes. An average of the 200-airplane program represents the per-unit flyaway cost.

### 4.3.1 BASELINE COSTS

The baseline costs for the control surfaces and related systems are representative of production program expenditures for the specified size commercial jet. They include conventional equipment and hardware used in subsonic jet aircraft produced at a historically delivered quantity per year. The baseline costs for explicit control surfaces and systems are shown in figures 23 through 28. On each chart, the baseline cost for conventional aluminum control surfaces is represented as one line with relative cost on the vertical scale and weight on the horizontal scale.

### 4.3.2 1990 TECHNOLOGY COST SENSITIVITIES

The primary factors used to determine cost for the incorporation of 1990 technology are types of new materials, complexity factors, and incremental weight variations to the baselines. The resulting dollar differences are in constant year; no economic escalation has been applied.

Each application of advanced technology defined in the trade studies was analyzed, and the net effect is identified and shown in figures 23 through 28. The line for cost on new technology control surfaces and system, when compared to the line representing conventional hardware, presents a relative cost and weight difference between the two designs.

### 4.3.3 ACTIVE CONTROL TECHNOLOGY SENSITIVITIES

The cost estimates for active controls are based primarily on complexity factors determined by Engineering. These factors were applied to conventional equipment costs. The electrical signal paths for a fly-by-wire system were analyzed separately from the hydraulic actuation system to assess the complexity of self-contained actuators and the amount of redundancy required in each system. The computer and sensing devices are excluded from the cost.

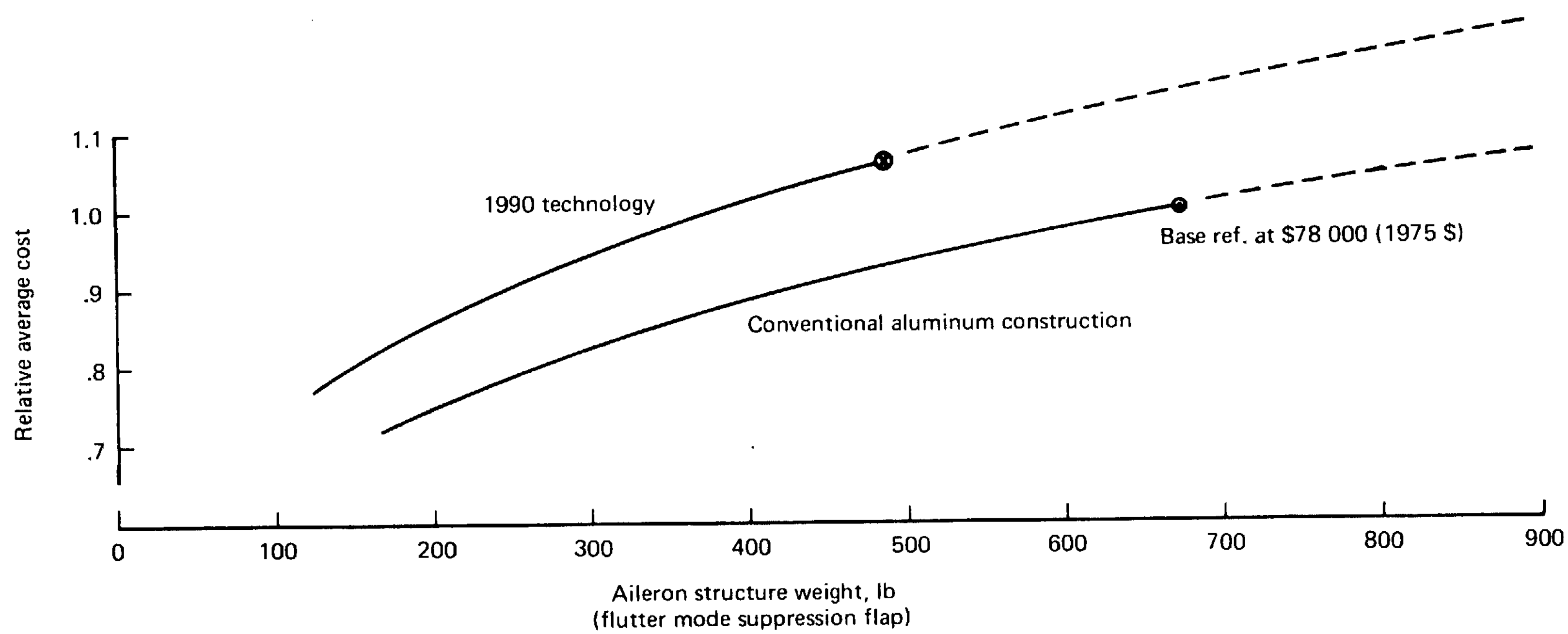



*Figure 23.—Ailerons Relative Average Cost per Airplane—200 Airplanes*

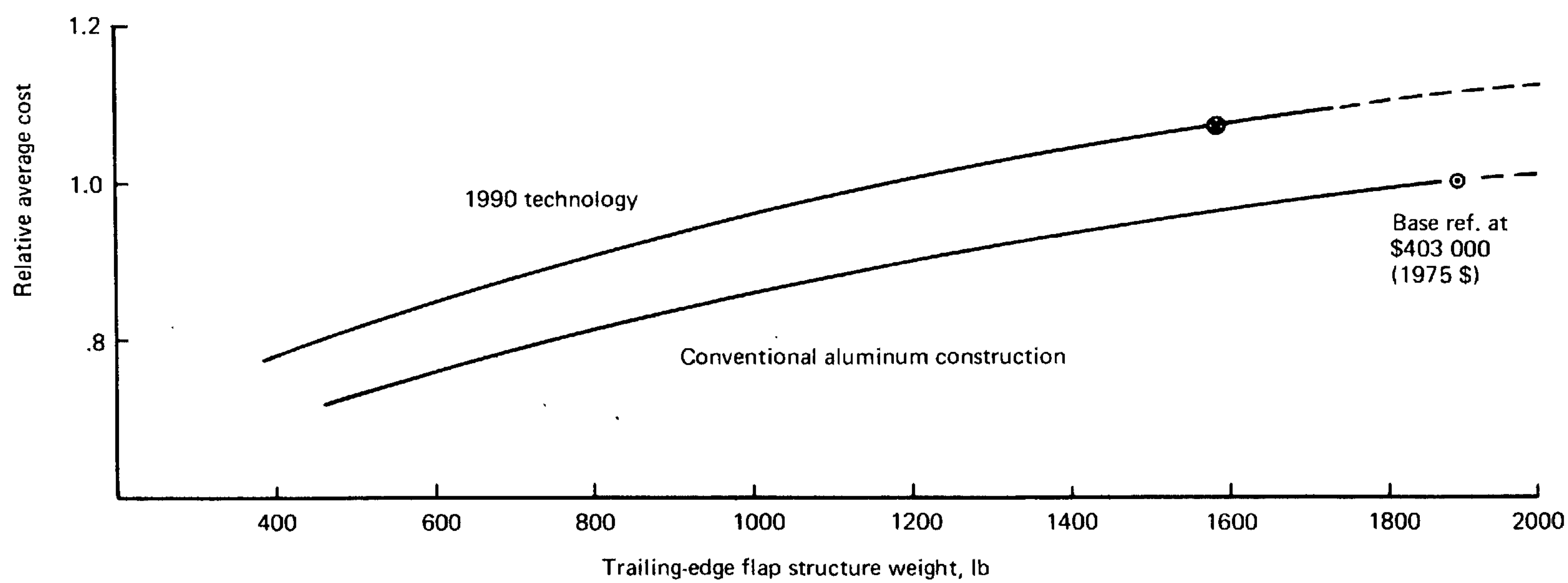



*Figure 24.—Trailing-Edge Flaps Relative Average Cost per Airplane—200 Airplanes*

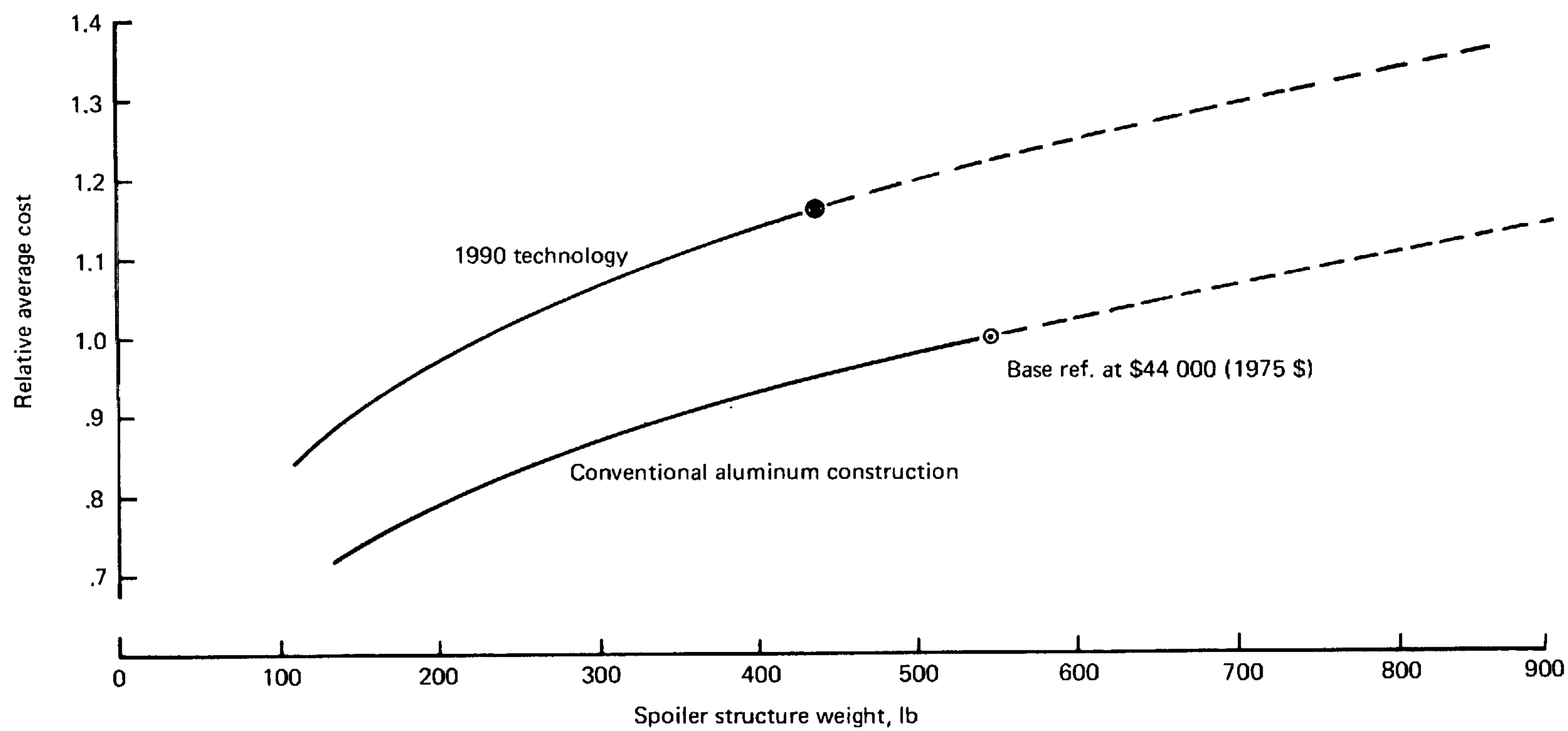



*Figure 25.—Spoilers Relative Average Cost per Airplane—200 Airplanes*

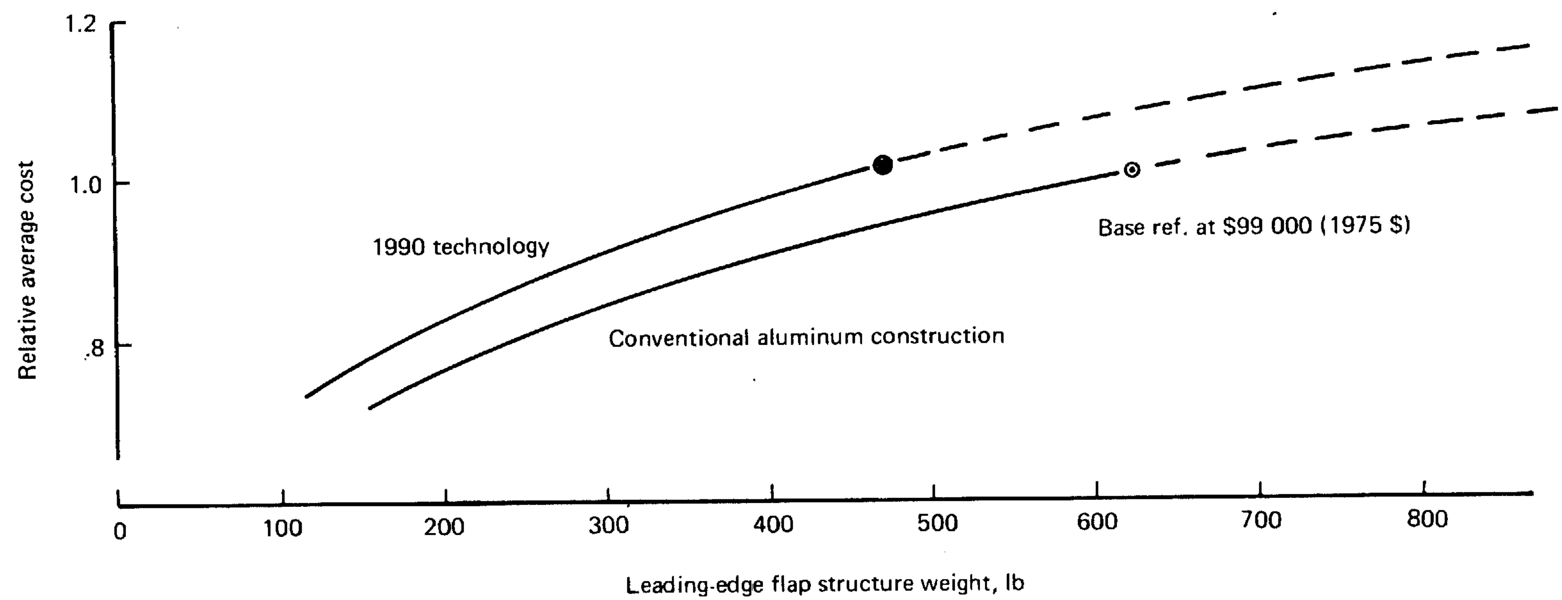



*Figure 26.—Leading-Edge Flaps Relative Average Cost per Airplane—200 Airplanes*

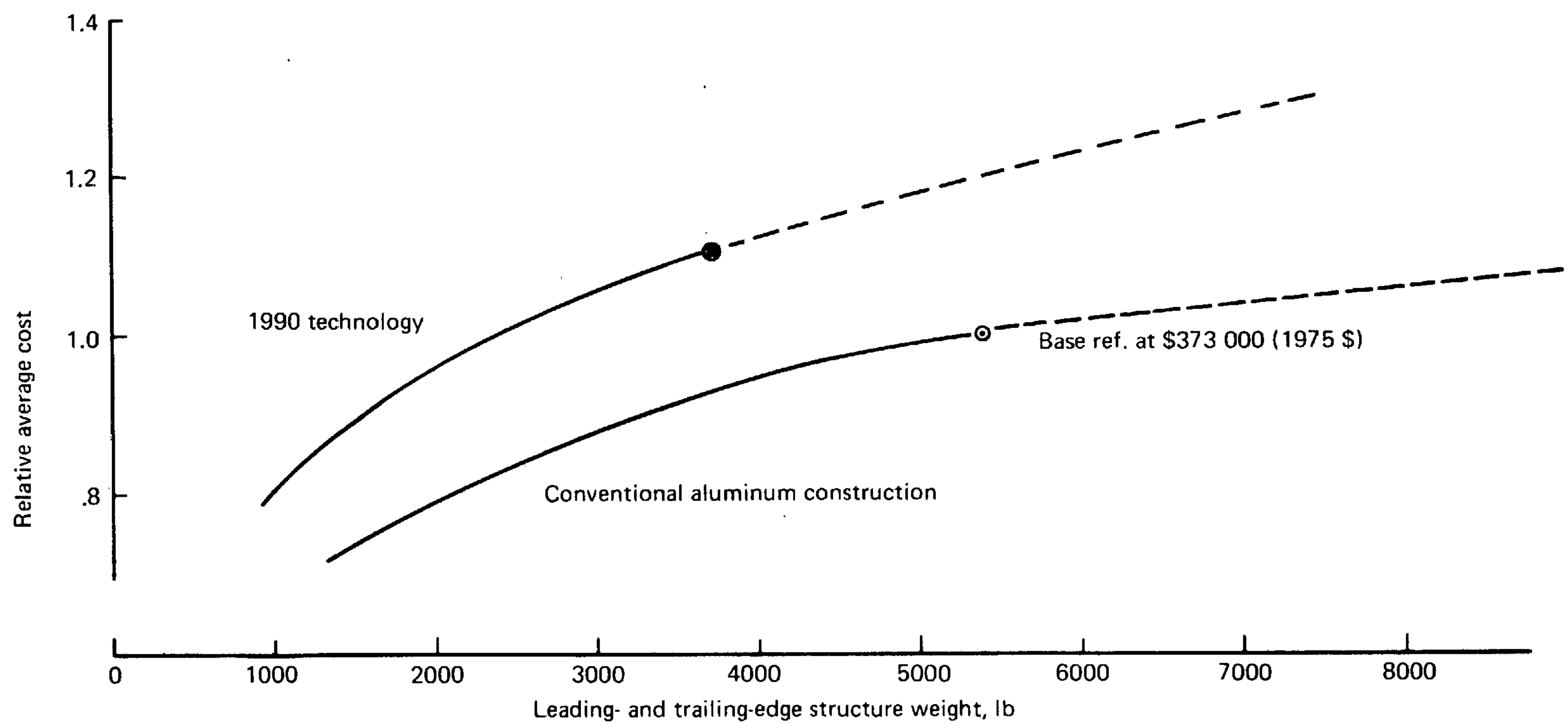



*Figure 27.—Fixed Leading- and Trailing-Edge Relative Average Cost per Airplane—200 Airplanes*

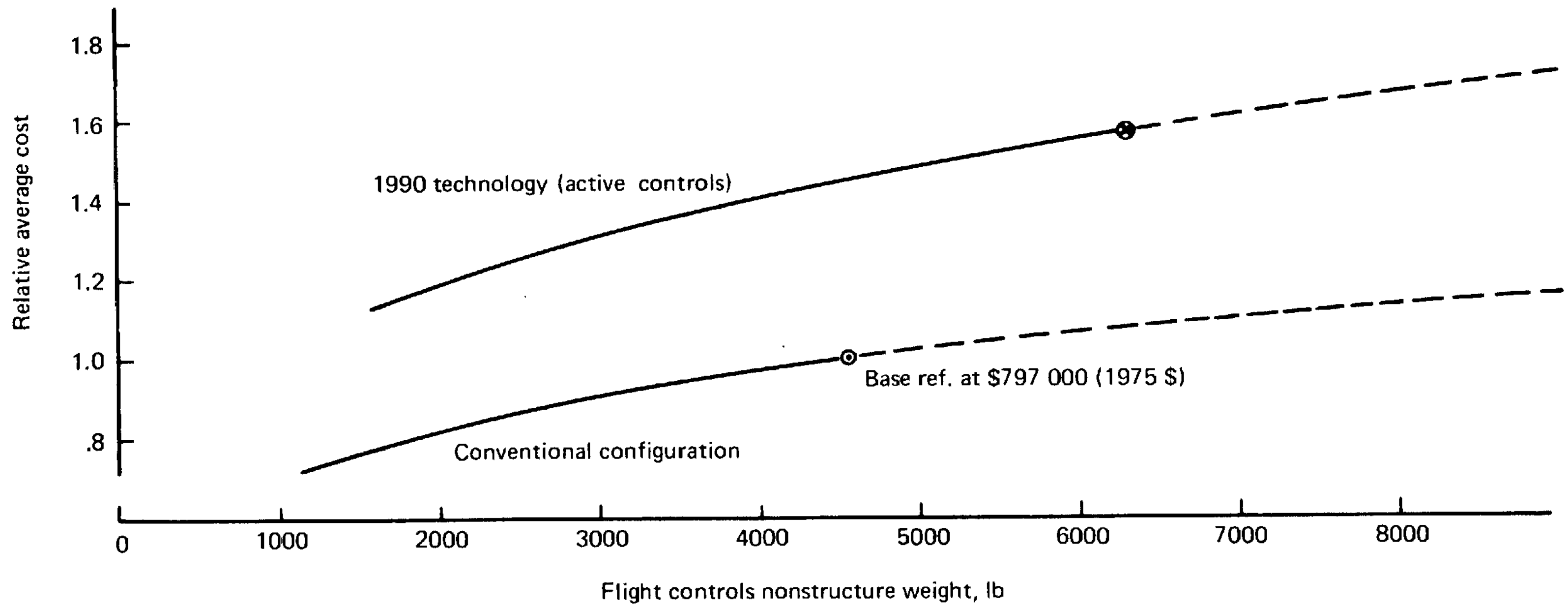



*Figure 28.—Flight Controls Systems Relative Average Cost per Airplane—200 Airplanes*

# 5.0 ILLUSTRATIVE EXAMPLE

Use of the methodology developed in section 4 is illustrated through a worked example. This section presents a description of the illustrative airplane and its control system (including ACT functions), weight and cost data that show the incremental impact of adding ACT functions to a subsonic CTOL airplane, and an end-to-end numerical calculation for one ACT function.

## 5.1 AIRPLANE DESCRIPTION

The illustrative airplane is the medium-range, wide-body trijet specified by Attachment A from NASA's statement of work for this contract. A general arrangement drawing of this vehicle is shown in figure 29. The illustrative airplane incorporates the following ACT functions: augmented stability, maneuver load control, gust load alleviation, and flutter mode control. Wing ACT and primary control surfaces are shown in figure 4. Pertinent design features of the illustrative airplane are the following:

1. Supercritical airfoils

2. Advanced materials control surfaces

3. Fully powered flight control system

4. Quadruplex hydraulic system

5. Slab horizontal tail for longitudinal control

6. Double-slotted, externally hinged flaps with load control flap segments

7. Power-by-wire actuation for the load control flaps

The assumption is made that the ACT functions are used to expand the illustrative airplane's operational envelope. The corollary to this assumption is that the airplane can be operated in a restricted flight envelope and that it has "get-home" capability with all ACT functions disengaged. The active control technology functions are implemented with a dual-redundant mechanization. With level of redundancy, the operational flight envelope must be reduced after the first failure (e.g., one hydraulic system), and the airplane can be dispatched with a restricted flight envelope with all ACT functions inoperative. The assumption is made that a revenue flight can be completed within the restricted flight envelope.

Weight and cost evaluation of the horizontal tail would require more information than is available from the example definition given. Comparisons of horizontal tail weights for normal and active functions would require a scalable drawing of the example with airfoil thickness, hinge axis, and actuator location defined. The weight equations are provided, however, including sensitivities to loading, geometry, redundancy, and horizontal tail configuration. The weight and cost data include an evaluation of a

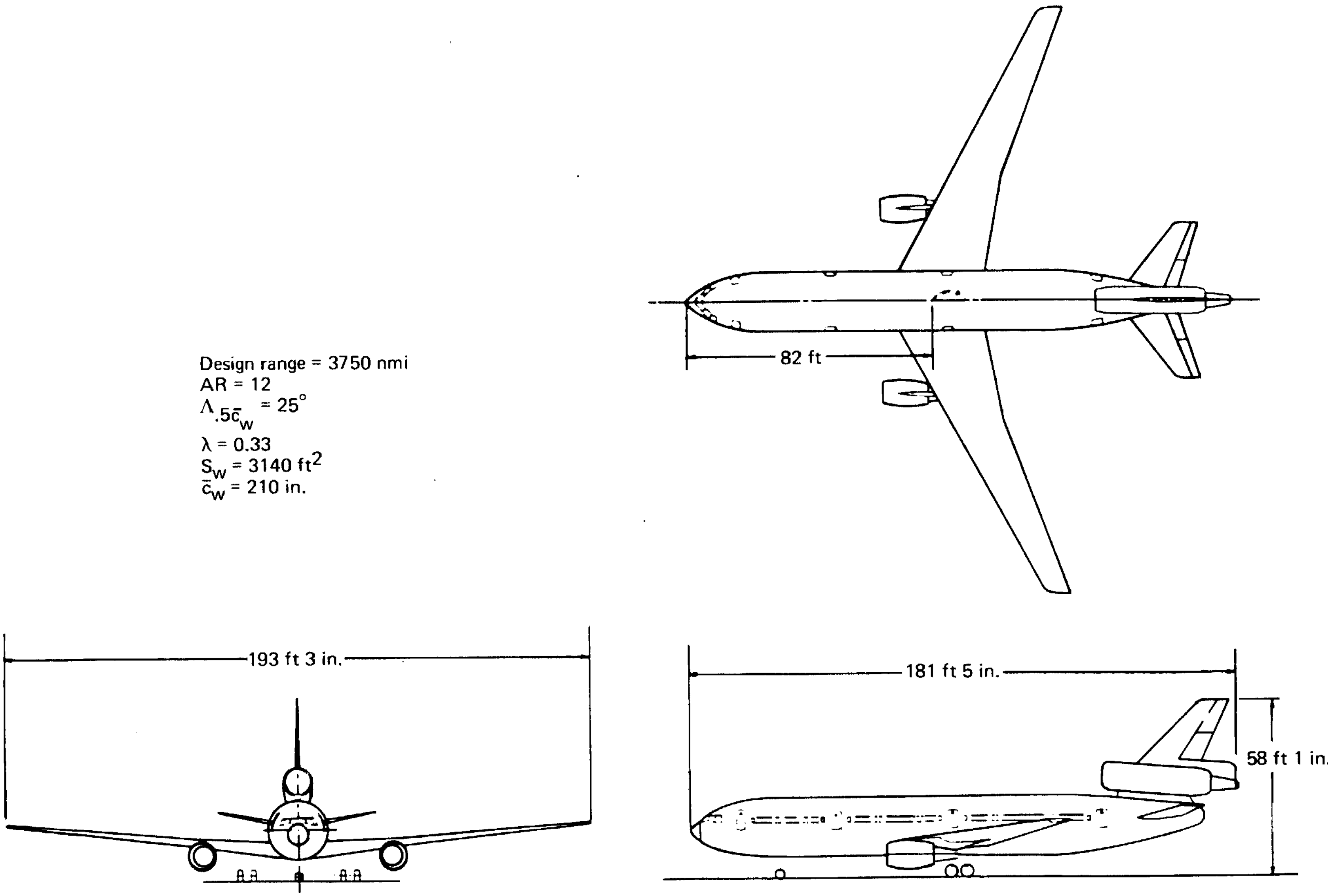



*Figure 29.—Illustrative Airplane Configuration*

conventional trimmable stabilizer and elevator system typical of the type shown for the example. A "slab" tail (similar to that on the Lockheed L-1011) would be suitable for performing the stability augmentation function.

## 5.2 FLIGHT CONTROL SYSTEM

This section illustrates the specification of control system actuators, the hydraulic system, and the electrical system characteristics that are used by the weight and cost equations. Table 5 presents the following information which describes the flight control system and the ACT functions:

1. Active control surface
   - Geometry
   - Number per airplane
2. Design flight conditions
3. Design hinge moments
4. Surface authority and rate limits
5. Hydraulic power and flow rate requirements

### 5.2.1 CONTROL SYSTEM ACTUATORS

In each of the following systems, it is assumed that active control signals from appropriate sensors are amplified and directly applied either to dedicated active control actuators or to actuators that are also used for primary flight control. If the latter are normally controlled by mechanical inputs, it is assumed that the active control signals would be fed to an electrohydraulic servovalve controlling a secondary actuator integrated in each primary actuator housing. If the primary flight control actuators are the full electric-command (fly-by-wire) type, it is assumed that the active control signals would be integrated with primary control signals in an electronic control unit and the integrated signals fed to the power actuators.

**Augmented Relaxed Pitch Stability Control System**

Four linear hydraulic servoactuators, each capable of receiving normal longitudinal control commands plus stability augmentation commands, are assumed for control of the flying slab horizontal stabilizer. Each actuator is capable of providing one-half of the required design hinge moment.

**Maneuver Load Control System**

Two dedicated load control system servoactuators are assumed installed in the large translating aft flap of the externally hinged inboard and outboard trailing-edge flap in

## Table 5.—Active Control Surface and Hydraulic Requirements

| Active control surface | Number per airplane | Dimensional relationships: $S_s/S_w$ | Dimensional relationships: $\bar{c}_s/\bar{c}_w$ | Design condition | Dynamic pressure, q, N/m² (lb/ft²) | Hinge moment coeff., $C_H$ | Design hinge moment, N·m (lb-in.) | Surface motion, rad (deg) | Surface rate, rad/s (deg/s) | Hydraulic requirements: Number of actuators: Per surface | Hydraulic requirements: Number of actuators: To meet design condition | Required actuator hinge moment, N·m (lb-in.) | Hydraulic power per actuator, kW (hp) | Hydraulic flow rate per actuator[a], cm³/s (gal/min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maneuver Load Control | | | | | | | | | | | | | | |
| Aft segment of inbd flap and | 2 | 0.0157 | 0.112 | Buffet $n_{max}$ corner | 14 940 (312) | 0.127 | 5 190 (45 940) | ±0.17 (±10) | 0.17 (10) | 2 | 1 | 5 190 (45 940) | 0.88 (1.2) | 60 (1.0) |
| Outboard flight spoilers, or | 10 | 0.0037 | 0.114 | Flap placard: 110 m/s (215 kn) | 7 470 (156) | 0.50 | 2 450 (21 700) | 0.79 (45) | 0.87 (50) | 1 | 1 | 2 450 (21 700) | 2.1 (2.9) | 150 (2.35) |
| Aft segment of outbd flap | 2 | Actuators sized to meet gust load alleviation control hinge moments | | | | | 6 410 (56 700) | ±0.17 (±10) | 0.17 (10) | 2 | 1 | 6 410 (56 700) | 1.1 (1.5) | 75 (1.2) |
| Gust Load Alleviation | | | | | | | | | | | | | | |
| Aft segment of outbd flap and | 2 | 0.0151 | 0.078 | $V_C/M_C$: 180 m·s⁻¹/0.90 (350 kn/0.90) | 19 900 (415) | 0.176 | 6 410 56 700 | ±0.17 (±10) | 0.87 (50) | 2 | 1 | 6 410 56 700 | 5.6 (7.5) | 385 (6.1) |
| Outboard flight spoilers | 10 | Data as above (under Maneuver Load Control) | | | | | | | | | | | | |
| Flutter Mode Control | | | | | | | | | | | | | | |
| Inbd panel of outbd aileron or | 2 | 0.0057 | 0.119 | 1.2 $V_D/M_D$ | 37 400 (781) | 0.247 | 9 740 (86 400) | ±0.17 (±10) | 1.75 (100) | 2 | 1 | 9 740 (86 400) | 17.0 (22.8) | 1175 (18.6) |
| Same without lower surface camber | | Data as above except for reduced $C_H$ | | | | 0.13 | 5 140 (45 400) | | | 2 | 1 | 5 140 (45 400) | 9.0 (12.0) | 620 (9.8) |
| Augmented Pitch Stability | | | | | | | | | | | | | | |
| Slab horizontal tail or | 1 | 0.191 | 0.541 | $V_D/M_D$ dive recovery | 25 950 (542) | 0.032 | 133 400 (1 188 000) | 0.26 (15) | 0.168 (9.6) | 4 | 2 | 66 700 (590 900) | 11.2 (15.0) | 770 (12.3) |
| Inboard elevators and | 2 | 0.0135 | 0.178 | Same | 25 950 (542) | 0.09 | 8 740 (77 300) | ±0.44 (±25) | 0.61 (35) | 2 | 2 | 4 370 (38 650) | 2.7 (3.6) | 180 (2.9) |
| Outboard elevators | 2 | 0.012 | 0.154 | Same | 25 950 (542) | 0.09 | 6 710 59 400 | ±0.44 (±25) | 0.61 (35) | 2 | 2 | 3 360 (29 700) | 2.0 (2.76) | 140 (2.3) |

Reference wing dimensions:
$S_w$ = 291.7 m² (3140 ft²)
$c_w$ = 5.33 m (210 in.)

[a]Flow rates are based on 14.5 MN/m² (2100 lb/in²) differential pressure across the actuator pistons.

each wing for control of the aft segment. Integrated fly-by-wire power-by-wire servoactuator packages are used, and each actuator is capable of providing the full required design hinge moment.

One fly-by-wire actuator–capable of receiving normal lateral-control, speed-brake control, and load control commands–is assumed for each of five outboard flight spoilers in each wing.

### Gust Load Alleviation System

Gust load alleviation is accomplished by actuation of the aft segment of the outboard trailing-edge flaps and the outboard flight spoilers. The only difference for gust load alleviation is that the maximum rate requirement for the trailing-edge flaps is higher.

### Flutter Mode Control System

Two side-by-side actuators are assumed installed on the aft wing spar for actuation of an inboard panel of each outboard aileron. The actuators are capable of receiving lateral control inputs in coordination with those to the basic aileron at low speed, which would be nulled out during cruise, and the high-rate flutter mode control commands at high speed.

## 5.2.2 HYDRAULIC SYSTEM

In the following sections, a fairly detailed assessment is given of the implications of ACT on the hydraulic power system. (A similar assessment of the electrial power system is given in section 5.2.3.) The main point to be shown is that since qualified system components such as pumps and generators are available only in specific sizes, system weights tend to be discontinuous functions of the sizing parameters. Hence some caution should be used in regard to system weight increments estimated by generalized equations.

### Hydraulic System Description

A hydraulic system arrangement for the illustrative example airplane might be as shown in figure 30. Three main systems (A, B, and C) share the majority of the hydraulic loads. A smaller, fourth system (system D) supplies flow only for actuation of the minimum critical flight control surfaces that will ensure a safe emergency descent and landing (i.e., the horizontal tail, the upper rudder, and the inboard ailerons) and is so routed as to present only minimum exposure to failure.

The active control actuators for the flutter suppression surfaces and the outboard flight spoilers are connected to only the three main systems, and the four horizontal tail actuators are connected one each to all four systems. The inboard maneuver load control flaps and the outboard gust and maneuver load control flaps are each actuated by two power-by-wire actuators, which do not extract flow from the central hydraulic systems.

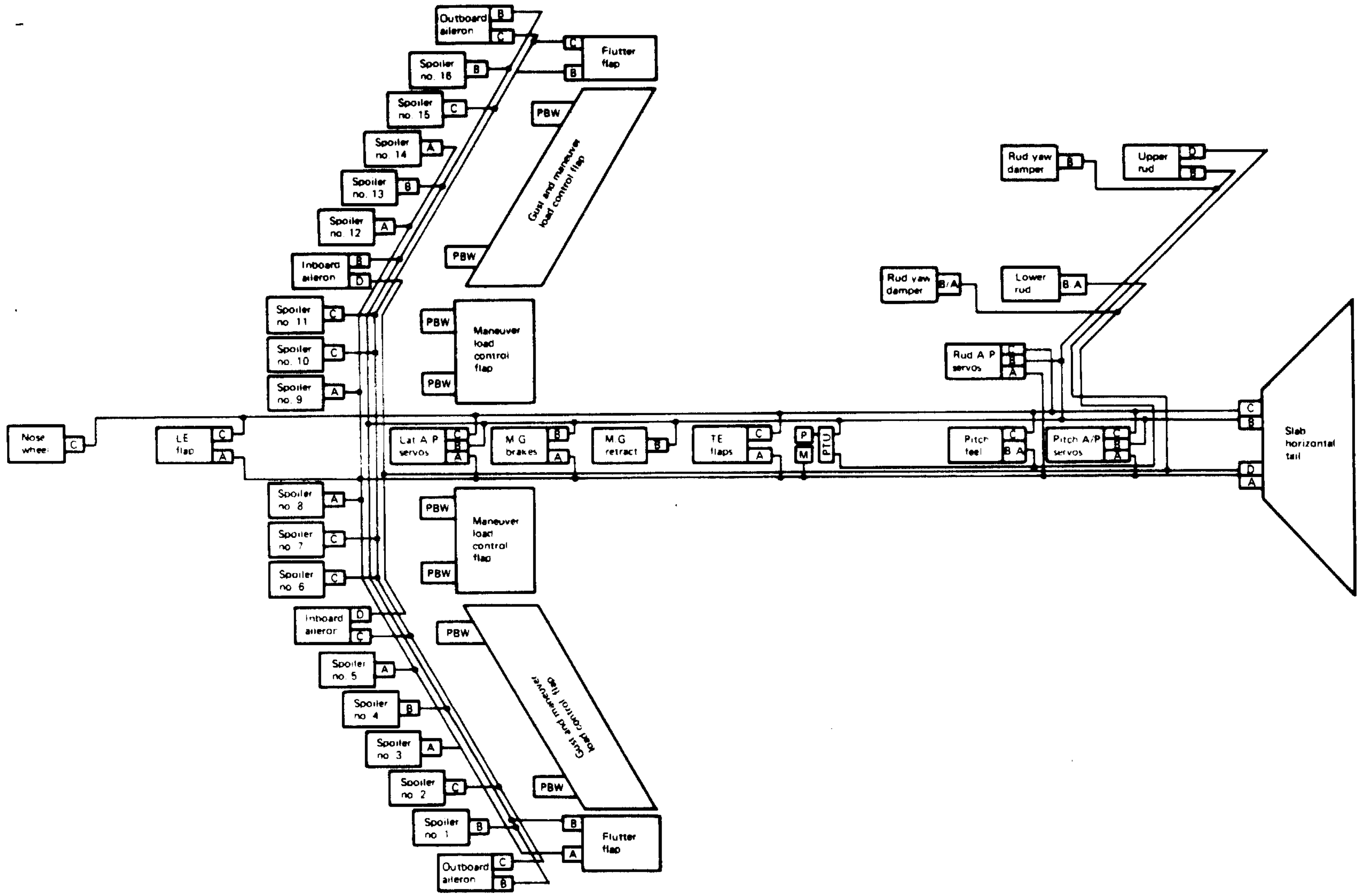



*Figure 30.—Hydraulic System Block Distribution Diagram*

## Hydraulic Flow Demands

For an airplane of the size represented in this example, typical hydraulic flow demands imposed on the four systems are itemized in tables 6 through 9 and are shown in bar chart form in figure 31. In columns ①, ②, and ③ of figure 31, peak demands are shown for each of the four hydraulic subsystems during three high-load conditions that generally determine the required pumping capacity: landing gear retraction, flap retraction, and stall recovery.

To meet these requirements, it is assumed that each of the three main systems has a large engine-driven pump, such as the existing 2400-$cm^3$/s (32-gal/min) size that is used on the 747, DC-10, and L-1011 airplanes, plus a bleed-air-turbine-driven pump such as the 2000-$cm^3$/s (32-gal/min) unit used on the 747. The latter would be preferably operated on an on-demand basis to supplement the engine-driven pumps when flow demands exceed their capacity, and to keep each system pressurized and meet normal cruise demands if its engine-driven pump fails. A bleed-air-turbine-driven pump of the same size is also assumed for system D but, unlike the others, it would be operated continuously rather than on demand.

For landing gear retraction and flap retraction, the flow capability of the engine-driven pumps at full engine rotating speed is shown, since these events occur during takeoff and climbout. For stall recovery, the flow capability at engine flight idle speed is shown, since these requirements must be met during descent and landing.

In columns ④, ⑤, and ⑥, the average flow demands estimated during cruise are shown. Column ④ depicts the combined demand for all primary flight controls, including the horizontal tail, operating at 15% of maximum rate but with no other active control activity. Column ⑤ shows the peak flow requirements for maneuver load control demands on the outboard spoilers added to the average primary flight control flow demands. Column ⑥ shows the peak flow requirements for gust load alleviation demands on the outboard spoilers plus the peak flow requirements for flutter suppression control demands on the outboard aileron flutter flaps added to the average primary flight control flow demands.

As seen in this graphic representation, the peak flow demands for these active control modes are high but well within the capacity of the system. As shown in columns ⑦ and ⑧, this would also hold true for a system arrangement where the load control flap actuators are also supplied by the three primary hydraulic subsystems rather than being the power-by-wire type. These examples support the assumption that incorporation of an active control system will not require an increase in hydraulic system flow capacity.

The fact that peak demands can exceed the capacity of the engine-driven pumps and require operation of the bleed-air-turbine-driven pumps is a matter of some concern, however, for it may be required that the latter be run continuously to ensure that their flow is available to meet the active control response requirements. It is desirable to leave these units off as much as possible both to reduce the propulsion penalty for bleed-air extraction and to extend their life. It is therefore worthwhile to explore means

*Table 6.—Hydraulic System A—Flow Demands*

| Surface | Hyd. flow at design surface rate, (gal/min) | Gear retract | | Flaps retract | | Stall recovery | | Cruise conditions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | No active control activity, (gal/min) | Maneuver load control, (gal/min) | Gust load and flutter suppression, (gal/min) |
| Horiz stab. | (12.3) | 25 | (3.1) | 33 | (4.1) | 100 | (12.2) | 15 | (1.8) | (1.8) | (1.8) |
| Inbd aileron | (9.7) | 33 | | 33 | | 100 | | 15 | | | |
| Outbd aileron | (6.4) | 33 | | 33 | | 100 | | nulled | | | |
| Inbd spoilers | (4.9) | 33 | (1.6) | 33 | (1.6) | 100 | (4.9) | 15 | (0.7) | (0.7) | (0.7) |
| Outbd spoilers | (2.3) | 33 | (1.5) | 33 | (1.5) | 100 | (4.6) | 15/100 | (0.7) | (9.2) | (9.2) |
| Lower rudder | (1.0) | 33 | | 33 | | 50 | | 15 | | | |
| Upper rudder | (0.5) | 33 | | 33 | | 50 | | 15 | | | |
| Valve leakage | | | (3.0) | | (2.0) | | (1.0) | | (3.0) | (3.0) | (3.0) |
| Main gear | (49) | 100 | | | | | | | | | |
| Nose gear | (6.0) | 100 | | | | | | | | | |
| Inbd LE flap | (24) | | | 100 | | | | | | | |
| Outbd LE flap | (19) | | | 100 | (19.0) | | | | | | |
| Inbd TE flap | (14) | | | 100 | | | | | | | |
| Outbd TE flap | (7) | | | 100 | (7.0) | | | | | | |
| Subtotal | | | (9.2) | | (35.2) | | (22.7) | | (6.2) | (14.7) | (14.7) |
| Man. load flap[a] | (1.0) | | | | | | | 100 | | (2.0)[a] | |
| Gust load flap[a] | (6.1) | | | | | | | 100 | | | (12.2)[a] |
| Flutter flap | (18.6) | | | | | | | 100 | | | (18.6) |
| Note: Power-by-wire actuator demands[a] are not included in the totals shown below. | | | | | | | | | | | |
| Total: $cm^3/s$ | | | 580 | | 2220 | | 1430 | | 390 | 930 | 2100 |
| (gal/min) | | | (9.2) | | (35.2) | | (22.7) | | (6.2) | (14.7) | (33.3) |

Table 7.—Hydraulic System B—Flow Demands

| Surface | Hyd. flow at design surface rate, (gal/min) | Gear retract | | Flaps retract | | Stall recovery | | Cruise conditions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | No active control activity, (gal/min) | Maneuver load control, (gal/min) | Gust load and flutter suppression, (gal/min) |
| Horiz stab. | (12.3) | 25 | (3.1) | 33 | (4.1) | 100 | (12.2) | 15 | (1.8) | (1.8) | (1.8) |
| Inbd aileron | (9.7) | 33 | (3.2) | 33 | (3.2) | 100 | (9.7) | 15 | (1.5) | (1.5) | (1.5) |
| Outbd aileron | (6.4) | 33 | (4.3) | 33 | (4.3) | 100 | (12.8) | nulled | | | |
| Inbd spoilers | (4.9) | 33 | | 33 | | 100 | | 15 | | | |
| Outbd spoilers | (2.3) | 33 | (1.5) | 33 | (1.5) | 100 | (4.6) | 15/100 | (0.7) | (9.2) | (9.2) |
| Lower rudder | (1.0) | 33 | (0.3) | 33 | (0.3) | 50 | (0.5) | 15 | (0.2) | (0.2) | (0.2) |
| Upper rudder | (0.5) | 33 | (0.2) | 33 | (0.2) | 50 | (0.3) | 15 | (0.1) | (0.1) | (0.1) |
| Valve leakage | | | (3.0) | | (3.0) | | (1.0) | | (3.0) | (3.0) | (3.0) |
| Main gear | (49) | 100 | (49.0) | | | | | | | | |
| Nose gear | (6.0) | 100 | | | | | | | | | |
| Inbd LE flap | (24) | | | 100 | | | | | | | |
| Outbd LE flap | (19) | | | 100 | | | | | | | |
| Inbd TE flap | (14) | | | 100 | | | | | | | |
| Outbd TE flap | (7) | | | 100 | | | | | | | |
| Subtotal | | | (64.8) | | (16.6) | | (41.1) | | (7.3) | (15.8) | (15.8) |
| Man. load flap | (1.0) | | | | | | | 100 | | | |
| Gust load flap | (6.1) | | | | | | | 100 | | | |
| Flutter flap | (18.6) | | | | | | | 100 | | | (37.2) |
| Total: $cm^3/s$ | | | 4090 | | 1050 | | 2590 | | 460 | 1000 | 3340 |
| (gal/min) | | | (64.8) | | (16.6) | | (41.1) | | (7.3) | (15.8) | (53.0) |

*Table 8.—Hydraulic System C—Flow Demands*

| Surface | Hyd. flow at design surface rate, (gal/min) | Gear retract | | Flaps retract | | Stall recovery | | Cruise conditions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | No active control activity, (gal/min) | Maneuver load control, (gal/min) | Gust load and flutter suppression, (gal/min) |
| Horiz stab. | (12.3) | 25 | (3.1) | 33 | (4.1) | 100 | (12.2) | 15 | (1.8) | (1.8) | (1.8) |
| Inbd aileron | (9.7) | 33 | (3.2) | 33 | (3.2) | 100 | (9.7) | 15 | (1.5) | (1.5) | (1.5) |
| Outbd aileron | (6.4) | 33 | (4.3) | 33 | (4.3) | 100 | (12.8) | nulled | | | |
| Inbd spoilers | (4.9) | 33 | (3.3) | 33 | (3.3) | 100 | (9.8) | 15 | (1.5) | (1.5) | (1.5) |
| Outbd spoilers | (2.3) | 33 | (0.8) | 33 | (0.8) | 100 | (2.3) | 15/100 | (0.3) | (4.6) | (4.6) |
| Lower rudder | (1.0) | 33 | | 33 | | 50 | | 15 | | | |
| Upper rudder | (0.5) | 33 | | 33 | | 50 | | 15 | | | |
| Valve leakage | | | (3.0) | | (2.0) | | (1.0) | | (3.0) | (3.0) | (3.0) |
| Main gear | (49) | 100 | | | | | | | | | |
| Nose gear | (6.0) | 100 | (6.0) | | | | | | | | |
| Inbd LE flap | (24) | | | 100 | (24.0) | | | | | | |
| Outbd LE flap | (19) | | | 100 | | | | | | | |
| Inbd TE flap | (14) | | | 100 | (14.0) | | | | | | |
| Outbd TE flap | (7) | | | 100 | | | | | | | |
| Subtotal | | | (23.7) | | (55.7) | | (47.8) | | (8.1) | (12.4) | (12.4) |
| Man. load flap[a] | (1.0) | | | | | | | 100 | | (2.0)[a] | |
| Gust load flap[a] | (6.1) | | | | | | | 100 | | | (12.2)[a] |
| Flutter flap | (18.6) | | | | | | | 100 | | | (18.6) |
| Note: Power-by-wire actuator demands[a] are not included in the totals shown below. | | | | | | | | | | | |
| Total: $cm^3/s$ | | | 1495 | | 3510 | | 3020 | | 510 | 780 | 1960 |
| (gal/min) | | | (23.7) | | (55.7) | | (47.8) | | (8.1) | (12.4) | (31.0) |

*Table 9.—Hydraulic System D—Flow Demands*

| Surface | Hyd. flow at design surface rate, (gal/min) | Gear retract | | Flaps retract | | Stall recovery | | Cruise conditions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | Flow rate, (gal/min) | Surface rate, % | No active control activity, (gal/min) | Maneuver load control, (gal/min) | Gust load and flutter suppression, (gal/min) |
| Horiz stab. | (12.3) | 25 | (3.1) | 33 | (4.1) | 100 | (12.2) | 15 | (1.8) | (1.8) | (1.8) |
| Inbd aileron | (9.7) | 33 | (6.5) | 33 | (6.5) | 100 | (19.4) | 15 | (2.9) | (2.9) | (2.9) |
| Outbd aileron | (6.4) | 33 | | 33 | | 100 | | nulled | | | |
| Inbd spoilers | (4.9) | 33 | | 33 | | 100 | | 15 | | | |
| Outbd spoilers | (2.3) | 33 | | 33 | | 100 | | 15/100 | | | |
| Lower rudder | (1.0) | 33 | | 33 | | 50 | | 15 | | | |
| Upper rudder | (0.5) | 33 | (0.2) | 33 | (0.2) | 50 | (0.3) | 15 | (0.1) | (0.1) | (0.1) |
| Valve leakage | | | (1.0) | | (1.0) | | (1.0) | | (1.0) | (1.0) | (1.0) |
| Main gear | (49) | 100 | | | | | | | | | |
| Nose gear | (6.0) | 100 | | | | | | | | | |
| Inbd LE flap | (24) | | | 100 | | | | | | | |
| Outbd LE flap | (19) | | | 100 | | | | | | | |
| Inbd TE flap | (14) | | | 100 | | | | | | | |
| Outbd TE flap | (7) | | | 100 | | | | | | | |
| Subtotal | | | (10.8) | | (11.8) | | | | (5.8) | (5.8) | (5.8) |
| Man. load flap | (1.0) | | | | | | | 100 | | | |
| Gust load flap | (6.1) | | | | | | | 100 | | | |
| Flutter flap | (18.6) | | | | | | | 100 | | | |
| Total: $cm^3/s$ | | | 680 | | 740 | | 2080 | | 370 | 370 | 370 |
| (gal/min) | | | (10.8) | | (11.8) | | (32.9) | | (5.8) | (5.8) | (5.8) |

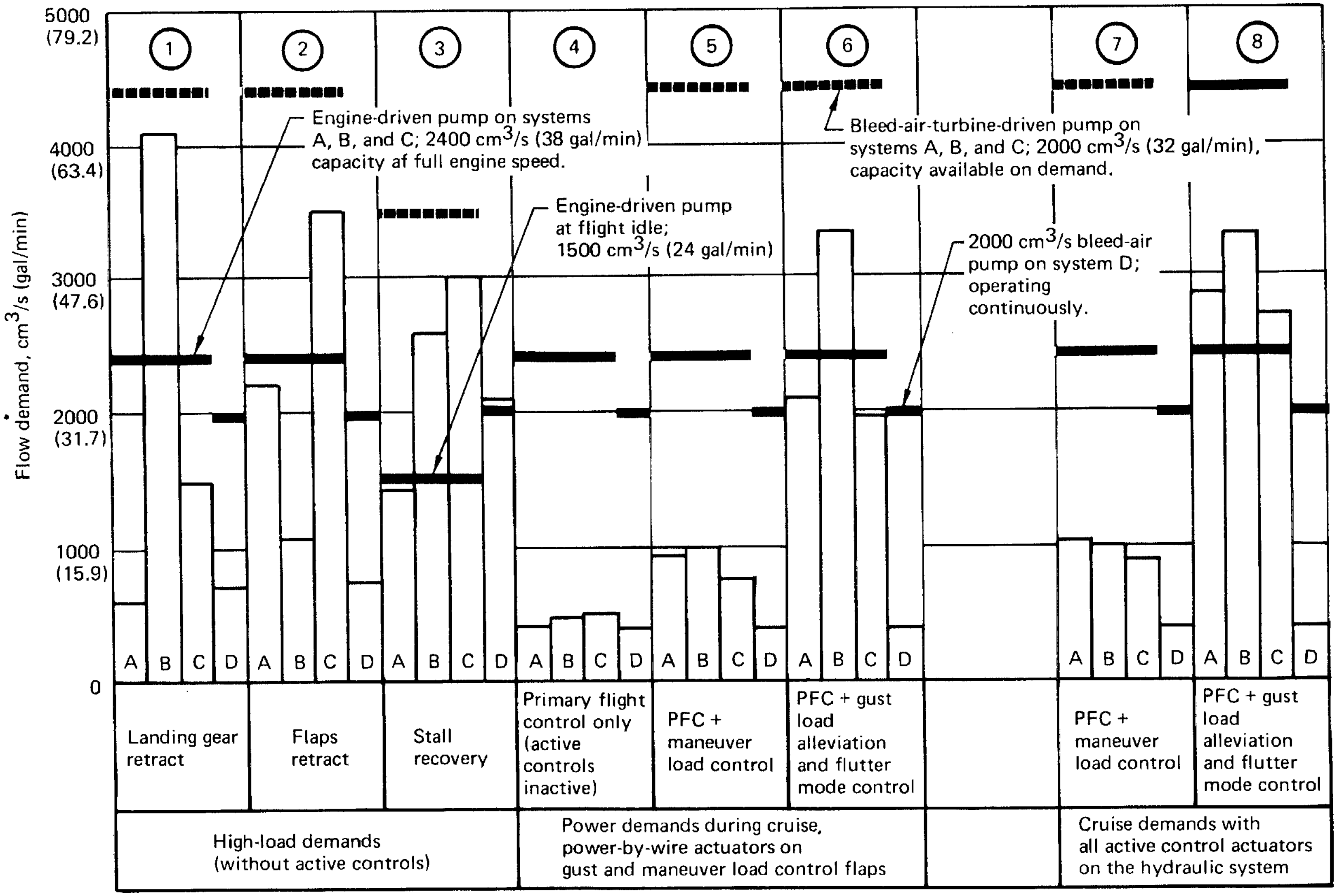



*Figure 31.—Hydraulic System Flow Demands*

of reducing the magnitude of the active control loads to bring the peak demands within the capacity of the engine-driven pumps.

The flutter suppression flap load, which is the largest single requirement, deserves first attention. The following four options are hydraulic system load-reducing possibilities that could bring the peak demands within the capacity of the engine-driven pumps:

1. Eliminating the lower surface camber on the flutter suppression flaps can reduce their hinge moment and power and flow requirements approximately 50%. However, aerodynamic drag might increase as much as 1% and possibly reduce the aircraft's range capability more than it would be increased by keeping the air-turbine drives off.

2. Substituting a power-by-wire actuator for at least the system B actuator on each flutter flap transfers the load peak from the hydraulic system to the electrical system. These integrated actuator packages would each require a large, approximately 23-kW (30-hp), electric motor that may prove too large for installation in the space available; and the load addition to the electrical systems would probably require larger (and heavier) generators.

3. Distributing the active control surface actuators in the wing among all four hydraulic systems would equalize their demands and reduce the peak on system B. However, this would require a larger pump for system D and also increase its exposure to failure because of routing tubing out to the outboard wing.

4. Using single-acting rather than dual-acting actuators on the flutter suppression flaps, with three-way valves to power the surfaces down and to let the airloads return them to the faired and to the full-up positions, could halve the flutter suppression control demands.

While none of these options might be adopted, it can be seen that a number of possibilities do exist.

It should also be noted that with the supercritical airfoil the design hinge moments for the wing trailing-edge control surfaces are considerably higher than for a standard wing. This, in turn, requires higher hydraulic flow rates than might be expected for aircraft of this size.

### 5.2.3 ELECTRICAL SYSTEM

A three-engine airplane of the size represented in this example would be likely to have an electrical system supplied by three 115/200-V 400-Hz generators operating in parallel. Typically, the generators might be of the 90-kVA size with a total generating capacity large enough to allow the airplane to be dispatched for revenue flights with one generator inoperative.

## Electric Power Demands for the Load Control Power-by-Wire Actuators

To meet the estimated hydraulic power demands, the power-by-wire actuators would require electric pump-driven motors of the following power ratings:

1. For the maneuver load control (inboard) flaps: 1.0 kW (1.4 hp)

2. For the gust load alleviation (outboard) flaps: 6.6 kW (8.8 hp)

The normal (continuous) power demand with no load control surface activity would be approximately 10% of rated output to keep the pumps running and maintain actuator pressure. With all eight units running, the continuous no-load 10% power demand on the electrical system would total approximately 20 kVA.

Full-rated power would not be demanded from any unit unless the companion actuator on the same control surface were inoperative. Normally, the maximum demand on any actuator would be only 50% of rated output. Since maneuver load control corrections would be commanded only occasionally and then for only a second or two, the maximum continuous electrical load for the eight units would result from the 50% power demand on the four gust load alleviation actuators added to the 10% power demand on the four maneuver load control actuators. This would total approximately 25 kVA and could continue as long as the aircraft remained in turbulent air.

A load addition of this magnitude could undoubtedly be absorbed by the basic system without increasing generator size. However, if the normal electric loads are barely met with only two generators operating, it may be necessary to keep the load control actuators shut off during generator-out conditions and restrict the flight speed to a safe envelope. Considering that the need to dispatch flights with an inoperative generator occurs relatively infrequently, such a restriction would be acceptable.

## Electric Power Demands for Flutter Mode Control Power-by-Wire Actuators

As noted in section 5.2.2, one possible means that might be considered to reduce the peak flow demand on the hydraulic system would be to substitute a power-by-wire hydraulic servoactuator package for one of the two conventional hydraulic servoactuators on each flutter suppression flap. Because of their high-rate requirements, these units each represent a relatively large power demand (i.e., 17.0-kW (22.8-hp) hydraulic output) and would require electric-pump-driven motors rated for 20 kW (27 hp).

The units would also have a 10% no-load demand and their maximum demand would be 50% of rated power unless the companion actuator on the same surface became inoperative or its hydraulic system failed. Considering that these loads would be additive to the load-control actuator demands, the combined demand for the 10 power-by-wire actuators could total approximately 70 kVA. A load addition of this magnitude could probably be absorbed by the system when all generators are operating, but would undoubtedly require that the flutter suppression power-by-wire actuators be shut off during generator-out conditions. This might require some limitation in flight speed but, again considering the relatively low frequency of occurrence, such a limitation would be acceptable.

## 5.3 WEIGHT PREDICTION

The weight summaries shown in tables 10 and 11 are the results of application of the equations shown in section 4.2 to the example configuration. Suggested default values were used where appropriate because of lack of definition of the example.

## 5.4 COST PREDICTION

The cost prediction includes all nonrecurring and recurring costs for a 200-airplane program. The dollars per unit are an average for 200 units in 1975 dollars. Included are engineering, development, tooling, production and quality control direct labor, material, and purchased equipment. The cost for weight variance is on an 85% curve, which means that the heavier the weight per airplane the cheaper the cost per pound for hardware containing the same technology as displayed in figures 23 through 28. As an example, if the weight doubles, the cost per pound is reduced by 15%. The example problem values are indicated by the symbols on the curves of these figures. The cost prediction for the major control surfaces is shown in table 12.

## 5.5 SAMPLE CALCULATION

A complete end-to-end calculation, starting with airplane reference geometry and ending with weight and cost increments, is presented to illustrate the numerical features of the developed methodology. Data are generated for the flutter mode control flap.

*Reference Wing Geometry and Design Flight Condition*

- $S_W$ = 291.7 $m^2$ (3140 $ft^2$)
- $\bar{c}_W$ = 5.33 m (210 in.)
- 1.2 $V_D$ (480 kn, M = 0.93)

*Control Surface Geometry, Authority Limits, and Deflection Rate Limits (data from table 2)*

- $S_S$ = 1.663 $m^2$ (17.90 $ft^2$)
- $\bar{c}_S$ = 0.634 m (24.99 in.)
- $\delta_{max}$ = 0.174 rad (10°)
- $\dot{\delta}_{max}$ = 1.745 rad/s (100°/s)

*Table 10.—Illustrative Example—Control Surfaces and Secondary Structure Weight Summary*

| | Baseline technology weight, kg | (lb) | Δweight, kg | (lb) | 1990 technology weight, kg | (lb) | Δweight kg | (lb) | ACT weight, kg | (lb) |
|---|---|---|---|---|---|---|---|---|---|---|
| Ailerons | 305 | (673) | -84 | (-187) | 221 | (486) | +10 | (+23) | 231 | (509) |
| Inboard ailerons | 163 | (359) | | | 118 | (260) | | | 118 | (260) |
| Outboard ailerons | 142 | (314) | | | 103 | (226) | | | 113 | (249) |
| Roll control surface | 142 | (314) | | | 103 | (226) | | | 65 | (144) |
| ACT flutter suppression surface | — | — | | | — | — | | | 48 | (105) |
| Trailing-edge flaps installation | 2169 | (4784) | -613 | (-1354) | 1556 | (3430) | +62 | (+135) | 1618 | (3565) |
| Inboard trailing-edge flaps installation | 1272 | (2805) | | | 908 | (2002) | | | 973 | (2145) |
| Inboard trailing-edge flaps surfaces | 350 | (772) | | | 263 | (579) | | | 328 | (722) |
| Inboard trailing-edge flaps supports | 741 | (1634) | | | 518 | (1143) | | | 518 | (1143) |
| Inboard trailing-edge flaps track fairings | 181 | (399) | | | 127 | (280) | | | 127 | (280) |
| Outboard trailing-edge flaps installation | 897 | (1979) | | | 648 | (1428) | | | 645 | (1420) |
| Outboard trailing-edge flaps surfaces | 381 | (841) | | | 286 | (631) | | | 283 | (623) |
| Outboard trailing-edge flaps supports | 458 | (1010) | | | 321 | (707) | | | 321 | (707) |
| Outboard trailing-edge flaps track fairings | 58 | (128) | | | 41 | (90) | | | 41 | (90) |
| Spoilers | 246 | (542) | -50 | (-109) | 196 | (433) | 0 | | 196 | (433) |
| Inboard spoiler installation | 128 | (282) | | | 102 | (255) | | | 102 | (225) |
| Outboard spoiler installation | 118 | (260) | | | 94 | (208) | | | 94 | (208) |
| Fixed trailing-edge structure | 499 | (1099) | -125 | (-275) | 374 | (824) | 0 | | 374 | (824) |
| Fixed leading-edge structure | 615 | (1356) | -154 | (-339) | 461 | (1017) | 0 | | 461 | (1017) |
| Leading-edge flaps installation | 281 | (620) | -70 | (-155) | 211 | (465) | 0 | | 211 | (465) |
| Outboard variable camber flaps | 203 | (477) | | | 152 | (335) | | | 152 | (335) |
| Inboard fixed camber flaps | 78 | (173) | | | 59 | (130) | | | 59 | (130) |
| Total surface and secondary structure studied | 4115 | (9074) | -1096 | (-2419) | 3019 | (6655) | +72 | (+158) | 3091 | (6813) |

*Table 11.—Illustrative Example—Surface Controls Weight Summary*

| | Baseline technology weight, kg | (lb) | Δweight, kg | (lb) | 1990 technology weight, kg | (lb) | Δweight, kg | (lb) | ACT weight, kg | (lb) |
|---|---|---|---|---|---|---|---|---|---|---|
| Aileron controls | 370 | (817) | +110 | (+242) | 480 | (1059) | +159 | (+351) | 639 | (1410) |
| Inboard aileron controls | 192 | (424) | | | 231 | (510) | | | 231 | (510) |
| Outboard aileron controls | 178 | (393) | | | 249 | (549) | | | 408 | (900) |
| Roll control | 178 | (393) | | | 249 | (549) | | | 197 | (435) |
| ACT flutter suppression | – | – | | | – | – | | | 211 | (465) |
| Trailing-edge flaps controls | 498 | (1097) | 0 | | 498 | (1097) | +523 | (+1154) | 1021 | (2251) |
| Lift augmentation | 498 | (1097) | | | 498 | (1097) | | | 498 | (1097) |
| ACT load relief—inboard flap | – | – | | | – | – | | | 310 | (684) |
| ACT load relief—outboard flap | – | – | | | – | – | | | 213 | (470) |
| Leading-edge flaps controls | 284 | (625) | 0 | | 284 | (625) | 0 | | 284 | (625) |
| Spoiler controls | 276 | (608) | 0 | | 276 | (608) | 0 | | 276 | (608) |
| Elevator controls | 294 | (649) | 0 | | 294 | (649) | 0 | | 294 | (649) |
| Stabilizer adjustment controls | 337 | (743) | 0 | | 337 | (743) | 0 | | 337 | (743) |
| Total surface controls studied | 2059 | (4539) | +110 | (+242) | 2169 | (4781) | +682 | (+1505) | 2851 | (6286) |

*Table 12.—Cost Predictions*

| Nomenclature | Baseline technology | | | 1990 technology | | | Active controls | | | 1990 technology and active controls difference | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Weight | Cost/lb | Cost | Weight | Cost/lb | Cost | Weight | Cost/lb | Cost | Weight | Cost |
| Ailerons | 673 | $116 | $78 | 486 | $171 | $83 | 509 | $165 | $84 | 23 | $1 |
| Trailing edge flaps | 1877 | 214 | 403 | 1580 | 270 | 427 | 1715 | 261 | 447 | 135 | 20 |
| Spoilers | 542 | 81 | 44 | 433 | 118 | 51 | 433 | 118 | 51 | 0 | |
| Leading edge flaps | 620 | 160 | 99 | 465 | 215 | 100 | 465 | 215 | 100 | 0 | |
| Fixed leading and trailing edge | 5362 | 70 | 373 | 3691 | 111 | 410 | 3691 | 111 | 410 | 0 | |
| Flight control systems | 4539 | 176 | 797 | 4781 | 176 | 797 | 6286 | 198 | 1247 | 1505 | 450 |

Note: 000's omitted on cost.

*Hinge Moment*

- Flutter flap chord ratio: $\bar{c}_s/\bar{c}_w = 0.19$
- Hinge moment coefficient (data from fig. 10)

$$C_H = K_\alpha \left(C_{H_0} + \Delta C_{H_{airfoil}}\right) + K_\delta \, \Delta C_{H_\delta}$$

$$= (0.83)(-0.202 + 0) + (0.94)(-0.084)$$

$$= -0.247$$

- Hinge moment

$$HM = q \, S_s \, \bar{c}_s \, |C_H|$$

$$= (37\ 394)(1.663)(0.634)(0.247)$$

$$= 9738 \text{ N}\cdot\text{m } (86\ 300 \text{ lb-in.})$$

*Actuator Sizing*

- Input (two actuators per surface, 14.5-MN/m$^2$ (2100 lb/in$^2$) differential pressure, $\dot{\delta}_{max}$ = 1.745 rad/s (100°/s)
- Hydraulic power per actuator

$$P = \frac{HM_a \cdot \delta_{max}}{1000}$$

$$= \frac{(9738)(1.75)}{1000}$$

$$= 17.04 \text{ kW } (22.8 \text{ hp})$$

- Hydraulic flow rate per actuator

$$Q = 1000 \, \frac{P}{\Delta P_a}$$

$$= 1000 \, \frac{17.04}{14.5}$$

$$= 1175 \text{ cm}^3/\text{s } (18.6 \text{ gal/min})$$

*Electric Motor Sizing*

(For driving the hydraulic pump in a power-by-wire servoactuator such as considered for reducing the peak flow demand on the hydraulic system. See section 5.2.2.)

$$\text{Required motor shaft power output} = \frac{\text{hydraulic power required per actuator}}{\text{hydraulic pump efficiency}}$$

With a pump efficiency of 85%,

$$\text{Required motor shaft power output} = \frac{17.04}{0.85} = 20.05\ \text{kW (26.9 hp)}$$

*Electric Power Demand*

$$\text{Motor power demand, kW} = \frac{\text{motor power output, kW}}{\text{motor efficiency}}$$

$$\text{AC motor power demand, kVA} = \frac{\text{motor power demand, kW}}{\text{motor power factor}}$$

- With no control activity:

  The hydraulic pump requires approximately 10% of maximum rated power to maintain output pressure and overcome internal losses.

  $$\text{Motor shaft power output} = (0.10)(20) = 2.0\ \text{kW}$$

  Assuming that the efficiency of a 20-kW motor operating at 10% load is 59%,

  $$\text{Motor electric power demand} = \frac{2.0}{0.59} = 3.39\ \text{kW}$$

  Assuming that the power factor of a 20-kW motor operating at 10% load is 0.22,

  $$\text{Motor ac power demand} = \frac{3.39}{0.22} = 15.4\ \text{kVA}$$

- At 50% hydraulic load:

  (This is the maximum demand on a motor when two actuators on the surface are operative.)

  $$\text{Motor shaft power output} = (0.50)(20) = 10.0\ \text{kW}$$

Assuming that the efficiency of a 20-kW motor operating at 50% load is 86%,

$$\text{Motor electric power demand} = \frac{10.0}{0.86} = 11.6 \text{ kW}$$

Assuming that the power factor of a 20-kW motor operating at 50% load is 0.63,

$$\text{Motor ac power demand} = \frac{11.6}{0.63} = 18.5 \text{ kW}$$

- At 100% hydraulic load:

(This is the maximum demand on a motor when its actuator is the only one operative on a surface.)

$$\text{Motor shaft power output} = 20 \text{ kW}$$

Assuming that the efficiency of a 20-kW motor operating at 100% load is 86%,

$$\text{Motor electric power demand} = \frac{20}{0.86} = 23.3 \text{ kW}$$

Assuming that the power factor of a 20-kW motor operating at 100% load is 0.80,

$$\text{Motor ac power demand} = \frac{23.3}{0.80} = 29.1 \text{ kW}$$

## WEIGHT ESTIMATION

*Surface Control System Weight*

- Outboard aileron (1990 technology)

$$\text{Controls weight} = 29.35 \left[ (2) \sum_{i=2}^{N} K_{HM} \left(k_i S\bar{c}_i\right) \right]^{0.44}$$

$$= (29.35) \left[ (2)(2.14)(2)(43.65)\left(\frac{24.99}{12}\right) \right]^{0.44}$$

$$= 549 \text{ lb/airplane}$$

- Outboard aileron (ACT)

$$\text{Controls weight} = 29.35\left[(2)\sum_{i=1}^{N}(K_{\omega}K_{HM})(k_i\,S\bar{c}_i)\right]^{0.44}$$

Controls weight $= 29.35\left[(2)(2.14)(2)(24.75)\left(\dfrac{24.99}{12}\right)\right]^{0.44}$
(roll control)

$= 435$ lb/airplane

Controls weight (ACT) $= 29.35\left[(2)\left(\dfrac{100}{60}\right)(2.14)(2)(17.90)\left(\dfrac{24.99}{12}\right)\right]^{0.44}$
(flutter suppression)

$= 465$ lb/airplane

$\Delta$ weight (controls) = (435 + 465) - 549 = +351 lb/airplane

*Control Surface Structure Weight*

- Outboard aileron (1990 technology)

$$\text{Structure weight} = 0.94\sin\delta_{max}\left[\frac{V_D}{100}\cos\Lambda_{HL}\right]^2 (A_p)^{0.845}$$

$$+ 2.16\,(A_p)^{0.87}$$

$$= 0.94\sin 10^\circ\left[\frac{400}{100}\cos 21^\circ\right]^2 (43.65)^{0.845}$$

$$+ (2.16)(43.65)^{0.87}$$

$= 113$ lb/surface

$= 226$ lb/airplane

- Outboard aileron (ACT)

$$\text{Structure weight} = (0.94)\sin 10^\circ\left[\frac{400}{100}\cos 21^\circ\right]^2 (25.75)^{0.845}$$

$$+ (2.16)(25.75)^{0.87}$$

$= 72$ lb/surface

$= 144$ lb/airplane

$$\text{Structure weight (ACT)} = (0.94) \sin 10^\circ \left[\frac{400}{100} \cos 21^\circ\right]^2 (17.90)^{0.845}$$

$$+ (2.16)(17.90)^{0.87}$$

$$= 53 \text{ lb/surface}$$

$$= 105 \text{ lb/airplane}$$

$$\Delta\text{weight (structure)} = (144 + 105) - 226 = +23 \text{ lb/airplane}$$

## COST ESTIMATION

The cost penalty per pound of control surface structure and control system mechanization for ACT is derived from data in table 12, e.g.,

$$\left(\frac{\Delta\$}{\Delta\text{weight}}\right)_{\text{structure}} = \$43.48 \text{ per lb}$$

$$\left(\frac{\Delta\$}{\Delta\text{weight}}\right)_{\text{system}} = \$299 \text{ per lb}$$

- Structural cost

$$(\Delta\$)_{\text{structure}} = \left(\frac{\Delta\$}{\Delta\text{weight}}\right)_{\text{structure}} \cdot \Delta\text{weight}_{\text{structure}}$$

$$= (43.48)\ (23)$$

$$= \$1000$$

- System cost

$$(\Delta\$)_{\text{system}} = \left(\frac{\Delta\$}{\Delta\text{weight}}\right)_{\text{system}} \cdot \Delta\text{weight}_{\text{system}}$$

$$= (299)\ (351)$$

$$= \$104\ 950$$

# 6.0 CONCLUSIONS AND RECOMMENDATIONS

Methods have been developed for making a preliminary design estimate of the weight and cost of active control surfaces and actuation mechanisms. These methods are generalized to the extent that only minimal definition of the baseline airplane configuration is required for their use. However, the weight equations are structured to accept more detailed input data definition if desired.

The weight methods presented herein are expected to achieve accuracy of approximately ±2.5% on total airplane OEW when used in conjunction with methods of similar complexity for the remainder of the airplane. Accuracies expected in estimates of individual components are shown in figures 11 through 16 and table 4.

Estimated accuracy of the costing methods is ±5% for the baseline technology. For the 1990 technology and the ACT costs, the accuracy is expected to be less, largely because of the unknowns associated with the material and fabrication costs for the composite structure that is assumed. Also, the ACT complexity factors have had to be assigned rather intuitively in the absence of detail system specification.

The most important items of uncertainty in both weight and cost estimates are the active control flaps. The incorporation of a high rate and authority control flap with the trailing-edge high-lift devices presents many technical questions that could impact the weight and cost of the ACT system as well as the airplane performance. Such flaps have been built and flight demonstrated on a large transport airplane (the Boeing 367-80 for NASA contract NAS2-4200, 1967-68) but the mechanization employed would have been unsatisfactory, from weight and drag considerations, for production application. A design study is recommended to assess the feasibility of mechanizing such a flap, considering loads, structural deformation, flap aerodynamic performance, and integration of the ACT and conventional flap functions.

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