NASA/CR-1999-209338

Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft

J. D. McLean, J. D. Crouch, R. C. Stoner, S. Sakurai, G. E. Seidel,
W. M. Feifel, and H. M. Rush
Boeing Commercial Airplane Group, Seattle, Washington

June 1999

The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/CR-1999-209338

Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft

J. D. McLean, J. D. Crouch, R. C. Stoner, S. Sakurai, G. E. Seidel,
W. M. Feifel, and H. M. Rush
Boeing Commercial Airplane Group, Seattle, Washington

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NAS1-20267

June 1999

Acknowledgments

This study was carried out under NASA Contract NAS1-20267, Integrated Wing Design, Technology Integration, and Environmental Impact, Task 27, Systems Benefit Study for Flow Control System on Civil Transport. R. D. Joslin was the NASA LaRC technical monitor. In addition to the authors, the following Boeing personnel contributed to the work: D. Akiyama, P. Anast,G. Boss, M. Curtin, D. Herbig, D. Jacot, F. Johnson, W. Jou, J. Kraft, D. Lacy, J. Noble, and P. Young.

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Abstract

This study provides a preliminary assessment of the potential benefits of applying unsteady separation control to transport aircraft. Estimates are given for some of the costs associated with a specific application to high-lift systems. High-leverage areas for future research were identified during the course of the study.

The study was conducted in three phases. Phase 1 consisted of a coarse screening of potential applications within the aerodynamics discipline. Potential benefits were identified and in some cases quantified in a preliminary way. Phase 2 concentrated on the application to the wing high-lift system, deemed to have the greatest potential benefit for commercial transports. A team of experts, including other disciplines (i.e. hydraulic, mechanical, and electrical systems, structures, configurations, manufacturing, and finance), assessed the feasibility, benefits, and costs to arrive at estimates of net benefits. In both phases of the study, areas of concern and areas for future research were identified. In phase 3 of this study, the high-leverage areas for future research were prioritized as a guide for future efforts aimed at the application of active flow control to commercial transport aircraft.

Nomenclature

α	Angle of attack
b_p	Spanwise length of plenum segment for which a piston is responsible = half the spacing between pistons
c	Airfoil chord
C_E	Power coefficient = $2P/s_{ref}\rho_\infty U_\infty^3$
c_f	Chord of the flap
C_l	2-D sectional lift coefficient
C_L	3-D wing or airplane lift coefficient
$<C_\mu>$	Jet momentum coefficient = $2\rho_j U_j^2/\rho_\infty U_\infty^2$
C_{pej}	Pressure coefficient on airfoil at location of jet slot = $2(p_j-p_\infty)/\rho_\infty U_\infty^2$
d_p	Plenum diameter in piston option for cyclic pumping
ECS	Environmental control system
f	Frequency
F_{plus}	Reduced frequency = $f\, c_f/U_\infty$
h	Blowing slot height
K_d	Fraction of time a pulsed jet is "on"
L/D	Lift-to-drag ratio
LE	Leading edge
Mj	Mach number of jet flow
N1	Engine fan rotation speed

OEW	Operating empty weight
p_{tj}	Total-pressure of jet flow
P	Power
R_v	Residual volume ratio in cyclic pumping = residual volume in plenum at end of "out" stroke / volume of jet flow in one "out" cycle
SFC	Specific fuel consumption
Sj	Spanwise spacing of discrete
s_{ref}	Reference area (For flap systems this is wing area ahead of the flaps)
TE	Trailing edge
u'	Fluctuating velocity component in mean-flow direction
u_{inf}	Far-field flow velocity
w_p	Chordwise width of full-span diaphragm in cyclic-pumping option
δ	Flap deflection

1.0 Phase 1: Coarse screening of candidates by the Aerodynamics discipline

1.1 Initial screening

The purpose of the initial screening was to look at a wide range of possible applications of separation control and to select those worthy of closer examination. At this stage, the purpose was to give at least some consideration to every conceivable situation in which separation control might provide a benefit and not to limit attention to applications covered by the current experimental database. In the first step, a team representing several sub-disciplines within aerodynamics assembled an initial list of applications and potential benefits. Qualitative assessments of the impact (magnitude of the benefit) and aerodynamic feasibility (whether the required control could be achieved and whether control, if achieved, would result in a satisfactory level of aerodynamic performance) were then made for each item. Feasibility assessments were based on a combination of the closeness of the flow situation to the current experience base and the team's physical intuition as to whether unsteady blowing would be able to produce the required performance. The list of applications for subsonic airplanes and the results of the impact/feasibility assessments are given in Table 1. As it turned out, high feasibility ratings were given only to the applications involving separation from airfoils and flaps. Reasons for the low feasibility ratings given to other applications are discussed in section 1.3. A list of HSCT-specific applications is given in Table 2. Since it was decided that the scope of the study would be limited to subsonic airplanes, the supersonic applications were not pursued beyond a cursory examination of the leading-edge flap application, as described in section 1.2. A list of concerns was also generated in phase 1, but these will not be discussed here, as they were subsequently dealt with in greater detail in phase 2.

Table 1: Initial list of applications and potential benefits for subsonic airplanes. Impact was rated from high (1) to low (3) and feasibility from fairly certain (1) to highly improbable (3). A + or ++ indicates a gradation toward the next higher numerical rating, but not by enough to incur the higher rating.

Application	Benefit	Impact (1 = high)	Aero feasibility
Bluff-body drag (e.g. landing-gear posts)	Reduced drag Increased approach CL Reduced noise	2	3
Effectiveness of simple TE control surface (Rudder, aileron, elevator)	Reduced chord of device Reduced size of surface	2	1
Engine inlet separation External Internal	Smaller inlet lip Reduced drag Make scarf inlet work	not rated	not rated
Enhance cruise-wing performance	Increased thickness, CL, or Mach	1	3
Replace or enhance slotted TE flaps	Reduced weight, cost, complexity, maintenance Higher T.O. flap settings (higher CL with low CD I.B. lateral control device more effective in lift	1	1
Drooped spoiler when flap is deployed	Increase flap effectiveness, reduce flap chord	2	1
Drooped aileron (takeoff only)	Better T.O. L/D Improved landing CL Better lateral control - Higher tail download	1+	1
LE separation: Eliminate slat Protect tip device without slat Protect area near struts Tailor pitch characteristics	Reduced weight, cost, complexity, maintenance	1	1+
Aft-body and fairing separation: Increased upsweep Rapid closure	Increased aft-body closure Reduced weight (OEW/seat) Longer cabin for some overall length	1++	2
Exhaust mixing	Short duct, reduced weight Better SFC without long duct Reduced noise	not rated	not rated
Local separations	Reduced drag, buffeting, noise	2	2

Table 2: Initial list of applications and potential benefits for supersonic airplanes. Impact was rated from high (1) to low (3) and feasibility from fairly certain (1) to highly risky (3)

Application	Benefit	Impact (1 = high)	Aero feasibility
LE vortex suppression	Higher L/D, reduced noise	1	2
LE flap hingeline	Avoid hingeline separation, LE vortex Higher L/D, reduced noise	1	1
TE flap hingeline	Higher L/D, reduced noise Body attitude, landing gear height and weight Reduced noise	1	1

1.2 HSCT leading-edge flap application

Satisfying the stringent noise rules during takeoff and climb-out is one of the most serious challenges facing an economical High Speed Supersonic Transport (HSCT). Overall takeoff weight is a simple and commonly accepted measure of aircraft economics. Takeoff noise and thus the amount and weight of engine silencing equipment to be carried by the aircraft for noise attenuation is a very strong function of aircraft weight and L/D. The development of a high L/D takeoff configuration therefore is one of the major tasks in the High Speed Research (HSR) currently conducted by NASA and Boeing.

The outboard wing of the HSCT has a supersonic leading edge which is deflected for low speed operations. If the leading edge flap deflection is too small, high drag leading edge flow separation / vortex formation will occur. Larger flap deflections will eliminate the leading edge separation but invite separation at the leading edge hinge line. In this situation, sufficient upper surface curvature in the hinge line region can eliminate the flow separation and significantly increase L/D. This increase in L/D alone will afford a large takeoff weight reduction, as is illustrated in Figure 1. However, a significant portion of the weight savings will be negated by the weight of the highly complex flap mechanisms. Replacing such a heavy, high maintenance flap system with a simple Flow Control device in the flap hinge line region would greatly improve the economics and thus the viability of a supersonic commercial aircraft.

1.3 More-detailed assessments of subsonic applications

After the initial screening, applications were examined for which the impact was judged to be either unquestionably large, or uncertain and worthy of further scrutiny.

1.3.1 Trailing-edge high-lift systems

The most promising application identified, and the only one for which impact and feasibility were both initially given the highest possible ratings, was the enhancement or replacement of slotted trailing-edge flaps. It was our judgment, based on the analysis discussed below, that it would be optimistic to rely on unsteady separation control to provide any improvement in aerodynamic performance for the landing configuration, relative to conventional high-lift systems, though control might possibly improve takeoff L/D or lateral-control effectiveness. We therefore decided the best strategy would be to try only to match the performance of a conventional system and to seek benefits in terms of reductions in complexity, weight, and manufacturing cost, resulting from simplifications and/or size reductions relative to current systems. The level of benefit will depend on the flap effectiveness that can be achieved by plain or single-slotted flaps with unsteady blowing, over a range of flap chords and deflection angles.

Our basic strategy of seeking benefits in terms of reductions in complexity, weight, and manufacturing cost of the high-lift system is supported by another line of reasoning as follows: Even if some improvement in aerodynamic performance relative to a conventional system turns out to be possible, the benefit is still more likely to be taken as a reduction in the size of the high-lift system than as a reduction in the overall size of the wing. Although the wing is often sized by high-lift requirements (landing approach speed), the wing size is never far from other constraints such as initial cruise buffet. Thus the leverage that high-lift performance has on overall wing size is usually very limited, and the additional benefits to the airplane, resulting from high-lift performance in excess of that associated with conventional systems, will be felt most strongly in the sizing of the high-lift system itself.

Our basis for estimating the effectiveness of trailing-edge flaps with active flow control and comparing it with that of conventional flaps is shown in Figure 2 for a flap-chord ratio of 0.25. The curves for conventional slotted flaps are from a Boeing preliminary-design document and are intended to represent typical expected levels of performance, based on tests of many different designs. Note that the lift-versus-flap-deflection curves for conventional slotted flaps are linear up to about 35 degrees and then curve over rapidly, presumably due to increasing separation, leveling off at about 50 degrees. If separation control is to allow reductions in flap size or Fowler motion, it must delay this leveling-off to higher deflection angles. For example, complete elimination of the Fowler motion would require linear behavior, as indicated by the heavy dashed line, up to deflection angles in the neighborhood of 50 to 55 degrees. If the actual curve for flaps with control turns out to have lower slope or to be curved, the required deflection angle could be even larger. Lift increments due to unsteady excitation at deflections of 20 and 40 degrees, taken from reference 1, are shown in figure 2 and are seen to be comparable to levels achievable with well-designed single-slotted flaps without Fowler extension. Since the current published database only covers deflections up to 40 degrees, this is an important area where further data will be needed. Elimination of Fowler motion would be a substantial benefit, as the tracks, rollers, and actuators currently used to provide it are very heavy and expensive and are high-maintenance items.

Figure 3 shows a range of possible design scenarios for applying separation control to trailing-edge flap systems. The first major row in this chart describes conventional systems without active flow control. The next three rows show options in which unsteady blowing is used to control separation, but direct lift control and roll control, if used, are effected by varying flap deflection. In the fifth row, lift and roll control are effected by articulation of the unsteady blowing. The degrees of simplification envisioned include a possible reduction in flap chord, reduction or elimination of the Fowler motion, and possible elimination of the spoilers. The drooped-aileron application identified in the initial screening can be considered one the possibilities outlined in this chart.

1.3.2 Leading-edge high-lift systems

The application to leading-edge high lift also received high ratings for both impact and feasibility, though the feasibility was initially rated somewhat riskier (1+ rating) than the trailing-edge flap application. The benefit here would be elimination of the leading-edge slat or Krueger flap and probably replacement with a simply-hinged drooped leading edge with flow control applied to the hinge line on the upper surface. Direct application of flow control to the cruise leading-edge contour, without droop, was deemed unlikely to work because of the severe suction peak and high local Mach number, and the associated difficulty of providing unsteady blowing of sufficient strength.

It was our judgment that leading-edge droop will be needed, in spite of the fact that some success was demonstrated in controlling leading-edge separation on an airfoil without droop (reference 2). In that case the airfoil was a NACA 0015 without trailing-edge flap deflection, on which the flow at the leading-edge suction peak was subcritical (The local boundary-layer edge velocity at the suction peak was just below sonic). On a transport wing, the leading-edge radius is smaller than that of the NACA 0015, and the powerful trailing-edge flap system greatly increases the circulation. An undrooped leading edge would generate a strong shock at angles of attack below C_{Lmax}, and we reasoned that this would make control difficult.

A practical concern regarding an undrooped leading edge is that the control actuator would have to be placed close to the leading edge, where a disruption of the smooth contour would likely exact a penalty at cruise (We had the same reservation about putting an actuator near the inlet lip, see section 1.3.4). A drooped leading edge, in addition to reducing the peak velocities, could, even with a simple hinge, be configured to hide the actuator during cruise.

For leading-edge flow control in general, there are two other concerns that might justify an even higher risk assessment: 1) the issue of performance degradation due to icing, and 2) the question of whether trailing edge flaps (conventional or controlled) would perform adequately downstream of the leading-edge flow control.

1.3.3 Rudder

In the application of flow control to the rudder, the main potential benefit identified was a 20-to-30 percent reduction in the size of the vertical tail, which is currently determined by the requirement for engine-out control. Unsteady separation control would only be required for flaps-down operation (e.g., engine-out and crosswind control). Maximum rudder deflection would have to increase compared to a conventional rudder, but the surface deflections would be within the range of the current database, so risk is low with regard to control effectiveness. The important concerns identified were in the areas of systems, actuators, and stability-and-control characteristics. The maximum benefit of about 1 percent airplane drag is relatively small and would probably not justify the increases in system complexity and cost. In addition to the complexity of the active control system, the costs include a probable increase in actuator size because of the increased maximum deflection. In order to ensure adequate Dutch roll damping, full-time yaw damping would be required. Also required would be more complex control laws to keep the balance between control authority and lateral stability. Reducing the tail size requires putting artificial limits on control authority, for example to avoid exceeding sideslip limits. Some of these difficulties were seen on the 777 airplane, which has about a 15% area reduction compared to a conventional tail, made possible by the use of a double-hinged rudder on the lower portion of the span. To avoid exceeding sideslip limits, the 777 wheel-to-rudder cross-tie is currently at maximum allowable authority. A larger area reduction would make it difficult to achieve certifiable flight characteristics.

1.3.4 Engine inlets

For the application to subsonic engine inlets the impact and feasibility were initially unrated. On closer examination, the potential drag benefit for conventional inlets was estimated to be very small, and the feasibility questionable, because of the disruption of the inlet lip contour by the blowing actuator, as explained below. Active control could be helpful on a scarf inlet, where the requirements for performance in crosswinds are otherwise difficult to meet.

For conventional inlets, the benefit would be taken in the form of reduced inlet area, resulting in lower external drag. A 5-percent reduction would be optimistic due to throat

Mach-number limitations and the already thin lip shape of existing inlets. Current Boeing inlets have very little drag rise at cruise, so that the benefit would be in the reduction of wetted area. A 5-percent inlet area reduction results in only a 0.1 percent airplane drag reduction due to nacelle profile drag. The disruption of the contour of the inlet lip by the unsteady-excitation actuator is a concern, since within the normal flight envelope the attachment line location varies from well inside to well outside of the highlight.

For scarf inlets, the benefit would be in the form of reduced inlet area to provide acceptable external flow. The scarf inlet lip shape is much thicker than a conventional inlet on the crownline due to internal performance requirements for high crosswinds. At engine-out mass flow, external flow separates at an unacceptably low angle of attack.

1.3.5 Engine exhaust mixing

The possibility of applying unsteady blowing to enhance mixing in exhaust-nozzle flow was suggested, but it was left unrated because we decided to limit the scope of the study to separation control. If it such control is feasible, the friction losses and weight associated with the hardware usually required for mixing would be eliminated. One theoretical benefit for mixing is due to an increase in ideal thrust resulting from combining the heat and total pressure of the primary and fan streams. This benefit is inversely proportional to the bypass ratio, making it small for modern engines. For engines used on the 777, the theoretical benefit - allowing for no dissipative losses - would be less than 1.5 percent of the specific fuel consumption. The actual benefit would be a small fraction of that. Another possible benefit is community noise reduction on takeoff.

1.3.6 Cruise-wing drag reduction

The application of control to the cruise wing to reduce drag was also considered. Recent experiments have shown that for a transonic airfoil, both drag and unsteadiness were reduced by unsteady control, but this was relative to a case with shock-induced separation in which both were relatively high. As discussed in section 2.10.1 regarding unsteady loads in the application of control to trailing-edge flaps, this is not the relevant basis for comparison for an airplane application. On a transport airplane wing in cruise, the shock is typically very weak, nowhere near the onset of shock-induced separation, and the drag level is quite low. For separation control to provide a significant benefit to the airplane, it would have to allow us to increase speed, thickness, or lift coefficient, or some combination of them, to a point where separation would occur without control. Our experience with other separation-control ideas (e.g. the cavity under a porous wall) has been that even when separation is prevented, the drag is generally not brought down to levels competitive with current conventional technology. If the separation in the uncontrolled case is at the foot of the shock, then the shock must be strong, and the shock drag itself will be prohibitive, even if the control is successful.

A general reason we are not optimistic that oscillatory control applied to the wing will prove to be compatible with the low drag levels required for cruise has to do with the fact that oscillatory control achieves its effect by extracting energy from the flow. The method depends on the stimulation of large-scale structures in the shear layer, and the energy contained in those structures must come mostly from the mean flow, given that the energy supplied to the actuator is low. At the low drag levels typical of cruise, the turbulence kinetic energy of the ordinary turbulent boundary layer (and the heat into which that energy dissipates) accounts for most of the wing's profile drag (defined as skin friction, plus pressure drag due to the boundary layer, plus shock drag). The structures produced by unsteady control are much more energetic than the turbulence of an ordinary boundary layer and are therefore not consistent with cruise drag levels. In terms of force and momentum, the result of this extraction of energy from the mean flow would be felt as a high form (pressure) drag and a large momentum deficit in the wake, compared to a conventional cruise airfoil. While control can make the drag much lower than that of a separated flow, it seems unlikely that the drag can be competitive with conventional technology at cruise.

1.4 Phase 1 Conclusion

A broad range of possible applications was considered in an initial screening exercise. As it turned out, high feasibility ratings were given only to the applications involving separation from airfoils and flaps.

It was decided that the effort in the remaining phases of the study should be devoted to the applications to wing high-lift systems, where the greatest potential benefits were identified. It was our judgment that it would be optimistic to rely on unsteady separation control to provide any improvement in aerodynamic performance for the landing configuration, relative to conventional high-lift systems. We therefore decided the best strategy would be to try only to match the performance of a conventional system and to seek benefits in terms of reductions in weight, complexity, and cost, resulting from simplifications and/or size reductions relative to current systems. The possibilities include reduction of the size of trailing-edge flaps, the reduction or elimination of trailing-edge Fowler motion, the elimination of spoilers, and the replacement of more complicated leading-edge devices with a simple drooped leading edge.

2.0 Phase 2: Multidisciplinary study of the application to wing high-lift

The objective of this phase of the study was to estimate the potential benefits of applying separation control by unsteady excitation to the high-lift system of a typical passenger transport airplane. It was concluded in Phase 1 of the study that the most promising application of unsteady flow control is the enhancement or replacement of slotted trailing-edge flaps. The benefits in this area are not likely to be in improved aerodynamic performance, but rather in reductions in weight, complexity, and cost, resulting from simplifications and/or size reductions relative to current systems. The simplification that is possible depends on the flap effectiveness that can be achieved by plain or single-slotted flaps with unsteady blowing, over a range of flap chords and deflection angles.

We begin in section 2.1 by considering the problem of estimating aerodynamic performance for trailing-edge flaps, so as to be able to define flap configurations likely to satisfy the performance requirements. In sections 2.2 through 2.5 we define the baseline conventional configuration and likely favorable configurations of both leading-edge and trailing-edge high-lift systems using active control and then assess their aerodynamic performance. In section 2.6 we present estimates of the savings in complexity, weight, and manufacturing cost associated with the simpler mechanical configurations of the proposed systems, excluding at this point the costs of the unsteady excitation system. These estimates thus represent the maximum potential benefits achievable, from which the costs of the excitation system will detract.

Having established the potential benefits of active control in the sections up through 2.6, it remains to consider the costs of providing the unsteady excitation. In sections 2.7 and 2.8 we consider the many options available and the minimum requirements for the unsteady excitation system. In section 2.9 we present estimates of the complexity, weight, and manufacturing cost for the option that would probably exact the heaviest penalties, a compressed-air system using engine bleed air. The resulting net benefits and the maximum benefits defined in section 2.6 can be thought of as bracketing the likely range of net benefits.

In section 2.10 we discuss operational concerns associated with high-lift systems using unsteady excitation.

2.1 Estimating aerodynamic performance of trailing-edge flaps with unsteady excitation

In Phase 1 an initial attempt was made to estimate the aerodynamic effectiveness of simple trailing-edge flaps with unsteady blowing, compared with the effectiveness of plain and slotted flaps without control. The comparison is shown in figure 2, and the discussion appears in section 1 of this report. In light of that discussion, it appeared that if active control was proven effective out to 55 degrees of flap deflection, active flow control on a plain unslotted flap could become competitive with the performance levels normally associated with slotted Fowler flaps. In the absence of active control data for flap deflection angles in excess of 40 degrees, and given the importance of these higher flap deflections in establishing the benefits of active control, improved estimates for $\Delta C_l(\delta)$ were required during phase 2 of the study. The improved estimates are based on the results presented in Seifert *et al,* reference 1, for a flapped NACA 0015 airfoil. The results used are for zero angle of attack (i.e. the published C_l values provide the ΔC_l for a given flap deflection δ).

The goal was to obtain a $\Delta C_l(\delta)$ curve with unsteady active control $<C_\mu> \neq 0$, but with no steady forcing $C_\mu=0$. For a value of $< C_\mu>=0.016$, reference 1, figure 7 gives $C_l(\delta=40)=1.5$, and their figure 10 gives $C_l(\delta=30)(1.2$. These values were used in conjunction with the "plain flap" curve of figure 2 and other experimental values (e.g. without forcing and with some steady forcing) to construct the curves of figure 4. The maximum Cl values could only be estimated by extrapolation.

The extrapolations used in the current phase are shown in figure 4 along with the earlier "upper bound" on active control effectiveness. This earlier estimate was based on the assumption that an actively controlled plain flap might be made to be as effective as a slotted flap with no Fowler motion.

Further examination of the available data for a simple airfoil with leading-edge forcing shows only a modest increase in the maximum angle of attack, say from 16 to 20 degrees (reference 1, figure 2, referenced to the zero lift angle). Thus the maximum flap angle was estimated to move from around 40 degrees to around 50 degrees. Beyond this angle, the Cl was optimistically assumed to remain constant for another 10 degrees. These estimates are reflected in the curve labeled "BestEst" in figure 4.

Figure 4 also includes an additional extrapolation labeled "MaxBene" that presumes a benefit for active control extending the useful range of flap deflections another 10 degrees, or to a total deflection of approximately 60 degrees. Both of these extrapolations are based on minimal data, but have been used in preparing the subsequent assessments of the configurations considered in phase 2. The expedient of extrapolating the available data to support the current phase of the active flap control concept evaluations further underscores the need to expand the available experimental data base.

2.2 Baseline high-lift configuration

The conventional high-lift system of the 737 Next Generation airplane was chosen as the baseline. On the outboard wing, the system consists of a leading-edge slat and double-slotted trailing-edge Fowler flaps. Figure 5 shows the layout of the high-lift system on the planform of the wing, and figure 6 shows cross-sections of this system at a typical station on the outboard wing with the devices in the retracted position and the landing position. The leading-edge slat is actuated by a single rotating shaft by racks and pinions. The trailing-edge flap system is actuated by a single rotating drive shaft with two gearboxes and a drive screw at each of the four flap supports on each side of the airplane.

2.3 Alternative configurations for trailing-edge flaps with active control

Consideration was given to numerous candidate configurations for trailing-edge flap systems to take advantage of unsteady separation control. Two basic alternative configurations were chosen to be studied in sufficient detail to assess the potential benefits:

- a single trailing-edge flap with an external pivot
- a plain, large-chord trailing-edge flap with a simple hinge

The objective of these configurations was to match the aerodynamic performance of the baseline system and to seek benefits in terms of savings in complexity, weight and manufacturing cost. All of the devices were sized as large as possible, consistent with the structure of a practical wing, as represented by the baseline airplane, particularly with regard to preserving the chordwise extent of the existing structural box. The flap deflections that are likely to be required to meet the aerodynamic performance goal are addressed below, and the aerodynamic effectiveness of the two basic flap options are compared in section 2.4. As can be seen below, the uncertainties associated with the aerodynamic-effectiveness are large, and for purposes of the benefits estimates in subsequent sections, it simply had to be assumed that the performance goals would be met.

2.3.1 External Hinge Configuration

An external hinge configuration with flap deflection provided by linear hydraulic cylinders is shown in figure 7. This arrangement retains the spoiler layout of the baseline configuration and provides approximately 11 percent of Fowler extension at the maximum flap deflection. The upper surface contour of the flap leading edge is a circular arc whose radius is determined by the location of the external hinge point. The flap chord and amount of Fowler extension are then determined by the resulting flap leading edge upper contour radius. At the maximum flap extension, the spoiler trailing edge remains in contact with the flap leading edge and the active flow control treatment is introduced at the spoiler trailing edge/flap leading edge junction.

With slight modifications to the relationship between the pivot location and the forward upper contour of flap, this configuration could be made to open a single slot between the main element and the flap. If the slotted version were to offer an improvement in aerodynamic performance, the size, weight, and cost of the flap could be reduced, but as we pointed out in section 1.3.1, there would not be much impact on the sizing of the entire wing. For the aerodynamic performance analysis in section 2.4 and the estimates of complexity, weight, and cost in section 2.6, we chose to concentrate on the unslotted configuration shown in figure 7.

The general mechanical arrangement shown in figure 7 is compatible with several different ways of providing the active flow control. In the particular scheme shown in Figure 7 it is effected by compressed air bled from the engines modulated by a pair of rotary valves imbedded in tubing running the spanwise length of the individual spoiler panels. The system employs two flow control tubes per spoiler panel; one supplied by the port and the other supplied by the starboard engine. This splitting of the active control supply between port/starboard engines provides active control redundancy in the event of an engine failure. An alternative to the duplicate plumbing would be to have only one set of plumbing with a central valve system to direct air into it from both engines, or only one engine in the event of engine failure. An alternative to compressed air would be to actuate a small aft portion of the spoiler chord as a flapper, probably with piezoelectric actuators. For this particular flap configuration the flapper would alternately open and close a slot from the lower surface.

The external hinge point is located below the airfoil on a line projected normal to the lower surface trailing edge of the spoiler panel and passing through the flap/spoiler contact point at cruise. Locating the flap pivot directly below the flap/spoiler contact point and defining the flap upper surface contour as a circular arc centered on the pivot yields a flap kinematic schedule that keeps the spoiler in it's cruise/non-deployed position for all flap deflection angles. Alternate flap pivot locations and leading edge radii could be considered as a means of effecting a drooped spoiler for added trailing edge lift performance. However, since drooped spoilers are an option with or without active control, evaluation of their benefits was not included in assessing the viability of active lift control.

Establishing the external hinge pivot location in the above manner yields a relationship between the maximum flap deflection and the pivot location. This relationship is depicted in Figure 8.

Since the flap chord and amount of Fowler motion are also dependent upon the assumed pivot radius, the performance of this flap concept was evaluated for a range of possible pivot radii.

The results of the parametric evaluation are summarized in figure 9 wherein the data are plotted in the form of incremental trailing edge lift as a function of maximum landing flap deflection for each of the assumed active control increments described earlier. For reference, the lift increments for unslotted and slotted flaps without active control are also given in this figure. As shown, the best estimate of active control benefit is roughly comparable to that of a typical slotted flap of the same chord, Fowler extension, and deflection.

Based on the best estimate of active control benefit at higher flap deflections, the trailing edge flap increment is maximum at approximately 50 degrees of deflection. If the curve representing the more optimistic active control benefit is used, maximum performance occurs for a hinge point providing approximately 60 degrees of deflection. Based on these data, the external hinge geometric location yielding a landing flap deflection of 52 degrees was selected for the configuration layouts of the external hinge illustrated in figure 7.

2.3.2 Large-chord plain flap configuration

A large-chord flap configuration with a simple hinge point near the lower-surface contour is shown in figure 10. This arrangement yields the maximum possible flap chord and most forward flap pivot location given the rear spar location of the baseline configuration. The spoiler chord is the same as the baseline, but the spoiler hinge is moved aft slightly to be compatible with the flap hinge, so that the spoiler and flap can move in unison for the deflected positions. Thus in addition to its usual upward motion the spoiler must be able to deflect downward through a large angle, and the range of travel of the spoiler is significantly increased over conventional transport configuration installations. With this arrangement it is not practical to provide a large radius in the upper surface at the flap shoulder, so it must be assumed that the unsteady blowing will be effective with the relatively sharp break in the upper-surface contour at the spoiler hinge line. The flap is deflected by rotary actuators that double as flap hinges. While the flap hinges are not totally internal in this configuration, the lower surface protrusions (actuator housings) appear to be small enough to be accommodated by simple blister fairings.

Similar to the external hinge flap arrangement, active control is effected through a pair of rotary valves imbedded in tubing running the spanwise length of the flapped portion of the wing. For this configuration the tubes are located in a fixed upper surface panel just aft of the rear spar rather than being imbedded in the spoiler as on the external hinge arrangement. Again, in an effort to provide active control redundancy in the event of an engine failure, this system employs two flow control tubes along the full span of the flapped portion of the wing with each tube being supplied by different engines. As before an alternative to compressed air would be to use a small piezoelectric flapper just upstream of the spoiler hinge line. In this case, because the flap remains sealed, the flapper would not open and close a slot from the lower surface.

Due to the space limitations imposed by the relatively large flap chord, the spoiler actuator penetrates the rear spar web. Other issues with this installation are the extremely large range of angular motion required of the spoiler and the sharp break in contour at the spoiler hinge line.

If the flap hinge line is moved aft slightly, a radiused nose is added to the flap, and blade spoilers are employed in place of the more conventional hinged spoilers, the issues raised by the required range of spoiler travel with this configuration can be allayed. Such a configuration is shown in figure 11. In this case the spoilers can be driven without recourse to a spoiler actuator penetrating the rear spar. However, blade spoilers are a departure from the more typical hinged spoilers found on commercial jet transports.

In addition to the implementation of a blade spoiler, the configuration of figure 11 also illustrates a somewhat shorter total flap chord installation than the configuration layout just discussed above. In this implementation a linear actuator is used to deploy the flap unlike the use of the rotary actuator in the earlier large chord flap. However, this linear actuator, while being fully contained within the contour of the wing, does penetrate the rear spar web as did the spoiler actuator in the previous configuration. This configuration also illustrates the application of a "rounded" flap upper surface leading edge similar to the external hinge arrangement discussed earlier.

2.4 Comparison of the aerodynamic effectiveness of external hinge and simple flap configurations

2.4.1 Landing Flap Performance

Delivered flap performance of the two principal flap configurations described herein was assessed using the estimated effectiveness of active flow control. The principal geometric parameters being traded between these two basic configurations were the flap chord and the Fowler extension. The external hinge provided the largest Fowler motion albeit at the expense of flap chord relative to the simple, large chord-flap configuration. Since neither configuration utilizes a conventional slot, the maximum flap deflection angles to which these devices would remain effective is assumed to be essentially the same, and determined by the estimated active control effectiveness curves.

As shown in figure 9, and based on the active control effectiveness assumptions (see section 2.1), the maximum usable flap deflection for an active flow controlled flap appears to be in the range of 50 to 60 degrees. As a result, the external hinge configuration assessed here is that as shown in figure 7 wherein the hinge pivot was located to provide approximately 52 degrees of maximum flap deflection. The relative effectiveness of the external hinge flap configuration and the large chord plain flap are shown compared in figure 12.

The data of figure 12 indicate that the benefits of additional chord for the large chord flap are less than the benefits afforded by the increase in Fowler motion for the external hinge configuration. The delta lift attributable to active flow control as indicated in this chart is quite significant when compared to the effectiveness without active flow control.
A more meaningful comparison, also included in figure 12, is that between the active controlled flaps and a simple slotted flap of the same chord, Fowler extension, and same kinematic schedule as the external hinge configuration. This comparison indicates that an active flow controlled flap provides only modest improvement over a relatively simple slotted device of the same basic geometry. And, whereas slotted flap performance is broadly understood, the active flow control estimates are based on significant extrapolations of the available experimental database.

2.4.2 Takeoff Flap Issues

Conventional Fowler flaps are generally programmed so that takeoff settings involve full Fowler extension and small angular deflections. Both the plain flap and the external hinge flap configurations have significantly different Fowler kinematics from what is typically available in a trailing edge configuration employing track and roller or 4-bar linkage support systems. In the case of the plain flap, of course, there is no Fowler motion. For the external hinge configuration the maximum Fowler motion is comparable to that of the existing baseline flap described for the 737-700, but the schedule of Fowler motion with flap deflection is quite different. This is illustrated in figure 13 where the variation in flap overlap is plotted against flap deflection angle for both the external hinge geometry of figure 7 as well as a typical 4-bar linkage arrangement.

The 4-bar linkage arrangement, provides significantly more Fowler motion for small flap deflections than that afforded by the simple external hinge geometry. This change in kinematic schedule reduces the available total Fowler motion at typical take-off flap settings which tend to be in the range of 15 to 25 degrees of deflection. This will tend to reduce the take-off L/D achievable with the external hinge configuration relative to a track and roller or 4-bar linkage system. On the other hand the loss in L/D will be offset somewhat by the potential for less flap support fairing drag associated with the external hinge system. Until the specifics of the active flow control effectiveness are assessed, and a fully integrated geometry can be sized and laid out, detailed estimates of high lift system take off performance must be deferred.

2.5 Application of active flow control to a drooped leading edge

The landing flap configuration of figure 7 included an illustration of a drooped leading edge with active flow control. This sketch was included only for purposes of illustration and was not factored into any of the analyses of the trailing edge flap effectiveness. Leading edge treatment would be primarily used to extend the usable angle of attack range and would have little direct impact on the lift at constant α used in assessing the trailing edge effectiveness discussed earlier.

There are no data available to assess the effectiveness of active flow control as applied to leading edges of high lift systems. However, it is worth mentioning a number of considerations facing the designer of such an implementation.

The leading edge devices of high lift transport configurations are typically sealed for take off to maximize takeoff L/D. While a sealed leading edge device is quite effective in minimizing drag for the takeoff configuration, such an arrangement typically leads to rather abrupt stall characteristics. Further, in the event of any asymmetry, whether due to geometric differences or flight condition, the tendency is for one wing to stall before the other. For this reason, leading edge devices are frequently designed to provide gaps when the aircraft approaches the stall, reducing the tendency for an abrupt loss of lift and the likelihood of a wing drop or roll-off. This adds to the complexity of the leading edge device through additional actuator complexity to provide this gapping capability.

The sizing of an active flow control system would have to effect a similar change in the stall characteristics of the wing, i.e. yielding a progressive loss in lift typical of trailing edge separation rather than an abrupt stall more typical of a sealed leading edge device. Investigations into leading edge applications of active flow control would have to consider this change in stall development as well as identifying the conditions under which the active flow control would be needed in order to provide this protection.

Another consideration in the application of active flow control to leading edges is to assess such a system under icing conditions. In current transport configuration high lift systems, the main wing element is in essence protected by the deployable leading edge. In the case of leading edge slats, the main wing element remains essentially free of ice and in combination with the slot flow, the lifting capacity of the main wing is essentially unaffected by the presence of the ice. Ice does however continue to be an issue on the slat proper and as a result the slats are typically provided with some form of protection, typically hot bleed air from the engine. Application of active flow control to leading edges would have to carefully consider how to protect the wing in icing conditions.

2.6 Estimates of parts-count, weight, and manufacturing-cost benefits of simplified flap and leading edge configurations

In this section we estimate the complexity (as reflected in part-card counts), weight and cost of candidate simplified trailing-edge flap systems and a simple drooped leading edge that might be used in conjunction with unsteady excitation, and compare them with corresponding data for our baseline 737-700 flap and slat systems.

For simplified trailing-edge flap systems we used data for similar structures and systems on existing Boeing airplanes as a reference. Table 3 shows data for the flap structure and all supports and systems aft of the rear spar on the B737 -700, which represents the baseline, the same for the B717, representing a flap with an external hinge, and the outboard aileron of the B777, representing a large moveable surface with a simple hinge. The complexity decreases in this sequence, as we go from a double-slotted flap on tracks, to an externally hinged vane-main flap, to a hinged aileron. In the first two cases, percentages are determined of the total airplane numbers. For the 777 aileron, the numbers for one set of ailerons were doubled and then related to 737 totals, because two sets of 777 ailerons should be roughly equivalent in area to simple moveable surfaces that might replace the 737 TE flap system. Figure 14 shows the surfaces used in these comparisons, drawn to the same scale. Table 3 shows, for example, that the flap system on the 737-700 constitutes almost 4 percent of the OEW, whereas a simple-hinge flap would be closer to 1.2 percent of OEW.

Table 3: Comparison of existing trailing-edge system components relative to totals for the reference airplane

		737-700 Flaps	717 Flaps	777 OB aileron (2 sets)
% Part Cards	Flap structure	2.44	1.65	0.65
	Actuators and tracks/hinges	0.69	0.47	0.16
	Total	3.13	2.12	0.81
% Weight	Flap structure	2.97	1.53	0.86
	Actuators and tracks/hinges	0.99	0.22	0.35
	Total	3.97	1.74	1.21
% Recurring cost	Flap structure	1.05	0.99	0.42
	Actuators and tracks/hinges	0.22	0.12	0.10
	Total	1.27	1.11	0.52

Table 4 shows estimates derived from the data in Table 3, by a process of interpolation and engineering judgment, for two simplified trailing-edge flap systems. Data for the baseline system are repeated for comparison. The two columns for the simplified systems differentiate between the two proposed flap configurations that were discussed in section 2.3.1, with:

1) an external pivot below the wing giving some Fowler motion, corresponding to the general configuration shown in figure 7, and

2) a simple hinge within the airfoil contour providing no Fowler motion, corresponding to the general configuration shown in two variations in figures 10 and 11.

No unsteady excitation system is included in these estimates, so that the benefit percentages (Delta) shown represent the estimated maximum potential benefit achievable with separation control. An estimate of the likely penalty incurred by including the unsteady excitation system will be given in section 2.9.

Table 4: Comparison of proposed simplified flap systems with 737 TE flap system. No unsteady excitation system is included.

		737-700 Flaps (baseline)	External-hinged flap	Large chord flap with simple pivot
% Part Cards	Flap structure	2.44	1.18	1.28
	Actuators and tracks/hinges	0.69	0.59	0.39
	Total excluding excitation system	3.13	1.77	1.67
	Delta	NA	-1.37	-1.47
% Weight	Flap structure	2.97	1.25	1.34
	Actuators and tracks/hinges	0.99	0.21	0.12
	Total excluding excitation system	3.97	1.46	1.46
	Delta	NA	-2.50	-2.50
% Recurring cost	Flap structure	1.05	0.61	0.62
	Actuators and tracks/hinges	0.22	0.10	0.05
	Total excluding excitation system	1.27	0.71	0.68
	Delta	NA	-0.56	-0.59

Table 4 indicates that simplifying the flap system could provide small but significant reductions in total airplane parts cards, airplane weight, and recurring airplane cost. Surprisingly, the simple-hinged flap configuration does not produce significantly greater savings than the external-hinge configuration. Note that for a $30M airplane, the simplified flap system could save approximately $180K.

Table 5 gives corresponding estimates for leading-edge systems, comparing a simple-hinged drooped leading edge with the baseline slat system. The saving in part-cards is comparable to that for the external-hinged TE flap, while the weight saving is only about a third as great.

Table 5: Comparison of drooped leading edge with conventional slat. No unsteady excitation system is included, so that the benefit percentages (Delta) shown represent the maximum potential benefit.

		737-700 Slats (baseline)	Drooped LE
% Part Cards	Slat structure	1.75	1.18
	Actuators and tracks/hinges	1.05	0.39
	Total excluding excitation system	2.80	1.57
	Delta	NA	-1.23
% Weight	Slat structure	1.08	0.48
	Actuators and tracks/hinges	0.48	0.12
	Total excluding excitation system	1.56	0.59
	Delta	NA	-0.97
% Recurring cost	Slat structure	1.28	0.61
	Actuators and tracks/hinges	0.55	0.37
	Total excluding excitation system	1.75	0.98
	Delta	NA	-0.77

Table 6 shows the combined savings for both leading-edge and trailing-edge devices. Applying both leading-edge and trailing-edge control, the potential saving in recurring cost for a $30M airplane is about $410K. The potential saving of about 3 percent in airplane empty weight would have significant performance implications. For constant fuel burn on a typical mission, the weight reduction is equivalent to a drag reduction of about 1.9 percent. The elimination of the current flap-track fairing "canoes" by the simple-hanged flap, would reduce cruise drag by an additional 1.3 percent.

Table 6: Savings for leading-edge and trailing-edge devices combined

		External-hinged flap	Large chord flap with simple pivot
% Part Cards	Delta TE only	-1.37	-1.47
	Delta LE only	-1.23	-1.23
	Delta combined	-2.60	-2.70
% Weight	Delta TE only	-2.50	-2.50
	Delta LE only	-0.85	-0.85
	Delta combined	-3.35	-3.35
% Recurring cost	Delta TE only	-0.56	-0.59
	Delta LE only	-0.77	-0.77
	Delta combined	-1.33	-1.36

2.7 Options for unsteady excitation

Because it was not known a priori how much of the potential benefit estimated in section 2.6 would likely be offset by the costs associated with the unsteady excitation system, it was deemed necessary to make projections for that system, even though the technical uncertainties were known to be large. In this section a wide range of possible means of providing the excitation are considered, and in section 2.8 rough estimates of system requirements are made for some of these options.

It was assumed that the energy for unsteady excitation would be supplied in the form of electrical power from an engine-driven generator or in the form of compressed air bled from the engine compressor. In this section we consider the various ways that this energy could be converted into the required unsteady perturbation of the flow field, presumably to be introduced just upstream of the separation point. All of the options that were considered are listed in Table 7. Options that were rejected outright are shown lined through, and the reasons for rejection are discussed following the table.

Note that the first two categories of options involve forcing flow in a direction nearly tangent to the surface, through a slot or spanwise array of discrete nozzles, with modulation at the desired frequency.

In the first of these two categories of options it is the compressed-air supply that forms the jet flow and that carries virtually all of the energy that will go into the excitation, and this air supply must be combined with a system to modulate the resulting flow.

In the second category, the options are systems in which there is no separate air supply, and in which cyclic internal volume changes are used to pump air in and out of the slot or nozzles, with zero net mass flux. In these options the pumping system supplies both the energy and the modulation. The characteristics of the excitation produced in this case are potentially very similar to those produced by options in the first category, since sucking air into the slot during part of the cycle should have very little effect on the flow field except very close to the slot. There are two main strategies available for pulsing the flow:

1) Pulsing at the desired excitation frequency directly, which, given the frequencies and slot or nozzle dimensions likely to be used, amounts to modulating a quasi-steady jet, and
2) Pulsing at a much higher frequency to produce a synthetic jet and modulating the intensity of this jet at the desired excitation frequency.

The implications of these strategies are explored further in the next section.

No obvious advantage was identified for combining a compressed-air supply with cyclic volumetric pumping, i.e. combining the first two categories above, and this was not pursued as an option.

Options in the third category involve flapping of a small, spoiler-like surface exposed to the flow.

Table 7: Options for unsteady excitation. Options that were rejected outright are shown lined through, and the reasons for rejection are discussed following the table.

Slot or array of discrete nozzles supplied with compressed air and modulated in time
- Air source
  - ~~Low-pressure engine bleed (<22 psia)~~
  - Higher-pressure engine bleed with throttling (waste excess pressure)
  - Higher-pressure engine bleed with ejectors
- Modulation
  - Electromechanically variable slot geometry (like flapping spoiler)
  - Electromechanical chopper in plenum
  - ~~Flow-actuated mechanical chopper~~
  - Fluidic valves in ducts

Slot or array of discrete nozzles with flow pulsed in and out at zero net mass flow
- Modes of pulsing
  - Pulse at aerodynamic frequency directly
  - Pulse at high frequency and modulate at aerodynamic frequency
- Modes of actuation
  - ~~Opposing pistons in a spanwise duct~~
    - ~~Solenoid~~
  - Diaphragm in plenum along full span of slot or array
    - Piezoelectric
    - ~~Solenoid~~
    - ~~Motor-driven (shafts, cams, etc.)~~

Flapping spoiler-like surface
- Configuration
  - Simple flapper
  - Flapper with lower surface contoured in conjunction with cavity
  - Flapper that opens and closes slot from the lower surface
- Actuation
  - Piezoelectric
  - ~~Solenoid~~
  - ~~Motor-driven (shafts, cams, etc.)~~

Options that were rejected and the reasons for rejection were as follows:

Low-pressure engine bleed (<22 psia) would not be compatible with current engine cycles and would require large-diameter ducts that would be complex and for which it would be difficult to find room.

Flow-actuated mechanical chopper was not pursued for lack of an attractive configuration.

Opposing pistons in a spanwise duct would require large piston strokes (see next section) for which the drive mechanism would be complex and heavy.

Solenoid drives in general were rejected on the basis of weight.

Motor-driven (shafts, cams, etc.) systems for flappers and diaphragms would be complex and expensive, and would be prone to fatigue and maintenance problems.

2.8 System requirements for unsteady excitation

In this section we make rough estimates of the minimum power required, and of the flow rates and minimum duct cross-sections, where appropriate, to effect the unsteady excitation. The analysis presented below is most directly applicable to the excitation options in which flow is forced through a slot or array of nozzles (the *Slot or array of discrete nozzles supplied with compressed air and modulated in time* options and the *Slot or array of discrete nozzles with flow pulsed in and out at zero net mass flow* options described in the preceding section). The *Flapping spoiler-like surface* option is not covered by the analysis, but an extrapolation from wind-tunnel data is made in section 2.8.4. The calculations in sections 2.8.1 through 2.8.4 are for control applied to the trailing-edge flaps only. These results are then extrapolated to the leading-edge system and the combined systems in section 2.8.5.

2.8.1 General considerations for pulsed blowing through slots or discrete nozzles

We start with the assumption that the jet flow will be pulsed on and off at regular intervals, with the "on" condition accounting for a fixed fraction K_d of the cycle. A constant, steady condition is assumed for the "on" condition and unsteady effects are ignored. In the "off" condition, zero jet flow is assumed for purposes of calculating the time-averaged momentum coefficient $\langle C_\mu \rangle$. For the zero-net-mass-flow options, air would flow in through the slot or nozzles during the "off" part of the cycle, but we assume this makes no contribution to $\langle C_\mu \rangle$. The flow rates estimated for the "on" part of the cycle can be used to estimate the time-averaged flow rates required for the options that use a compressed-air supply and are also applicable to the zero-net-mass-flow cases for purposes of estimating the displacement required of whatever pumping mechanism is used.

The flow through the slot or jet nozzles is assumed compressible and inviscid. For the calculations presented here, the following variables were fixed to represent the application to the inboard trailing-edge flaps of the 737 NG:

Characteristic total chord	c	247 inches
Wing area ahead of flaps	s_{ref}	1100 square feet
Flap-chord ratio	c_f/c	0.25
Free-stream velocity	u_{inf}	150 knots

$<C_\mu>$ was fixed at 0.06%, a value that gave good effectiveness for a trailing-edge flap on a NACA 0015 airfoil in the Langley 0.3m cryogenic tunnel (Reference AIAA 98-0214). The jet Mach number M_j was used as an independent design variable for the jets, and the other parameters defining the system were calculated and plotted versus M_j.

Figure 15 shows the required slot height, or alternative discrete nozzle diameter for a spanwise nozzle spacing of 2.0 inches, and the jet total-pressure (neglecting losses), all for a duty-cycle fraction $K_d = 0.5$. Only subsonic jets were considered, and jet static pressure was matched to the local static pressure on the upper surface of the airfoil, which in turn was set at $C_{pej} = -5$ to reflect a typically high level of upper-surface suction. These results are applicable to the options using a compressed-air supply and to the cyclic-pumping options when the pumping is done at the excitation frequency directly. The results are independent of the excitation frequency.

2.8.2 Pulsed blowing with compressed air

Figure 16 applies specifically to the options using a compressed-air supply and shows the required time-averaged pumping power, time-averaged weight flow, and duct diameter base on a duct Mach number of 0.3. The power is the pump output, not including pump efficiency and is based on the assumption that upstream of the pump the air begins at free-stream total-pressure and that losses in ducts are negligible. Assuming that the engine compressor serves as the pump, the assumption about the starting total-pressure is reasonable, and on a twin-engine airplane under normal conditions (both engines running), each engine would supply half the power and weight flow. Under engine-out conditions, the remaining engine would have to supply all of the power and weight flow. The required duct diameters were calculated and are shown both ways: Per side (or per engine with both engines running), and total, on the assumption of one engine out, with the one remaining engine supplying the entire requirement through a single duct.

Now we look at how the requirements shown in figure 16 match the bleed capabilities of the CFM56, the engine used on the 737-700. At takeoff power, the maximum bleed is 7 to 10 lb/sec at 150 psia, which is more than enough weight flow, at considerably higher pressure than we need. At landing-approach idle (70% N1), however, maximum bleed is only 4 lb/sec at 36 psia, and this is barely enough to run the current systems (deicing and

ECS). It might be possible to get the additional air by running a higher power setting, but that would require deploying spoilers to hold the glide slope, which could impact passenger comfort and community noise.

Thus, on the landing approach, getting adequate air for a compressed-air system may be a problem. Because the mass flow available from the engine is more of a limiting factor than the power used, the jets should be run at a high subsonic Mach number in order to minimize the mass flow.

The required duct diameters are also a possible cause for concern. Fortunately, the pressure available from the engine is higher than required, and this can be used to keep the duct diameters smaller than shown in figure 16. The high pressure should be maintained as far downstream in the system as possible so as to minimize duct cross-sections. If the bleed air is used directly, without augmentation by ejectors, the flow can simply be throttled at the entrances to the plenums that directly feed the jets, wasting the excess pressure at that point. Using ejectors to trade some of the supply pressure for increased mass flow might be a good way to reduce the demand on the engines. If ejectors are used, they should be placed at the inlets to the plenums so that high supply pressure is maintained in the ducts from the engine to the ejectors. In this case, the mass flow drawn from the engine is reduced, and the ducts can be smaller, relative to the case where the bleed air is used directly.

2.8.3 Pulsed blowing by cyclic pumping at zero net mass flow

Now we consider further the options based on cyclic pumping at zero net mass flow. The slot/nozzle dimensions and jet total-pressures of figure 15 still apply, but in order to assess the pumping requirements, we must make some further assumptions.

First, we assume that the compression cycle for the air that is pumped out on the out stroke starts not at free-stream total-pressure, but rather at the static pressure of the flow through the slot during the in stroke. For simplicity, we assumed that the slot Mach number on the in stroke is the same as that on the out stroke (M_j), which would probably not be the case unless both conditions are choked. We also assume that at the end of the out stroke there is some residual volume in the plenum ($Rv = 0.5$, which corresponds to a residual volume equal to half the volume displaced while the jet air is actually being expelled), and that the work done in compressing that air is not recovered.

Based on these assumptions, the power for the out strokes only, time-averaged over the entire cycle, is shown in figure 17, and is seen to be considerably greater than the power required in the compressed-air options. In place of a more complete analysis, we assume that the time-averaged power for both the in and out strokes is simply double that for the out strokes alone, and that curve is also shown in figure 17. Of course it exceeds the power required for the compressed-air options by an even greater margin. These power levels are high for an electric-powered system and would favor low jet Mach numbers.

The calculation of the volume displacement requirements took into account the initial compression of the air to the jet total-pressure and the volume displaced while the air is expelled at M_j. The displaced volume does depend on the excitation frequency, and for these calculations a reduced frequency of 1.0 based on the flap chord (pumping at the aerodynamic excitation directly) and a flap-chord ratio of 0.25 were assumed. For the option of using opposing pistons in a spanwise duct, with a piston-to-piston spacing of 0.2 chord, so that each piston is responsible for a spanwise segment of length 0.1chord on the out stroke, the required piston strokes are shown in figure 17 for a piston diameter of 0.02 chord. For low jet Mach numbers, these strokes are quite large, which discouraged further consideration of the opposing-pistons option. The stroke of a diaphragm that forms one wall of a plenum that occupies the full span of the array of jets is also shown in figure 17. For a plenum width of 0.02 chord, these strokes are more reasonable than the piston strokes, but for the low jet Mach numbers favored by power considerations they are still fairly large.

As was described in section 2.7, one way to reduce the required piston or diaphragm stroke would be to pump at a frequency far above the excitation frequency, thereby replacing the quasi-steady jet with a synthetic jet, and to modulate the synthetic jet at the excitation frequency. Because the effective duty-cycle fraction is reduced in this case (We assumed K_d is reduced from 0.5 to 0.25, equivalent to having the low-frequency modulation effectively turn the synthetic jet off half the time), the required slot height or nozzle diameter is increased for the same $\langle C_\mu \rangle$, but the jet total-pressure remains the same (compare figure 18 with figure 15). As seen in figure 19, the time-averaged power remains the same, but the piston or diaphragm stroke is dramatically reduced at the expense of much higher pumping frequency (20 fold was assumed for these calculations).

2.8.4 Piezo-electric flapping devices

We did not do a detailed analysis of the option of using a spoiler-like flapping device. For the one case for which we have wind-tunnel data available (reference 3) the actuation was provided by small piezoelectric flappers, and the input electric power required was given in the form of a power coefficient C_E. The actuators were divided onto ten segments spanwise, and two modes of flapping were tried: "2D" in which all the flappers were in phase, and "3D" in which adjacent flappers alternated in phase. Both modes produced about the same lift increase relative to no control. We scaled these results to the application to the trailing-edge flap system of the 737NG airplane with results given in Table 8:

Table 8: Power requirements for piezo-electric flappers based on reference 3

Flapping mode	C_E	Total power (HP) for 737 TE system
2D	0.0143	551
3D	0.0035	135

These power levels should be considered as very preliminary, and probably overly pessimistic, estimates of what would be required on a real airplane (The flappers in the experiment of reference 3 were not of a highly refined design). The power for the 2D mode is quite high, but perhaps could be reduced by detail design of the cavity under the flapper. The power for the 3D mode is comparable to our estimates for the cyclic pumping option with a jet Mach number in the middle range (See figure 17). The generator on each engine of the 737-700 is rated at 60 kVA, and much of that capacity is already used for other needs. Thus unless the power required by electrically actuated flapping devices is considerably less than that estimated above, and assuming that one generator must be able to run the system in case of an engine out (see section 2.10.3), it is likely that generator size would have to be increased.

Table 9: Summary of power and weight-flow estimates

			TE only		LE only		Combined	
Option	Mj	ptj psia	HP	lb/sec	HP	lb/sec	HP	lb/sec
Bleed air	1.0	22.8	32.4	1.5	38.3	1.8	70.7	3.3
Cyclic pumping	0.4	13.4	61.6	0.0	72.8	0.0	134.4	0.0
Synthetic jets	0.4	13.4	61.6	0.0	72.8	0.0	134.4	0.0
Piezoelectric flapper	NA	NA	135.	0.0	160.	0.0	295.	0.0

2.8.5 Summary of system energy and flow estimates

All of the above analysis considered only the trailing-edge flap system. If control is applied to a drooped leading-edge device as well, all of the total power and total flow-rate estimates must be increased accordingly, by a factor of somewhat more than two, since the LE and TE would be treated by separate systems, and the leading-edge device treats more wing area than the TE flaps. Slot heights, nozzle diameters, piston strokes, and diaphragm strokes would remain the same, assuming the same excitation frequency is used. Table 9 summarizes the power and weight-flow estimates of the preceding paragraphs, scaled both for the TE and LE systems separately and for combined systems.

2.8.6 Practical implications of power extraction from the engines

Engines can provide either pneumatic blowing from bleed air or mechanical power from the compressor shaft. The mass flow given in Table 9 as required for blowing is about the same as that required for anti-icing. If the blowing bleed requirement is added to the anti-ice bleed requirement, the engine idle speed would probably be objectionably high. Using an alternative anti-ice or deice scheme such as electric-impulse deicing could make enough bleed air available for blowing, although bleed air temperature may present another problem. There may not be sufficient engine bleed air energy available if bleed air is cooled to a temperature that would allow practical ducting. Additional bleed air could be available by running the APU while blowing. For a two-engine airplane, sufficient bleed air must be available with one engine not operating.

Transmitting the power electrically entails a different set of problems. Power quoted in Table 9 for cyclic pumping and synthetic jets is the output power of the pumps or jets. The higher power quoted for the piezoelectric flappers is input electrical power. If power conversion losses are included, the three methods may require similar amounts of input power. In any case the power requirement will be large enough to have a significant impact on the design of the airplane's electrical system. Engine generators operate at near capacity (currently 60kVA on the 737-700) during engine-out approach, so blowing power would require additional generator capacity. This capacity increment could be lessened by requiring that the APU run during blowing operation. The APU and one engine could then bear the generator load when one engine or generator is not working (The APU would then be dispatch critical, and would have to have air-start capability). Assuming the piezoelectric-flapper values of Table 6, the following is a rough estimate of incremental generator weight and cost, assuming a baseline of 60kVA generators:

Table 10: Costs associated with additional electric generator capacity, based on power requirements for piezo-electric flappers from Table 9. Those requirements are most likely pessimistic; real requirements will probably be less.

Surfaces blown	HP required	kVA required	Delta kVA each engine (also total kVA APU)	Delta recurring cost % total AP	Delta OEW % total AP
LE only	160	119	60	0.10	0.11
TE only	135	101	50	0.08	0.09
LE & TE	295	220	110	0.60	0.24

The large values for weight and cost for the case of blowing both LE and TE are due to the requirement of adding APU generator capacity and the current high cost of generators of capacity greater than 120kVA, which might change if such generators are manufactured in larger numbers. No cost is shown for power transmission or conversion to a form useful to the blowing device.

2.9 Estimates of costs with an the unsteady excitation system included

In section 2.6 estimates were presented for the savings in part-card count, weight, and manufacturing cost resulting from replacing current leading-edge and trailing-edge high-lift systems with simplified systems made possible by the use of unsteady excitation. Those estimates represented maximum potential benefits, since the costs of providing the unsteady excitation were not included. Here we show to what extent these costs are likely to detract from the upper-limit benefits.

In order to bracket this effect, consider the system with the largest likely penalties in all of the cost categories: a compressed-air excitation system using engine bleed. Rough estimates for such a system, scaled according to the system requirements estimated in section 2.8, are presented in Table 11, showing that accounting for the excitation system cancels more than half the benefits in part-card count and manufacturing cost but only reduces the weight benefit slightly. Similar trends are seen for a leading-edge high-lift system in Table 12 and for the combined benefits in Table 13. Other systems for providing the unsteady excitation, such as piezo-electric flappers would presumably exact smaller penalties, providing net benefits lying between the maximum potential (Tables 4, 5, and 6) and the heavily penalized values given in Tables 11, 12, and 13. The potential performance benefits due to reduced weight that were discussed in section 2.6 are not strongly affected by the penalties associated with the excitation system.

Table 11: Comparison of proposed simplified flap systems with 737 TE flap system. A pneumatic unsteady excitation system ("Blowing system") supplied by engine bleed is included, showing how the maximum potential benefit percentages given in Table 4 are reduced by the costs of the excitation system. A less costly excitation would yield net benefits between these value and those in Table 4.

		737-700 Flaps (baseline)	External-hinged flap	Large chord flap with simple pivot
% Part Cards	Delta excluding blowing system (from Table 4)	0.0	-1.37	-1.47
	Blowing system	NA	1.08	0.98
	Delta including blowing system	NA	-0.29	-0.48
% Weight	Delta excluding blowing system (from Table 4)	0.0	-2.50	-2.50
	Blowing system	NA	0.36	0.30
	Delta including blowing system	NA	-2.15	-2.21
% Recurring cost	Delta excluding blowing system (from Table 4)	0.0	-0.56	-0.59
	Blowing system	NA	0.29	0.24
	Delta including blowing system	NA	-0.26	-0.34

Table 12: Comparison of leading-edge high-lift systems with blowing system included

		737-700 Slats (baseline)	Drooped LE
% Part Cards	Delta excluding blowing system (from Table 5)	0.0	-1.23
	Blowing system	NA	0.69
	Delta including blowing system	NA	-0.54
% Weight	Delta al excluding blowing system (from Table 5)	0.0	-0.85
	Blowing system	NA	0.19
	Delta including blowing system	NA	-0.66
% Recurring cost	Delta excluding blowing system (from Table 5)	0.0	-0.77
	Blowing system	NA	0.37
	Delta including blowing system	NA	-0.40

Table 13: Savings for leading-edge and trailing-edge devices combined, with blowing system included. A less costly excitation would yield net benefits between these value and those in Table 4.

		External-hinged flap	Large chord flap with simple pivot
% Part Cards	Delta TE only	-0.29	-0.48
	Delta LE only	-0.54	-0.54
	Delta combined	-0.83	-1.02
% Weight	Delta TE only	-2.15	-2.21
	Delta LE only	-0.66	-0.66
	Delta combined	-2.81	-2.87
% Recurring cost	Delta TE only	-0.26	-0.34
	Delta LE only	-0.40	-0.40
	Delta combined	-0.66	-0.74

2.10 Operational concerns

2.10.1 Unsteady loads

An area of concern in the application of unsteady control to trailing-edge flaps is unsteady loads. The experiments have shown that the application of control reduces unsteadiness, but this is relative to a post-stall case without control, where the flow is very unsteady. For an airplane application, this isn't the relevant basis for comparison, since post-stall isn't really part of the flight envelope. With control applied, the unsteadiness should not exceed that associated with current flap systems at landing-approach angles of attack, well below stall. There is typically a small amount of separation well aft on trailing-edge flaps under these conditions, but the associated unsteadiness is much less than in a post-stall case.

The test data show a 6-percent peak-to-peak variation in the lift for a simple airfoil with leading-edge control. A spanwise variation in the forcing phase may be used to reduce the level of lift variation. However, some increase in unsteady loads will result from the use of active control. Assuming the control is used only during the final approach, a large airplane would experience about 2500 cycles per flight. Thus it is important that the unsteady-load levels be minimized to permit a reasonable fatigue life without an excessive increase in structural weight.

2.10.2 System failures

To minimize the effects of system failures it will be advisable to divide the unsteady blowing system into small segments along the span. As mentioned above, varying the phase of the unsteady excitation between these segments can be used to reduce unsteady loads. Presumably loss of a small number of isolated segments in such a system would not be catastrophic. A large-scale failure of the system would have implications for stability and control that would need to be examined.

2.10.3 Engine out

In the event of the loss of one engine, the other engine (twin-engine airplane) must be able to supply the unsteady-blowing requirements to provide full system effectiveness. Loss of an engine on takeoff will require effectiveness with the flaps in the takeoff position. Loss of an engine during a go-around will require effectiveness with the flaps in the landing position. For systems using engine bleed this will require either duplicate systems (one driven by each engine with each capable of full effectiveness) or one set of plumbing in each wing with cross-ducting and valves to switch from two-engine operation to operation by one engine or the other. For electrically-driven systems, each engine will need to have sufficient generator capacity to drive the entire system, or if the APU is depended on to supply part of the power, the APU becomes dispatch critical and must have air-start capability.

2.10.4 All engines out

The usual reason for a loss of all engine power is running out of fuel. Thus in this eventuality the system cannot depend on the Auxiliary Power Unit (APU), since it depends on the same fuel supply. On our current airplanes the deployment of the flaps is provided by hydraulic power that is lost when all engines fail. Although some hydraulic power is provided by the Ram Air Turbine (RAT) that is deployed when needed, that power is limited to the primary flight controls and is not available to actuate flaps. The flaps thus cannot be moved after loss of all engines, and this would presumably also be the case for flaps using active flow control.

If the flaps are in a deflected position when power is lost, the question arises as to whether flow control can be applied. In order to have unsteady excitation in the absence of engine power, the unsteady excitation system would have to be hydraulically powered, for which the existing RAT does not have sufficient capacity, or electrically powered by an additional electric RAT. Unsteady excitation by hydraulic power would involve complex mechanical parts (rotating shafts and cams or push-rods) that we would prefer to avoid. A possibility that should be considered would be to do without unsteady excitation in this emergency, even though flaps designed for use with flow control would, without control, provide less lift capability than conventional flaps.

2.10.5 Contamination

The unsteady excitation system must be able to operate in the presence of contamination in the form of ice, water, or dirt. One possible advantage of a bleed-air system is that the hot air would very likely be able to deice the entire system or to blow out water that might accumulate in the slots or ducts. One of the requirements for a piezoelectric flapper system would be that the flappers be able to break off a certain amount of ice. Cyclic pumping installations (zero net mass flow) might be vulnerable to accumulations of ice or water.

2.10.6 Maintenance and repair

To minimize costs of maintenance and repair, the mechanical design of the unsteady excitation system should be as modular as possible, so that components are easy to remove and replace. Electrically-driven flappers could have a substantial advantage in this regard.

2.10.7 Response of spoilers for roll control

On current airplanes, spoilers are used to augment roll control, both flaps-up and flaps-down. When the flaps are down, the spoilers form the lip of the first slot of the flap system, and actuating the spoilers increases the gap. The roll-control response, however, still does not display unacceptable non-linearity. It is not known whether this will be the case for a spoiler upstream of a flap with separation control by unsteady excitation.

3.0 Phase 3: Areas for future research

During the course of this study, several areas were identified where additional research is needed in order to facilitate a successful application to commercial aircraft. The research topics are oriented towards three primary objectives: (1) the improvement of aerodynamic-performance estimates, (2) improvements to the characterization and effectiveness of actuators, and (3) documentation of the broader impact of actuation for specific applications. These numbers signify a prioritization based on the perceived needs from this study and based on their potential impact for future detailed applications studies. The basic aerodynamic data are considered the most important since they provide the foundation for estimating the potential value of active control. Once the benefits are established, the active control system needs to be optimized to yield these benefits with a minimum of costs. This requires a better characterization of the forcing mechanism. Then with specific configurations in mind, the operational concerns can be more fully addressed.

3.0.1 Basic aerodynamic performance

The largest motivation for future research is the need for basic aerodynamic-performance data. The basic aerodynamic performance dictates the configuration layout, and thus the potential benefits of active control. In this study it was necessary to assume the achievable lift increments for given flap sizes and deflection angles. The failure to meet these lift increments would likely render the proposed configurations infeasible. On the other hand, lift increments in excess of the assumed values could enable more novel and potentially beneficial configurations.

The type of data needed for better performance estimation was outlined in the section 1. The benefits of active control appear to be at the higher flap deflections where there are currently no data. To obtain the necessary data, a simple-flap symmetric airfoil could be used (e.g. a NACA 0012). Some attention should be given to the effects on high-lift performance of detailed surface contouring at the flap break. The key result would be the increment in lift as a function of flap-deflection angle $\Delta C_l(\delta)$ and guidelines on the requirements for local contouring of the flap shoulder. The results should extend to flap deflections of 70 degrees or more to capture the maximum lift increment, and to show

how the lift increment falls off past the maximum level. Ideally, results would be given over the full range of conditions both with and without active control. Measurements at zero and positive angles of attack would be useful.

A similar set of data to that described in the previous paragraph should also be obtained for a single-slotted flap, so that the pros and cons of slotted and unslotted trailing-edge systems can properly be addressed. It is possible that a slotted flap could provide greater benefits than those estimated in the preceding sections for unslotted flaps, though the lack of data prevented an assessment in this study. In the slotted case, careful thought will have to be given to the choice of airfoil, since the results are likely to be more sensitive to design details.

Another area where aerodynamic performance data are needed is for leading-edge control in combination with leading-edge droop. This is an application with potential benefit if the active control is effective enough to eliminate the slat and provide sufficiently benign stall characteristics, as discussed in section 2.5. The lack of existing data for this type of application prevented any detailed assessment of the benefit for specific commercial applications. It will also be important to demonstrate that control applied to a trailing-edge flap works simultaneously with control applied to a drooped leading edge.

The testing of separation control by unsteady excitation is moving from the initial concept-validation phase to a phase in which the data will be used to support detailed application studies. The testing should therefore be moving in the direction of greater fidelity to the intended applications, as in matching the Mach number of the applications, and using higher test Reynolds numbers. In 2-D testing, efforts should be made to reduce 3-D effects, for example through the use of larger test facilities and higher model aspect ratios. If results continue to look promising, 3-D tests of realistic configurations will have to be carried out.

3.0.2 Actuator performance

The second area identified for future research is in the characterization of actuator performance. While the benefits of active control are tied to the achievable lift increments, the costs of active control are tied to the method of actuation. For unsteady blowing, the level of forcing is reasonably well characterized by the momentum parameter $\langle C_\mu \rangle$. For a mechanical actuator, such as a localized flapper, some other parameters are required. In either case, it would be desirable to link the energy or momentum inputs more directly to the relevant flow unsteadiness in order to generalize the results to other actuation methods. For example, if the u'-energy in a particular mode of instability determines the control effectiveness, it would be useful to measure this modal response for different actuators and forcing levels.

An improved characterization of the actuator performance would help in generalizing results from one actuator to another, in scaling results to flight, and in optimizing actuators for specific applications. The ability to generalize in the course of a trade study can be very important since new alternatives may be imposed by unanticipated constraints, and because of the strong link between actuator complexity and cost.

3.0.3 Impact of unsteady actuation on the total airplane performance

Assuming the benefits of active control are achievable with a reasonable level of costs and complexity, the impact of active control in operation must be considered. Most notably, the potential structural impact due to unsteady loads and the potential noise impact due to flow unsteadiness must be documented. While some of this has already been done (e.g. unsteady loads with leading-edge control), additional research will be needed for candidate configurations as they become more clearly defined.

3.0.4 Development and application of CFD methods

It is expected that the progress on the above research topics will depend primarily on experiments. However, if CFD methods were available they would have a significant impact on this research and on any future detailed systems studies. The development of CFD methods for flow-control applications is in itself an area for future research. Based on the needs of this study, research on CFD methods is considered a lower priority compared to topics (1) and (2) above.

With some additional care, the experiments to address topics (1) and (2) could provide valuable data for CFD development. Once a method is developed and tested for flow control, it could serve a critical function in the characterization and optimization of the flow actuators.

3.0.5 Potential application of MEMS

The configurations considered in this study were selected based on the highest potential benefits resulting from the active-control performance increments. These increments were estimated from existing wind-tunnel data for specific actuation systems. This study assumed that the performance increments would also be achievable at flight conditions. Since the existing data is based on macro actuators (and the scale of the actuator will be increased for flight conditions), there is no reason to expect MEMS actuators to be effective for the configurations considered in this study. Therefore, the actuators considered are macro-scale devices.

There may be a role for MEMS sensors on an active-control configuration. The basic control is open loop -- so sensor feedback is not required for operation. None-the-less, sensor information about the routine performance of the control system would be useful for maintenance and for reducing the risks of unexpected system failure. While the sensors need not be micro scale, low costs and ease of application could make MEMS sensors attractive.

4.0 Conclusions

The objectives of this study were to provide a preliminary assessment of the potential benefits of applying unsteady separation control to transport aircraft, to estimate the costs associated with the high-benefit applications, and to identify high-leverage areas for future research.

Phase 1 of the study consisted of a coarse screening of an extensive list of candidate applications within the aerodynamics discipline. The applications with the greatest potential benefits were determined to be those associated with wing high-lift systems. These benefits were expected to be in reduced cost and weight rather than in improved performance relative to conventional high-lift systems.

Phase 2 concentrated on these high-lift applications. A team of experts from several disciplines considered numerous candidate configurations for trailing-edge and leading-edge high-lift systems to take advantage of unsteady separation control. The 737-700 airplane was chosen as the baseline for the evaluations, and three alternative configurations were chosen for more-detailed study:

- a single trailing-edge flap with an external pivot
- a plain, large-chord trailing-edge flap with a simple hinge
- a drooped leading edge with a simple hinge

The objective was to match the aerodynamic performance of the baseline system and to seek benefits in terms of savings in complexity, weight and manufacturing cost. All three devices were sized as large as possible, consistent with the structure of a practical wing, as represented by the baseline airplane. It was estimated that to match the baseline landing-approach performance the proposed trailing-edge flaps would require deflection angles between 50 and 60 degrees. This is beyond the range for which experimental data are available for unsteady control applied to trailing-edge flaps, and no data at all are available for drooped leading edges. Thus there is considerable uncertainty for all the candidates as to whether the performance requirements can be met. The risk in this regard was judged to be greater for the flap with the simple hinge than for the flap with the external pivot.

Estimates were made of the raw savings in complexity, weight and manufacturing cost for the three candid configurations listed above, excluding the costs and penalties of the unsteady excitation system. These estimates represent the maximum potential benefit, from which the costs of the excitation system will detract. For application of control to both the leading- and trailing-edge devices, the potential reductions were roughly 2.6 percent in part-card count, 3.3 percent in empty weight, and 1.3 percent in manufacturing cost. For part-card count and OEW, most of the reduction came from the trailing-edge system, while for manufacturing cost, most of the reduction was in the leading-edge system. The simple-hinged trailing-edge flap configuration did not appear to produce significantly greater savings than the external-hinged configuration. This surprising result would be worth further investigation in a more-detailed study.

Because it was not known a priori how much of the potential benefit estimated above would likely be offset by the costs associated with the unsteady excitation system, it was deemed necessary to make projections for that system, even though the technical uncertainties were known to be large. A wide range of possible means of providing the excitation were considered, and rough estimates of system requirements were made for blowing systems using compressed air (engine bleed), zero-net-mass-flow blowing systems using (piezo)-electrically actuated pistons or diaphragms, and piezo-electrically actuated flapping devices exposed directly to the external flow. It appears that piston or diaphragm devices would require large strokes and be difficult to implement unless they could be operated in a "synthetic-jet" mode at high frequency and small displacement and modulated at the desired lower excitation frequency. In either case, a zero-net-mass-flow blowing system potentially has a significantly higher average power requirement than a compressed-air system.

The bleed requirements for a compressed-air system are large but probably not impossible to meet. This option was used as the basis for "worst-case" estimates of the costs of the excitation system in terms of part-card count, weight, and manufacturing cost. Comparing these costs with the maximum potential benefits estimated for the mechanical simplification of the flap and slat systems, it was found that accounting for the excitation system cancels up to half the benefits in part-card count and manufacturing cost but only reduces the weight benefit slightly. Because the weight reduction is not strongly affected by the excitation-system penalties, most of the potential performance benefit due to the weight reduction should be realizable. The weight reduction is equivalent to reducing cruise drag by about 1.9 percent, while the elimination of the current flap-track fairing "canoes" by the simple-hanged flap, would reduce cruise drag by an additional 1.3 percent. Though we have no basis for a quantitative estimate, it may be possible that a piezo-electric flapper system would entail much smaller penalties and restore some of the potential benefit in part-card count and manufacturing cost.

In Phase 3 of the study, the high-leverage areas for future research identified in the first two phases were documented and prioritized. The highest-priority identified was the acquisition of additional data defining basic aerodynamic performance, particularly for higher flap-deflection angles, since this was the greatest source of uncertainty in our estimate of the practical value of active control. Then in descending order of priority would be research in the areas of actuator performance, impact of unsteady actuation on the total airplane performance, and the development of CFD methods.

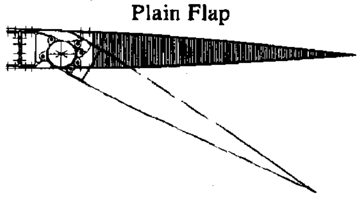
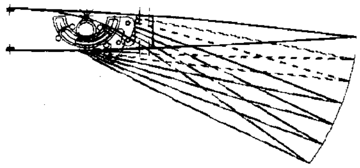
The potential benefits identified for applying active control to high-lift systems are not large, but they are significant, and it appears to us that an effort to acquire additional data defining basic aerodynamic performance, the highest-priority item identified in Phase 3, is justified.

References

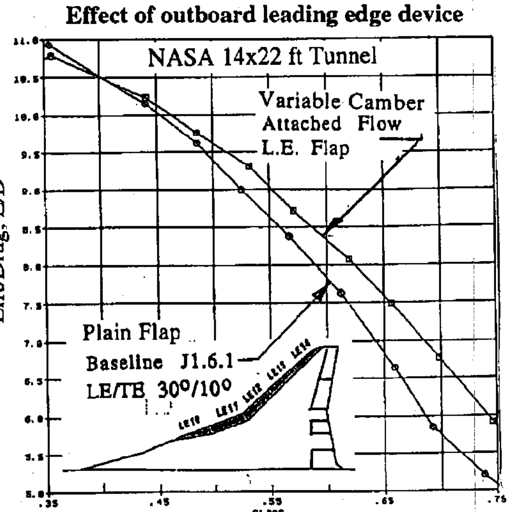
1) A. Seifert, T. Bachar, D. Koss, M. Shepshelovich, and I. Wygnanski, "Oscillatory Blowing: A tool to Delay Boundary-Layer Separation", AIAA Journal, Vol. 31, No. 11, November, 1993

2) A. Seifert and L. Pack, "Oscillatory Excitation of Unsteady Compressible Flows over Airfoils at Flight Reynolds Numbers", AIAA Paper 99-0925, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January, 1999

3) A. Seifert, S. Eliahu, D. Greenblatt, and I. Wygnanski, "Use of Piezoelectric Actuators for Airfoil Separation Control", AIAA Journal,.Vol. 36, No. 8, August, 1998

Leading Edge Type	Advantages	Disadvantages
Plain Flap 	• Simplest design. • Lightest of the devices studied. • Structurally the stiffest. • No front spar penetration. • Clean when deployed Lower high speed drag. • Best deflection capabilities.	• Small hinge line radius, Higher climb-out & high speed drag Difficult high speed integration • Sliding seal at panel trailing edge. • Small step at flap trailing edge (high speed drag). • Complex corner panel design.
Variable Camber 	• Larger hinge line radius, Lower climb-out drag. • No sliding seal at panel trailing edge. • No front spar penetration. • No step at panel edge. • Clean when stowed and deployed. Lowest high speed drag. • Carries side load efficiently through skin • Simplest corner & #11 panel design.	• Heavier than Plain Flap. • Higher stresses in flex panel. • More complex design than plain flap. (higher cost & maintenance) • Unproven design. • Most adversely effected by aeroelastic bending. • Structurally softer than plain flap. • More restricted deflection capabilities.

Effect of outboard leading edge device

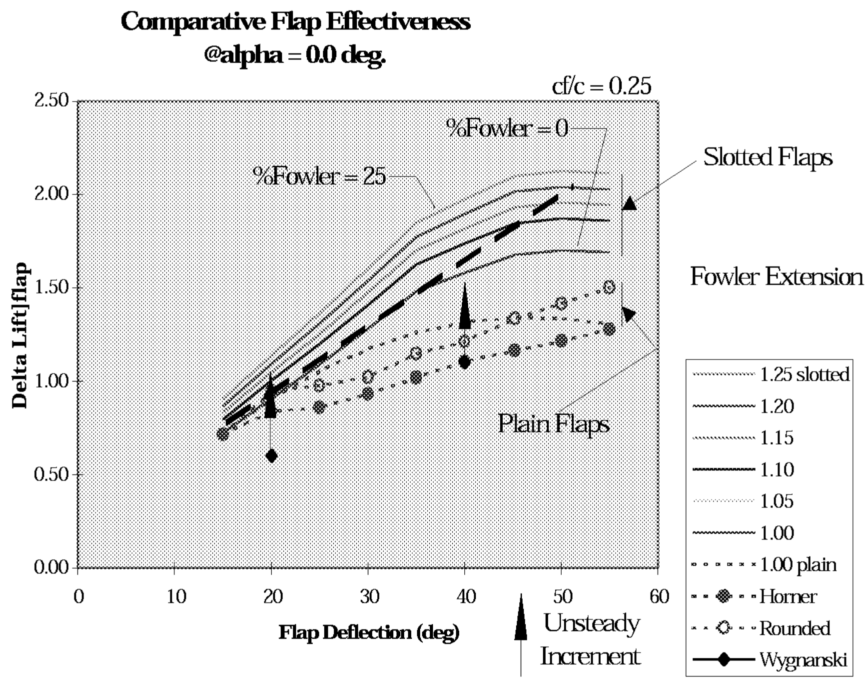


Benefits of HSCT leading edge hinge line Flow Control:

- $\Delta L/D = 0.6$
- 7% increased L/D at takeoff CL
- 30000 lb TO weight reduction
- Additional weight savings from elimination of flap mechanism
- Reduced flap maintenance cost

Fig. 1: **Benefits of Leading Edge Flap Hinge-Line Flow Control for High Speed Civil Transport**

wmf



References in above chart:
Line data w/o symbols from internal Boeing guidelines
Symbol line data from Fluid-Dynamic Lift , Hoerner and Borst
Wygnanski data from Seifert, et al (reference 1)

Figure 2: Plot used as the basis for preliminary estimates of lift increments available with active flow control

Application Scenarios for Trailing Edge Devices

	Design Scenario	Physical Elements	Functionality: Lift Augmentation	Lift Enhancement	Lift Control	Roll Control	Maintain Glide Slope	Comments/Issues/Benefits
No Flow Control	Conventional High Lift System Layout (Part-span, slotted flaps) Airplane control effected through device deflections	Trailing Edge Devices	✓					The physical elements of a conventional high lift system provide a range of functionalities that are directed at modulating airplane lift and rolling moment. Typical transport high lift systems yield a low enough L/D at landing approach that some thrust is typically required to maintain a 3° glide slope.
		Spoiler			✓	✓		
		Aileron				✓		
		Engine Thrust					✓	
Flow Control to Provide Enhanced Device Performance	Active Flow Control Option #1 (Part-span, slotted flaps) Airplane control effected through device deflections	Trailing Edge Devices	✓					1) - Need to demonstrate the ability to augment effectiveness of single slotted flaps to flap deflection angles beyond current practice (i.e.δflap > 45°). Quantify maximum δflap feasible with active flow control for single slotted flaps. <u>Benefit:</u> Potentially simpler, reduced Fowler extension actuation/ support systems.
		Periodic Flow Generator		✓ 1				
		Spoiler			✓	✓		
		Aileron				✓		
		Engine Thrust					✓	
	Active Flow Control Option #2 (Part-span, plain flaps) Airplane control effected through device deflections	Trailing Edge Devices	✓					2) - Same as 1) above, but for plain flaps. <u>Benefit:</u> At δflap = 50 degrees, the effectiveness of an actively controlled flap might approximate the effectiveness of a slotted flap with typical Fowler extensions. 3) - Need to explore influence of deflected spoiler on flap lift and the linearity of spoiler control response with flow controlled plain flap. 4) - Simpler flap system may result in significant increase in L/D on landing approach. Is spoiler response under 3) above acceptable for glide path control?
		Periodic Flow Generator		✓ 2				
		Spoiler			✓ 4	✓ 3	✓ 4	
		Aileron				✓		
		Engine Thrust					✓ 4	
	Active Flow Control Option #3 (Full-span, non-slotted flaperons) Airplane control effected through device deflections	Trailing Edge Devices	✓		✓ 5	✓ 5		2), 3), and 4) - As above. 5) - Need to explore the use of actively controlled plain flaps for control effectiveness both for direct lift control as well as for lateral control.
		Periodic Flow Generator		✓ 2				
		Spoiler			✓ 4	✓ 3	✓ 4	
		Aileron						
		Engine Thrust					✓ 4	
Flow Control Modulated as Airplane Control Mechanism	Active Flow Control Option #4 (Full-span, non-slotted flaperons) Airplane control effected through modulation of active flow control	Trailing Edge Devices	✓					2) and 4) - As above. 6) - Need to explore the use of flow control as a flight control mechansm. <u>Benefit:</u> Reduced reliance on movable devices to effect airplane control reduces actuator and system sizing demands. Results in simpler, lower cost, and ligher weight mechanical, electrical, and hydraulic systems associated with airplane control system.
		Periodic Flow Generator		✓ 2	✓ 6	✓ 6	✓ 6	
		Spoiler						
		Aileron						
		Engine Thrust					✓ 4	

Figure 3

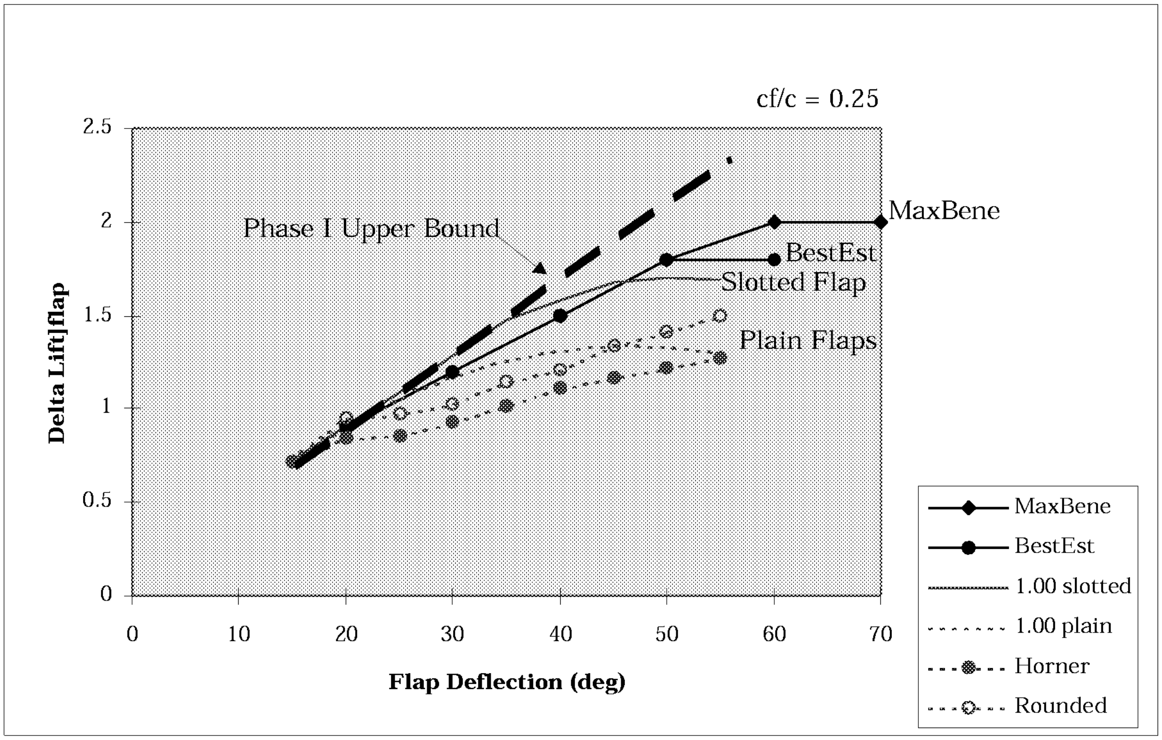


Figure 4: Estimated Active Control Effectiveness @ $\alpha = 0$ degrees.

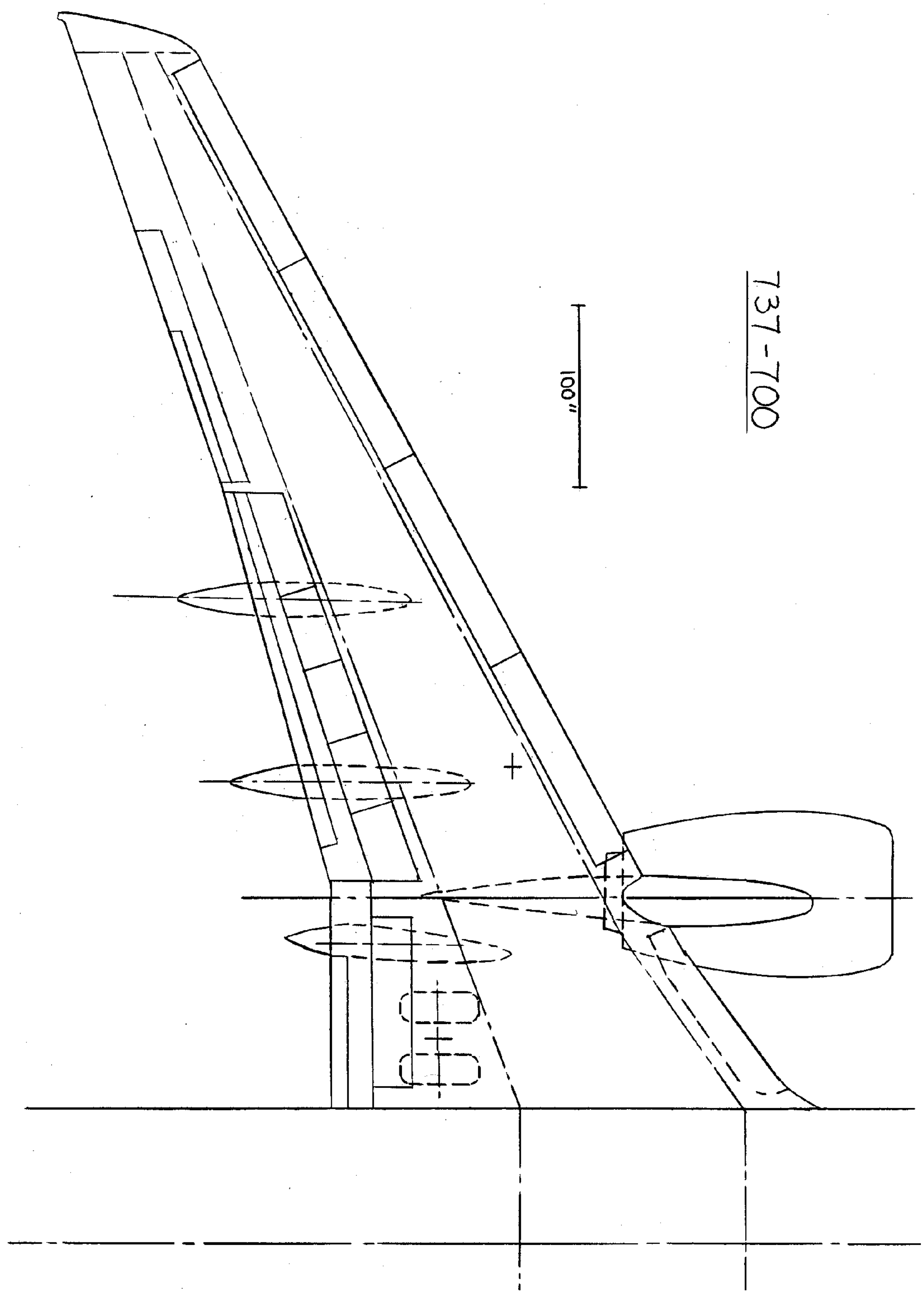


Figure 5: Plan view of 737NG high-lift system

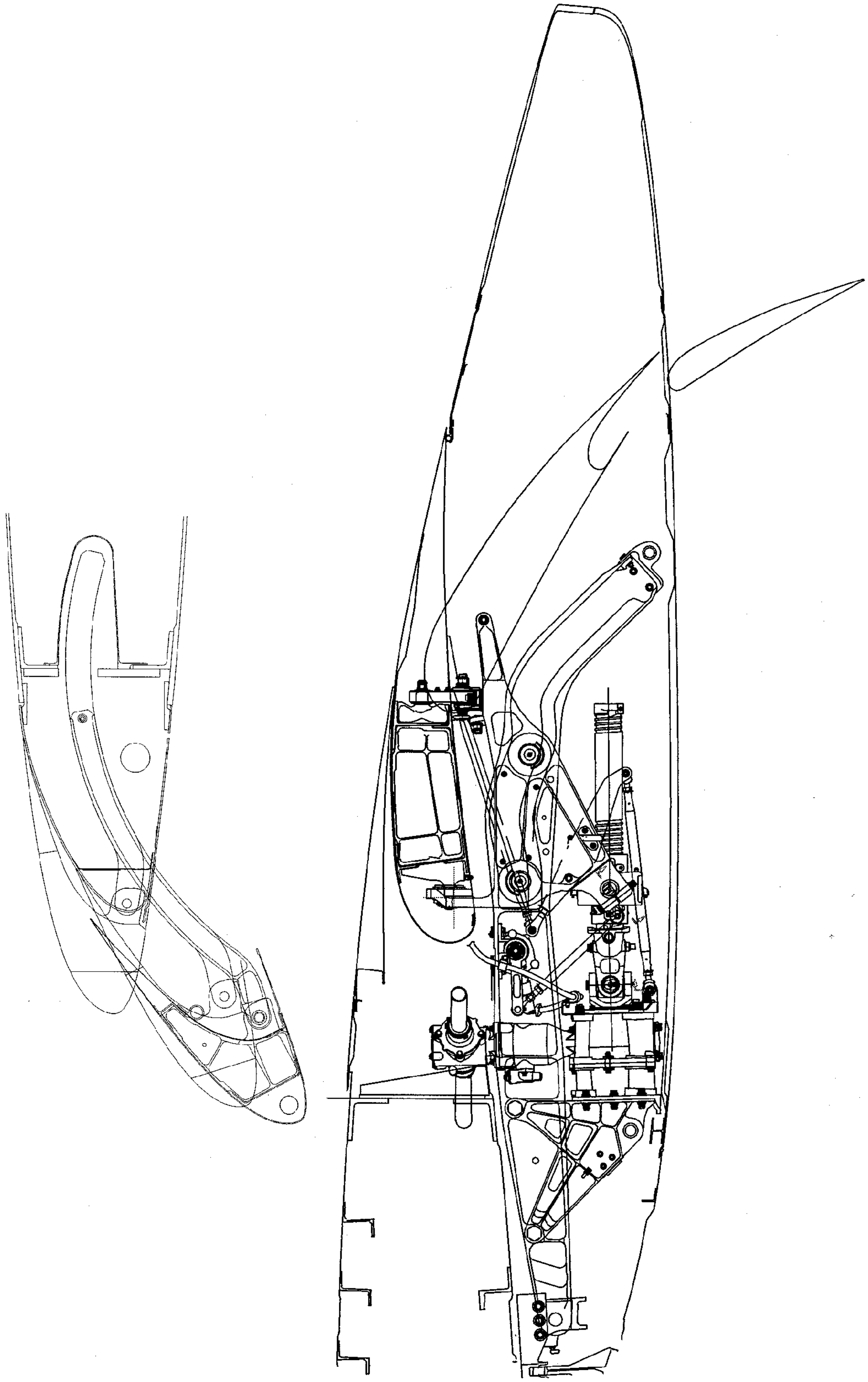


Figure 6: Outboard wing x-section of 737 NG

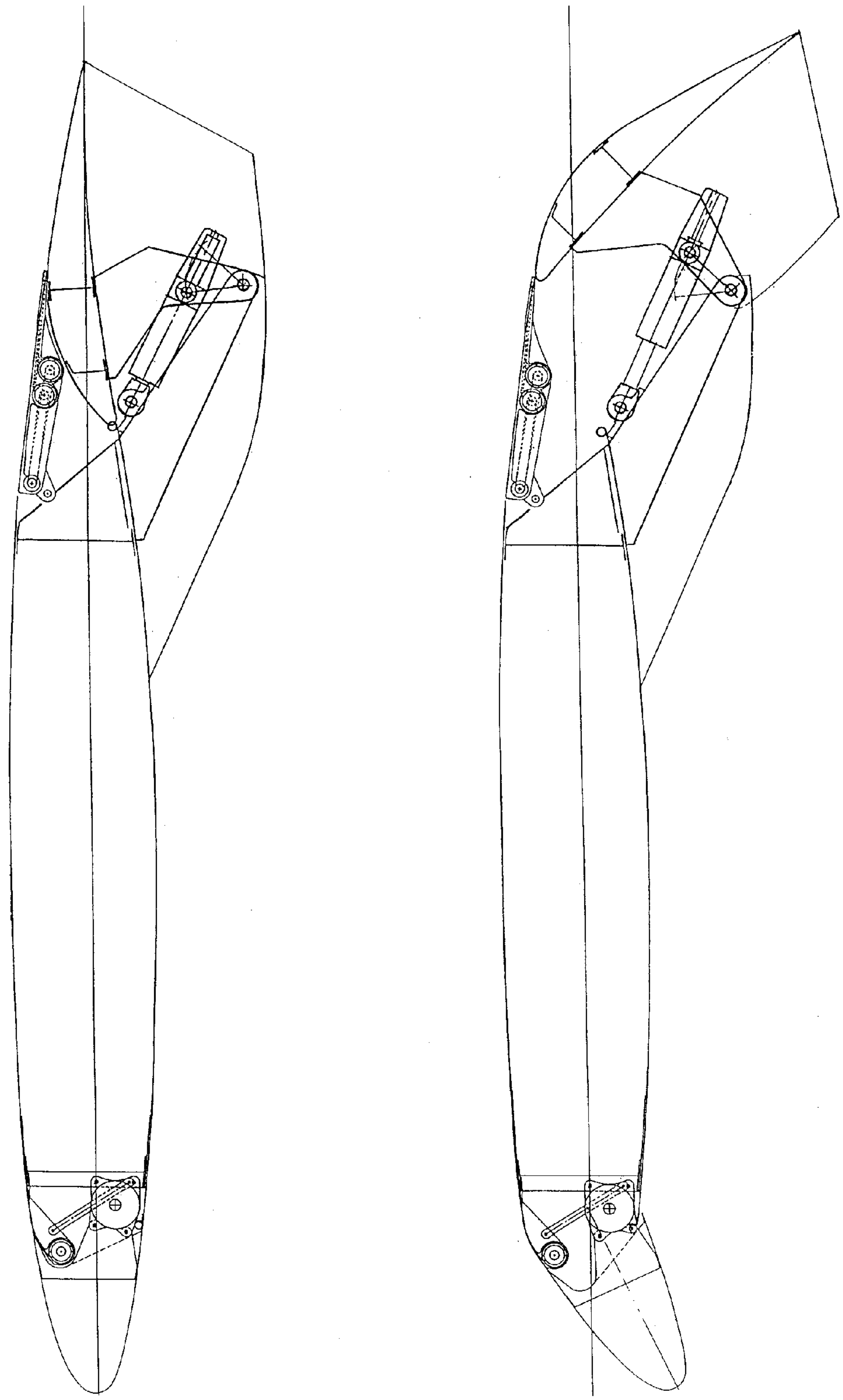


Figure 7: External hinge configuration

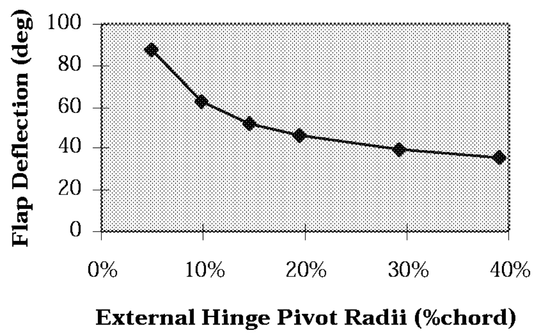


Figure 8: Max Flap Deflection Variation with External Pivot Radii for External Hinge

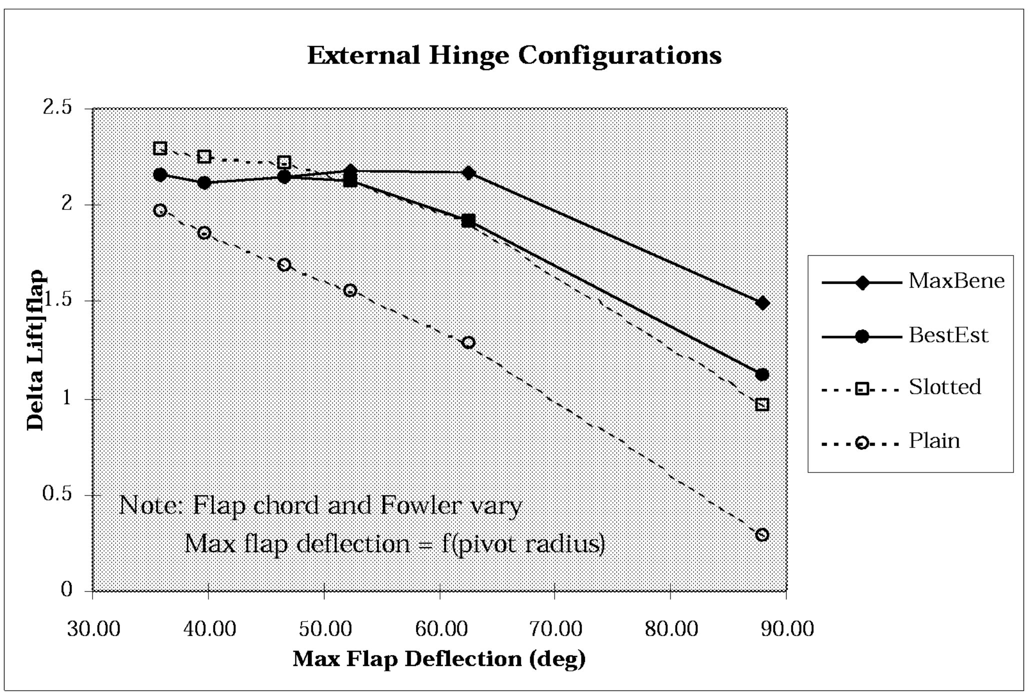


Figure 9: Flap Effectiveness for External Hinge Flap Configuration

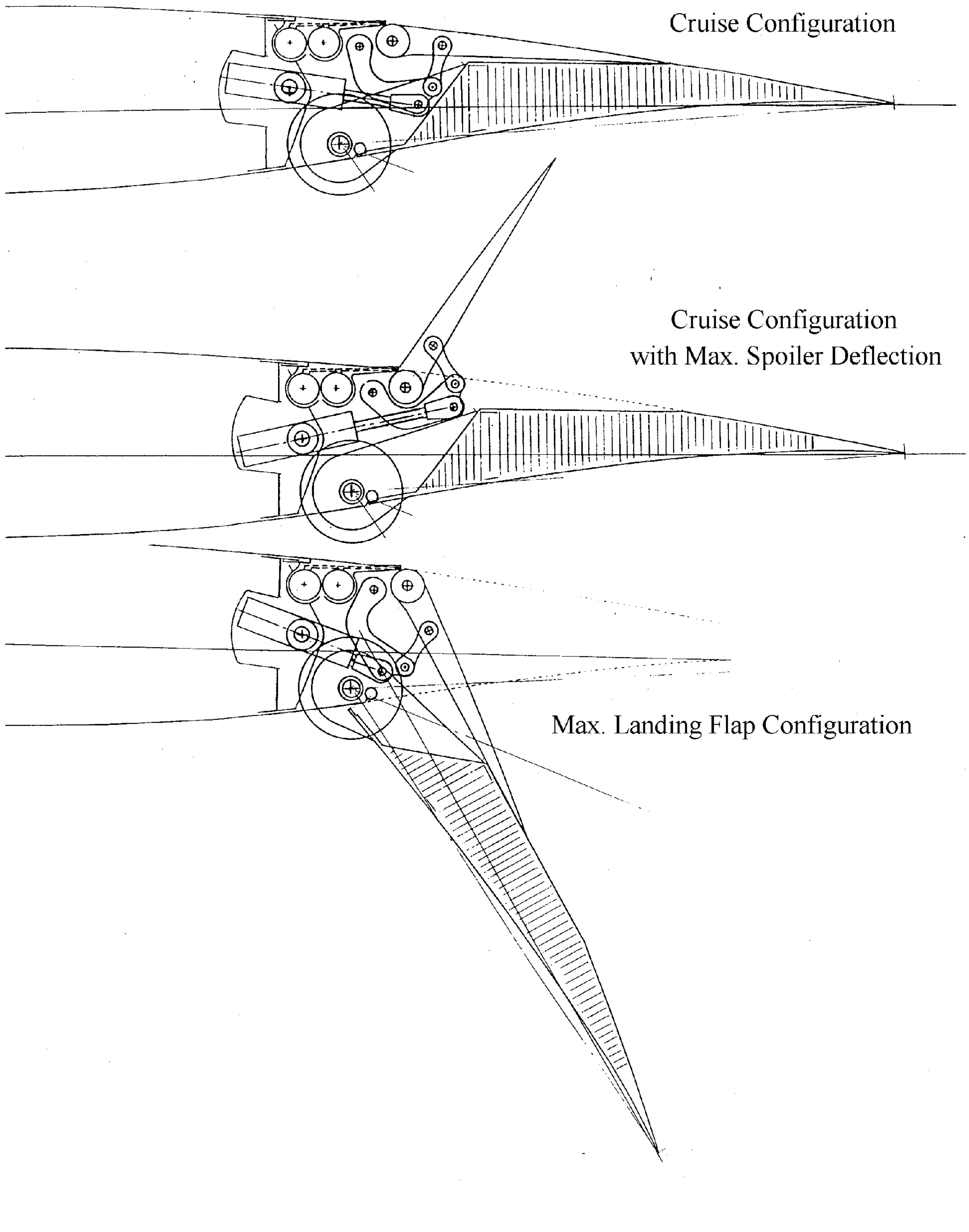


Figure 10: Large-chord plain flap with integral spoiler

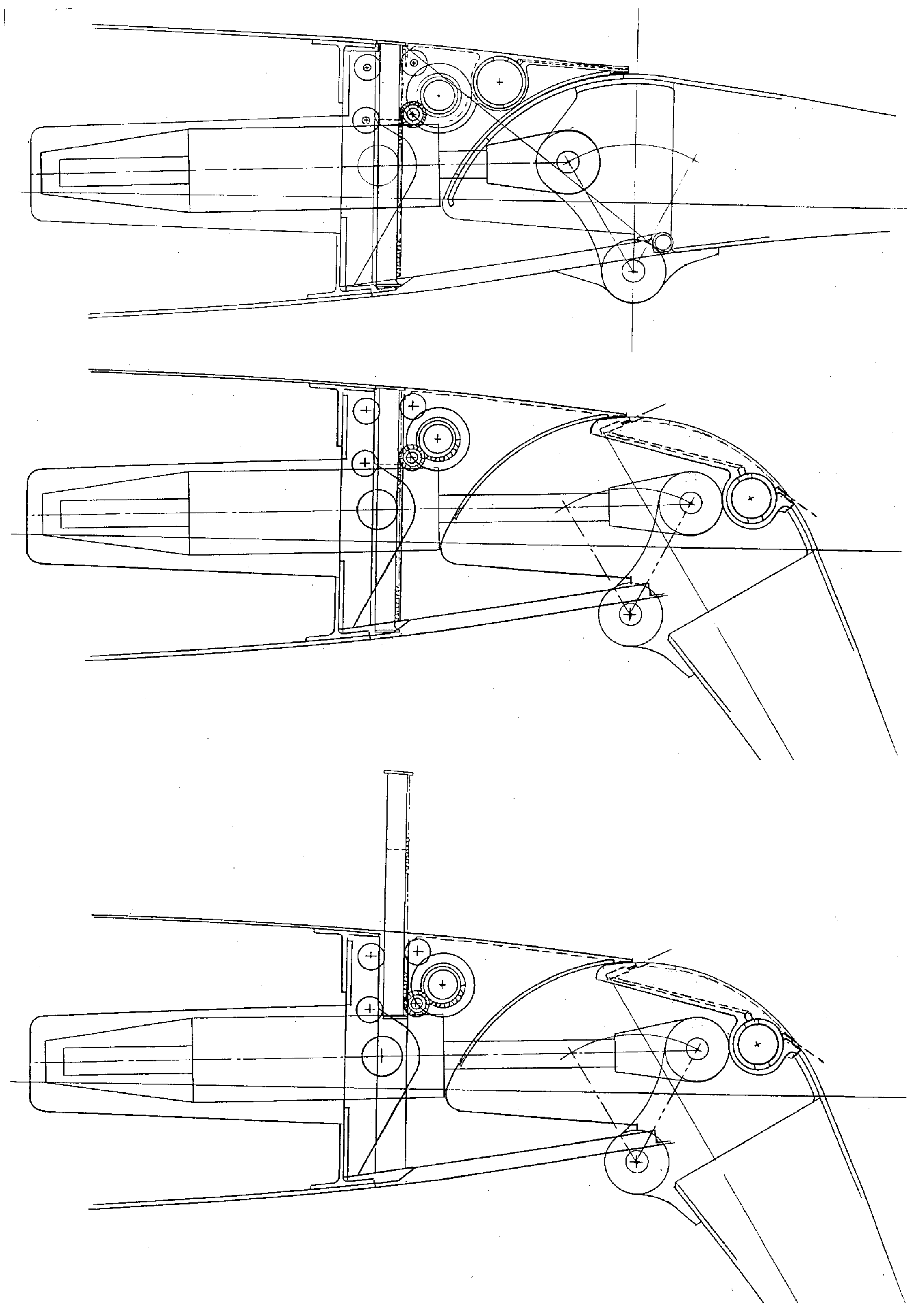


Figure 11: Large-chord plain flap with blade spoiler

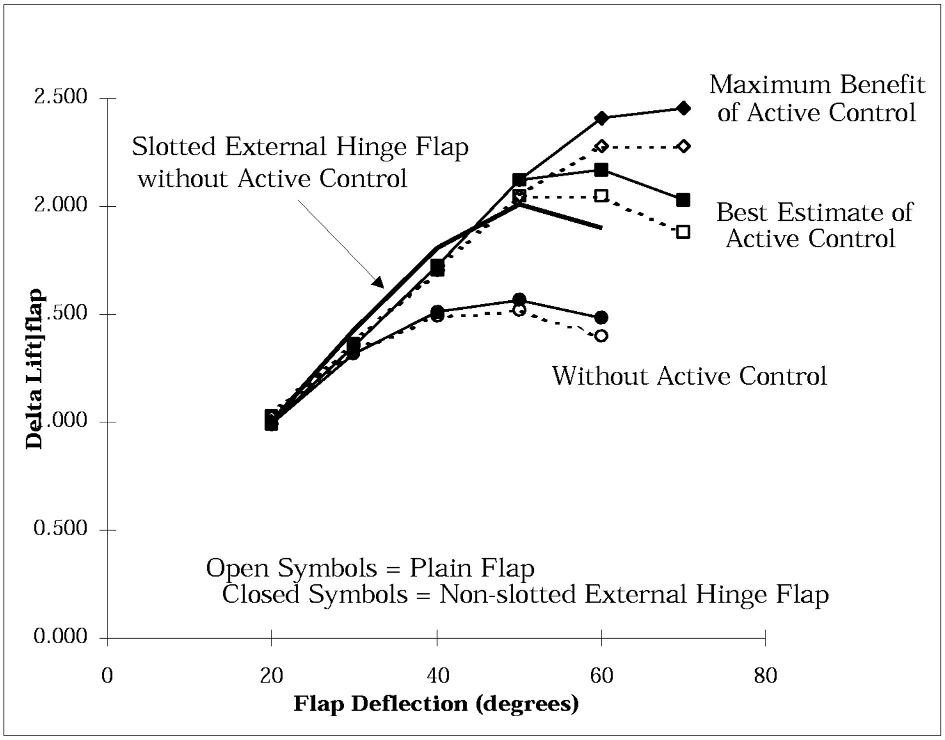


Figure 12: Relative Flap Effectiveness of External Hinge Configuration and Large Chord Plain Flap Configuration

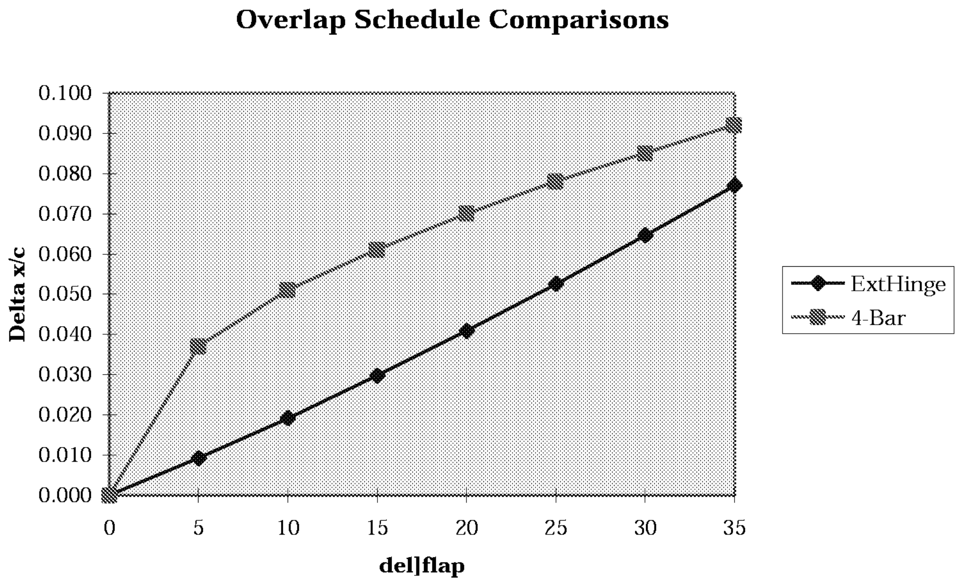


Figure 13: Comparison of External Hinge Configuration Overlap Schedule to a that of a Typical 4-Bar Linkage Schedule

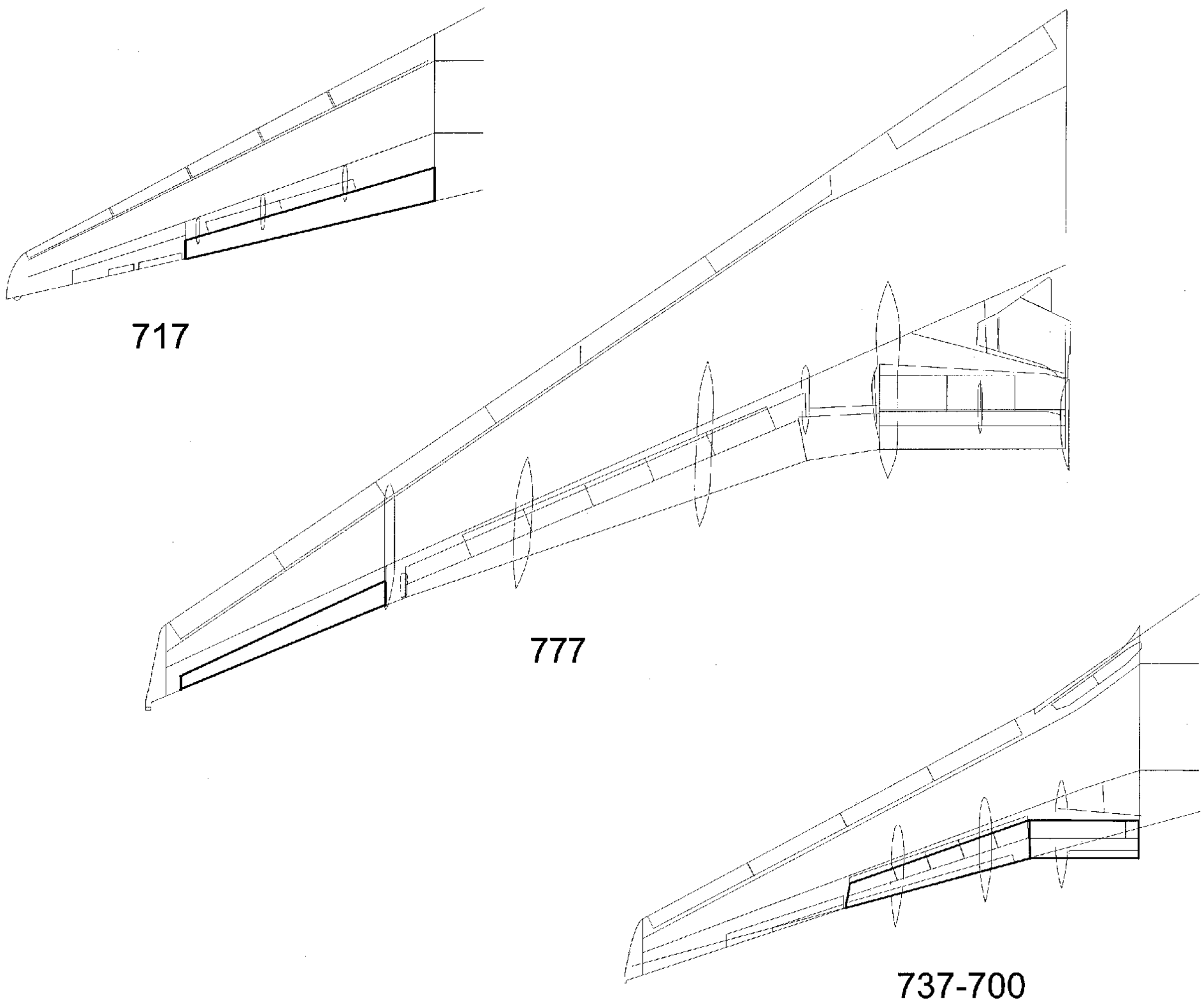
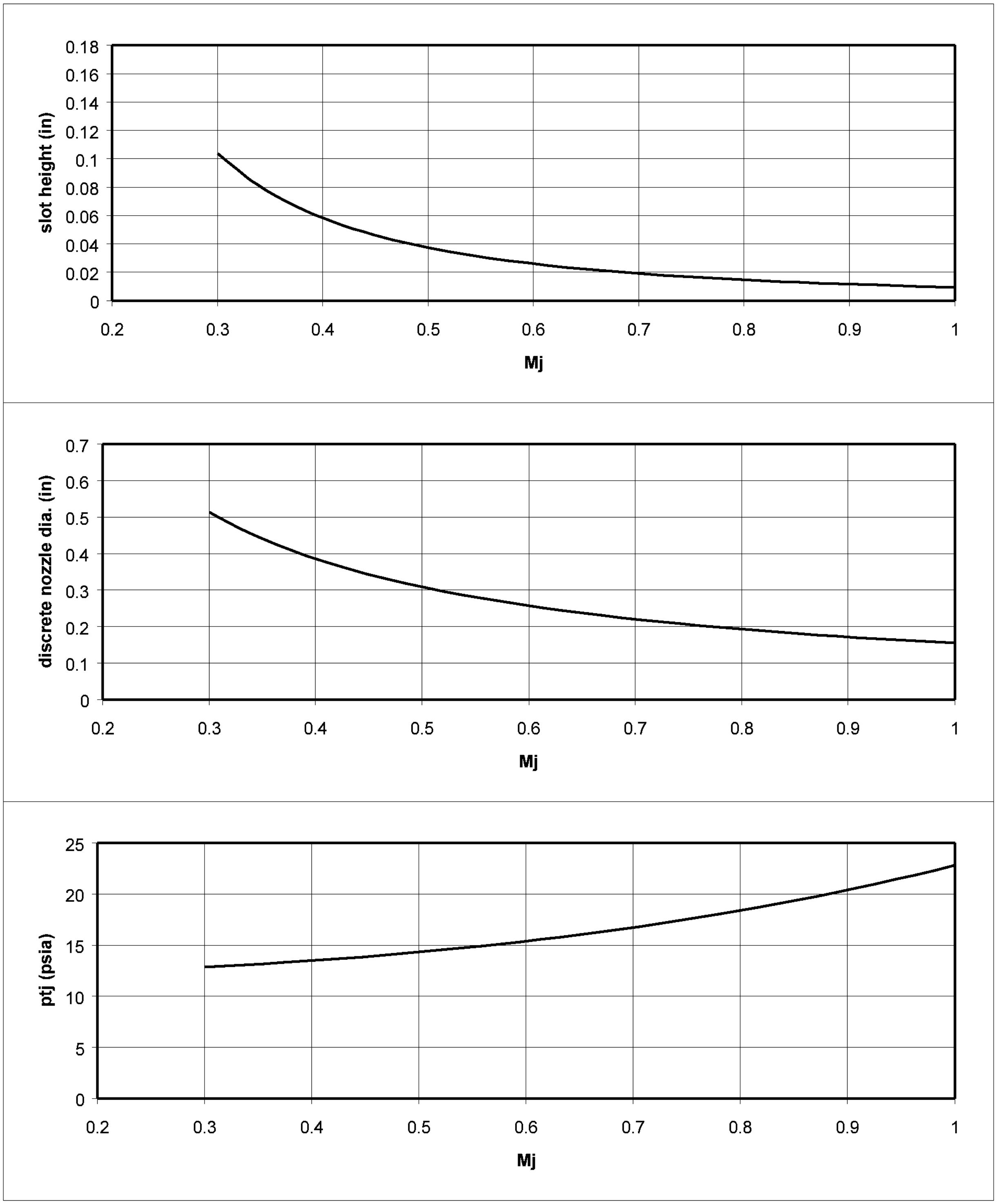


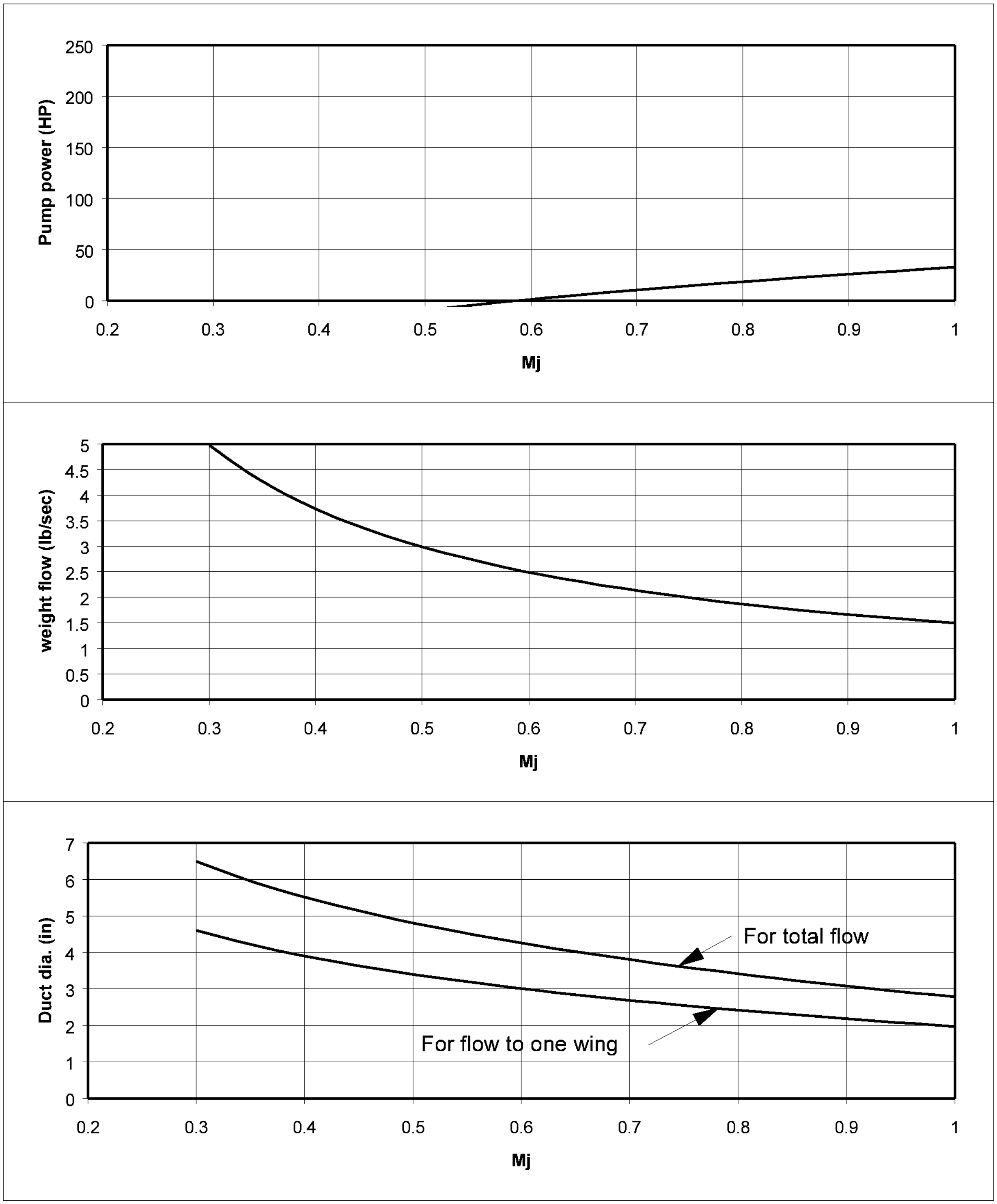
Figure 14: Planforms used in the comparisons of complexity, weight, and cost



c (in)	sref (ft^2)	cf/c	uinf (kt)	Cpej	<Cmu> %	Kd
247	1100	0.25	150	-5	0.06	0.5

Sj (in)
2.00

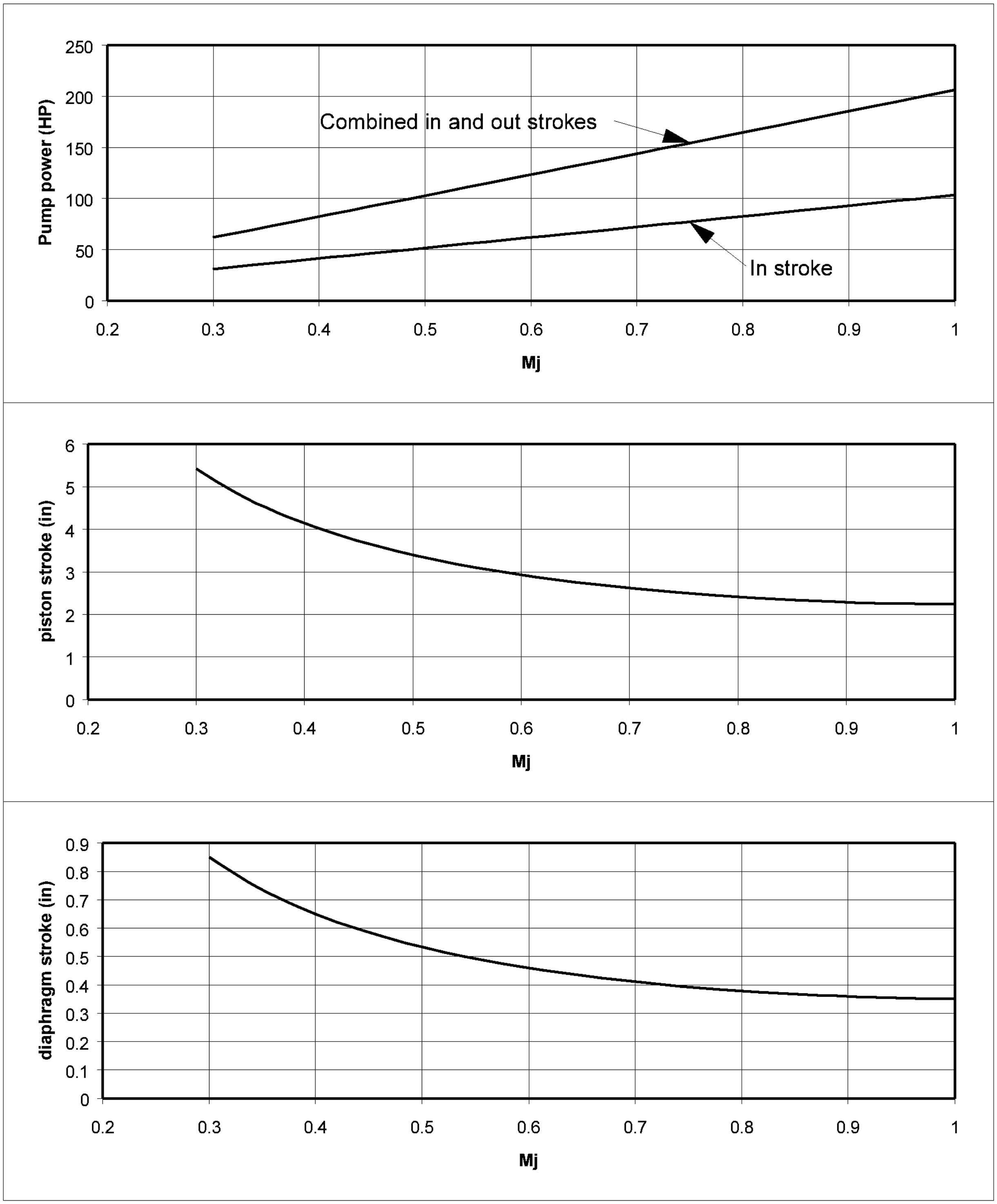
Figure 15: Estimates of required slot/nozzle dimensions and jet total pressure



c (in)	sref (ft^2)	cf/c	uinf (kt)	Cpej	<Cmu> %	Kd
247	1100	0.25	150	-5	0.06	0.25

M duct
0.3

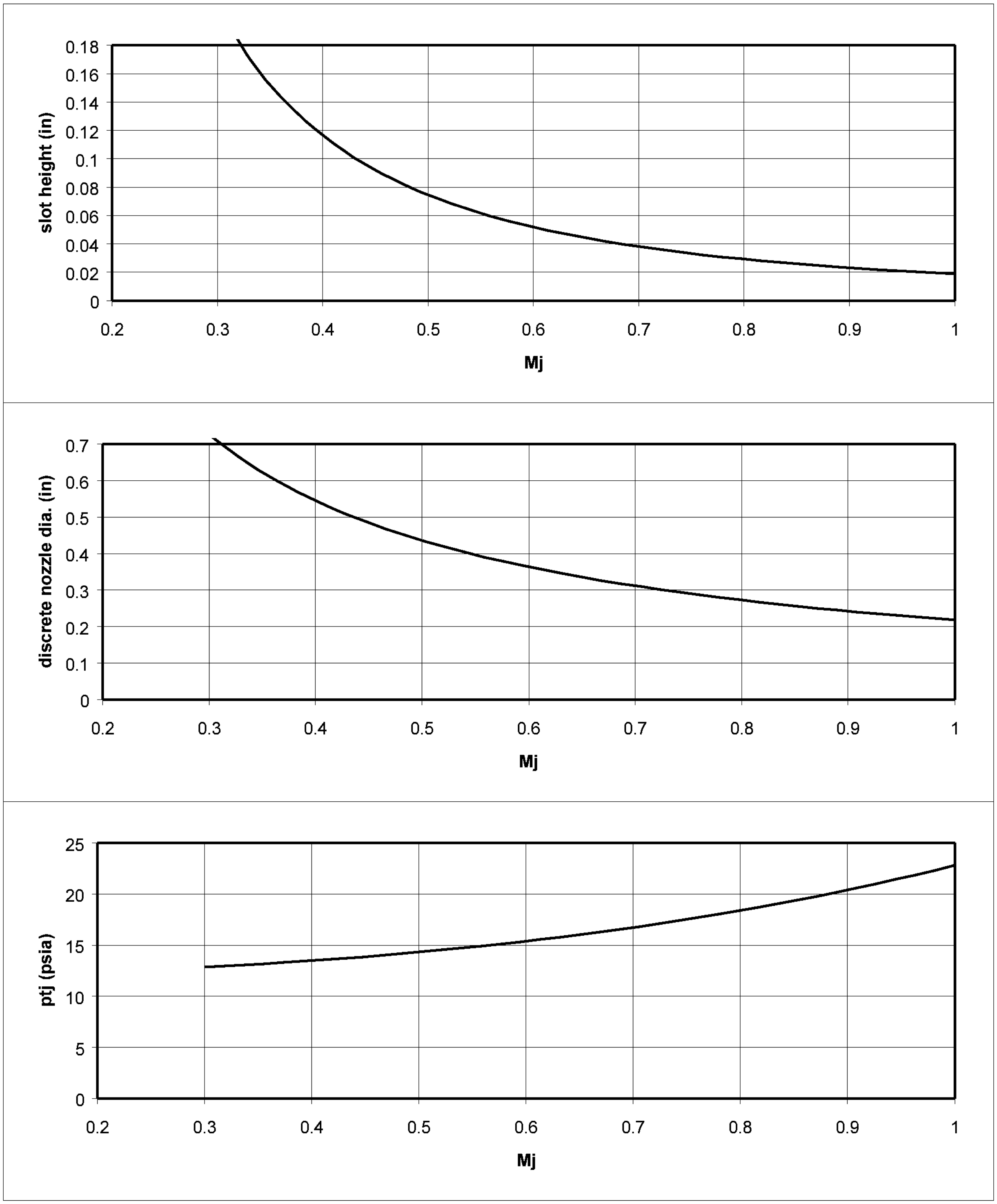
Figure 16: Power, weight flow, and duct size for options using a compressed-air supply



c (in)	sref (ft^2)	cf/c	uinf (kt)	Cpej	<Cmu> %	Kd	Fplus	f (HZ)
247	1100	0.25	150	-5	0.06	0.5	1	49

wp/c	dp/c	bp/c	Rv
0.02	0.02	0.1	0.5

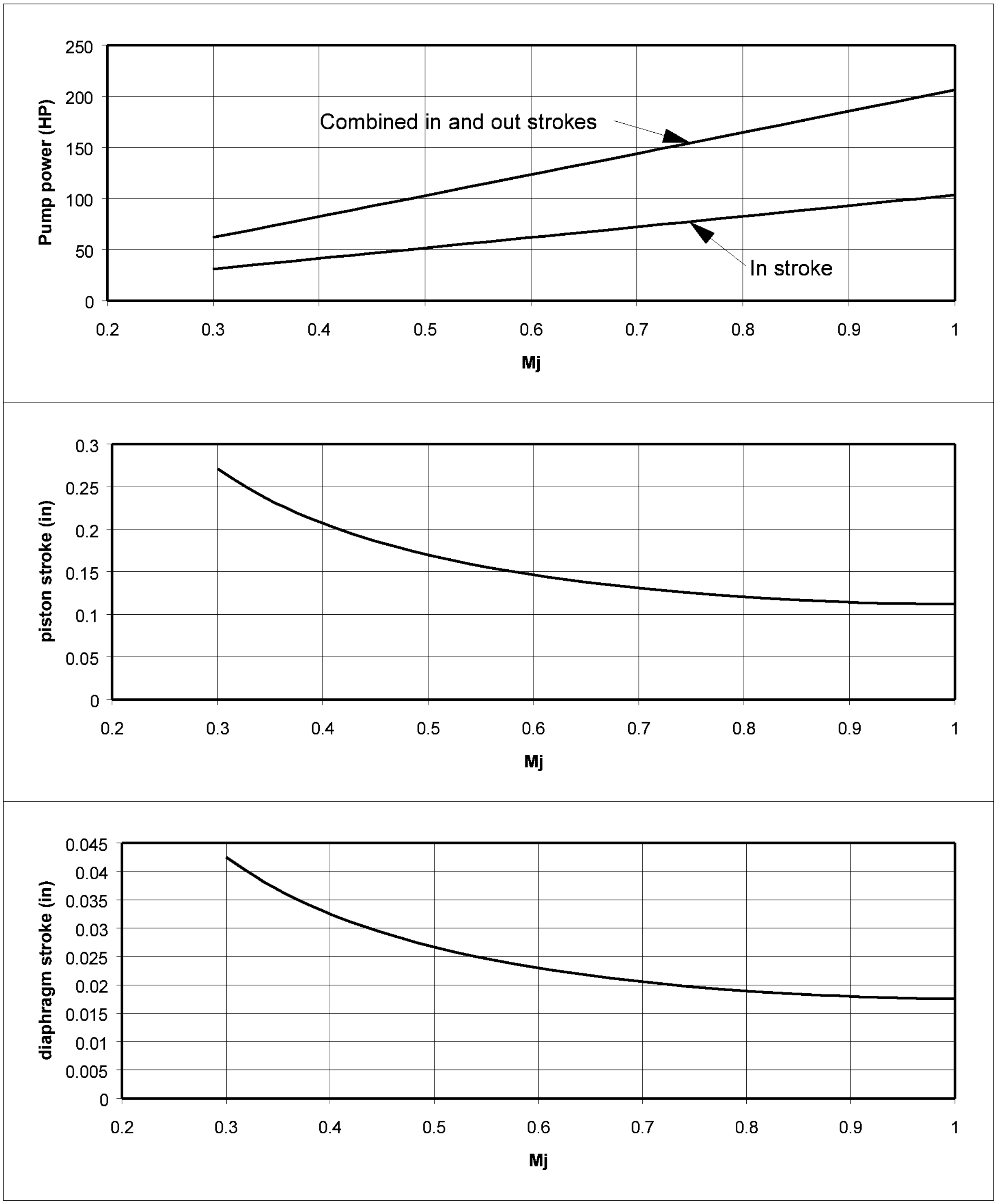
Figure 17: Power and piston/diaphragm strokes for options using cyclic pumping



c (in)	sref (ft^2)	cf/c	uinf (kt)	Cpej	<Cmu> %	Kd
247	1100	0.25	150	-5	0.06	0.25

Sj (in)
2.00

Figure 18: Slot/nozzle dimensions and jet total pressure for options using synthetic jets



c (in)	sref (ft^2)	cf/c	uinf (kt)	Cpej	<Cmu> %	Kd	Fplus	f (HZ)
247	1100	0.25	150	-5	0.06	0.25	20	984

wp/c	dp/c	bp/c	Rv
0.02	0.02	0.1	0.5

Figure 19: Estimated power and piston/diaphragm strokes for options using synthetic jets

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1999	Contractor Report

4. TITLE AND SUBTITLE
Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft

5. FUNDING NUMBERS
WU 522-32-31-01

6. AUTHOR(S)
J. D. McLean, J. D. Crouch, R. C. Stoner, S. Sakurai, G. E. Seidel, W. M. Feifel, and H. M. Rush

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boeing Commercial Airplane Group
P. O. Box 3707
Seattle, WA 98124-2207

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/CR-1999-209338

11. SUPPLEMENTARY NOTES
The task was co-funded by the DARPA MEMS program under NASA Contract NAS1-20267
Langley Technical Monitor: R. D. Joslin

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 05 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This study provides a preliminary assessment of the potential benefits of applying unsteady separation control to transport aircraft. Estimates are given for some of the costs associated with a specific application to high-lift systems. High-leverage areas for future research were identified during the course of the study. The study was conducted in three phases. Phase 1 consisted of a coarse screening of potential applications within the aerodynamics discipline. Potential benefits were identified and in some cases quantified in a preliminary way. Phase 2 concentrated on the application to the wing high-lift system, deemed to have the greatest potential benefit for commercial transports. A team of experts, including other disciplines (i.e. hydraulic, mechanical, and electrical systems, structures, configurations, manufacturing, and finance), assessed the feasibility, benefits, and costs to arrive at estimates of net benefits. In both phases of the study, areas of concern and areas for future research were identified. In phase 3 of this study, the high-leverage areas for future research were prioritized as a guide for future efforts aimed at the application of active flow control to commercial transport aircraft.

14. SUBJECT TERMS
Systems Costs/Benefits Study; active flow control; separation control; high-lift

15. NUMBER OF PAGES
64

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL