N88-17609

# A POTENTIAL FLIGHT EVALUATION OF AN UPPER-SURFACE-BLOWING/CIRCULATION-CONTROL-WING CONCEPT

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## SUMMARY

The technology data base for powered-lift aircraft design has advanced considerably over the last 15 years. NASA's Quiet Short-Haul Research Aircraft (QSRA) has provided a flight verification of upper surface blowing (USB) technology. The Navy/Grumman A-6 Circulation Control Wing Flight Demonstration Aircraft has provided data for circulation control wing (CCW) technology. Recent small-scale wind-tunnel model tests and full-scale static flow-turning tests have shown the potential of combining USB with CCW technology. A flight research program is deemed necessary to fully explore the performance and control aspects of CCW jet substitution for the mechanical USB Coanda flap. The required hardware design would also address questions about the development of flight-weight ducts and CCW jets and the engine bleed-air capabilities versus requirements. NASA's QSRA would be an optimum flight research vehicle for modification to the USB/CCW configuration. This report discusses the existing QSRA data base, the design simplicity of the QSRA wing trailing edge controls, availability of engine bleed-air, and the low-risk/low-cost potential of the suggested program. Recommendations are made for follow-on efforts to this USB/CCW QSRA modification study.

## INTRODUCTION

The requirements for improved lifting, maneuver capability and STOL characteristics for both military and civil aircraft have led to the development of several technology demonstrator aircraft which perform research in powered-lift aerodynamics. Two of these, NASA's QSRA (ref. 1, fig. 1) and the Navy/Grumman A-6 CCW Flight Demonstration Aircraft (ref. 2, fig. 2), have provided extensive data for USB and CCW powered-lift concepts. A powered-lift concept developed at the David Taylor Naval Ship Research and Development Center (DTNSRDC) replaces the mechanical Coanda flap system of the USB airplane with a CCW flap which deflects the USB engine thrust as shown in figure 3. The resulting increase in wing circulation and vertical thrust component augments aerodynamic lift in a manner similar to that of the Coanda USB flap concept used in the QSRA and the USAF/Boeing YC-14 airplanes. In addition, the full-span CCW system provides circulation lift augmentation over the entire wing. The USB/CCW configuration has the potential for improved performance and versatility for STOL airplanes due to the ability of the CCW pneumatic thrust deflector to rapidly vary horizontal force from thrust to drag while maintaining constant vertical force (ref. 3). Because the circulation lift augmentation is driven by the CCW, the loss of a thrust (USB) engine would create a lower lateral upset than with a Coanda flap, thus requiring less corrective control input. There is a potential for an adequately controllable two-engine USB powered-lift airplane by the combination of USB with CCW.

The ability of this USB/CCW configuration to deflect engine thrust was verified in two QSRA static ground tests conducted for the U.S. Navy in 1981 and 1983 (ref. 4 and 5). The second test series investigated USB/CCW geometries which would be representative of flight configurations where cruise drag is a major consideration. A typical configuration is shown in figure 4. A 90 degree circular arc with a small slot height provided the best performance, demonstrating that adequate thrust turning can be produced by a trailing edge shape which may have minimal cruise performance penalty (ref. 5). Thrust deflections were achieved at considerably lower blowing momentum than was required in the 1981 baseline tests. Small-scale, low-speed wind-tunnel model tests have also shown the ability of the CCW jet, with a small trailing edge flap, to control the thrust deflection of USB engine configurations (ref. 6). This data base was generated by Lockheed-Georgia on an ejector powered model with a twelve foot wing span.

The QSRA, shown in figure 5, is a high performance STOL powered-lift research aircraft which uses the USB technique to achieve maximum lift coefficients of slightly over ten (ref. 1). The QSRA first flew in July 1978 and has logged over 550 flight hours since. The propulsion system consists of four AVCO-Lycoming YF-102 turbofan engines, shown in figure 6, mounted in above-the-wing nacelles (figure 7). These engines, which are prototypes of Lycoming's ALF-502 turbofan, each produce slightly less than 6,000 pounds static sea-level installed thrust. A low-pressure, low-temperature boundary layer control (BLC) air distribution system was designed and built for the QSRA. This system originally provided wing leading edge and aileron BLC blowing from a mix of engine compressor bleed and fan air. The wing leading edge BLC blowing was removed early in the flight research program, having been replaced by a fixed, conventional aerodynamic slat. Thus, a source of engine fan and compressor bleed air exists for blowing a CCW jet. The QSRA fuselage and empennage is that of a deHavilland C-8 Buffalo. The landing gear is fixed in the down position and has been modified to accommodate gross takeoff weights of 60,000 pounds. The empty weight is approximately 43,000 pounds which includes an extensive onboard data acquisition, recording and telemetry system. An extensive low-speed wind-tunnel, flight simulation and flight research data base exists which fully documents the performance and control characteristics of the QSRA Coanda USB flap configuration.

There are four primary objectives for the proposed USB/CCW flight evaluation program. First would be the assessment of the feasibility of flight-weight, airworthy hardware during the QSRA modification design and fabrication period. Second would be the assessment of the engine bleed air availability versus that required by the CCW jet for a full range of flight conditions. During the detail design phase, the use of an auxiliary air compressor may be deemed necessary, especially as a back-up for single engine-out conditions. Third would be a flight evaluation of the low-speed performance of the USB/CCW configuration. Lift, drag and pitching moment characteristics would be measured and takeoff and landing airspeed and angle-of-attack margins would be determined. Fourth would be a flight evaluation of the STOL control characteristics of the USB/CCW configuration. The ability to maintain high levels of lift (and thus, airspeed and angle-of-attack margins) while varying drag to provide steep STOL landing approach glideslope control would be determined. Performance and control comparisons would be made between the USB/CCW and USB Coanda flap configurations. There is also a potential objective of a wind-tunnel/flight low-speed aerodynamic data correlation. Discussions have been ongoing concerning a wind-tunnel test of the QSRA in the NASA-Ames Research Center 80 by 120 ft. low-speed wind tunnel. This could be timed to be done with the USB/CCW configuration prior to or after the flight tests.

## QSRA USB/CCW MODIFICATION POTENTIAL

The existing wing trailing edge controls consist of two USB flap panels, one conventional double-slotted flap, and one aileron on each side of the aircraft as shown on the lower half of the QSRA planform in figure 8. There are also two spoiler panels on each wing which are used in three control modes: 1) asymmetrical deflection for lateral control in conjunction with the ailerons, 2) gross landing approach glideslope control and landing roll lift dump by manual symmetrical deflection, and 3) direct lift control (DLC) for accurate glideslope tracking using symmetrical incremental deflections tied to throttle movements to quicken flight path response. Further details of the flight control systems and characteristics are presented in references 7, 8 and 9.

## Structural Modifications

The design of the QSRA basic wing structure is such that all trailing edge control surfaces and fairings can be removed aft of the rear spar, thus providing maximum flexibility for the design and installation of a new CCW trailing edge and associated air ducting. The upper half of the QSRA planform in figure 8 identifies the potential elements of the USB/CCW modification. The existing spoiler panels would be retained to assure adequate lateral control power for the flight research program. Figure 9 provides more detail of the inboard USB segment of the QSRA wing. The upper wing cross-section shows the existing USB Coanda flap and associated hardware. The lower wing cross-section shows a conceptual USB/CCW modification with an identification of new hardware. The trailing edge could be either a small flap as shown or a fixed cylindrical arc as tested in the QSRA static tests in 1983. The existing USB flap support arm, which is attached to the front and rear spars of the wing, would be retained to provide a structural load path to react the CCW trailing edge aerodynamic loads. Figure 10 presents similar wing structure details at the existing double-slotted flap location. Note that the spoiler panels are retained without any modification. CCW trailing edge aerodynamic loads would be reacted through the existing double-slotted flap support arm. Figure 11 details the structure at the ailerons, again showing the ease with which a USB/CCW modification could be made. A potential CCW aileron would be very similar to the existing blown aileron panel except for a shorter chord length. Another possibility would be a cylindrical trailing edge with upper and lower surface blowing for lateral control and a blown base jet for neutral lateral control requirements. The blowing to the proper jet would be controlled by a rotating, slotted cylinder valve within the jet duct. Both of these thoughts are detailed in figure 11.

## Control System Modifications

The wing trailing edge flight control system can also be adapted easily to the control of the CCW jet blowing and small aft flap movements. The current lateral control system is shown in figure 12. The ailerons are hydraulically operated with the command coming from the pilots' control wheels via mechanical linkage. There are also lateral trim and lateral stability augmentation system (SAS) electrical commands which are mechanically summed into the aileron command. The summed mechanical command which drives the aileron hydraulic cylinder transfer valve could be made to drive a CCW jet blowing control valve and a CCW aft flap hydraulic transfer valve. Thus, the CCW aileron function would include pilot wheel inputs, lateral trim inputs and lateral SAS inputs as for the current QSRA system. No change would be made to the electronic pilots' wheel-to-spoiler panel gearing.

The existing USB and double-slotted (or outboard) flaps are hydraulically actuated in response to electrical inputs to the hydraulic transfer valves as shown in figure 13. The electrical driving signals come from flap analog computers which sum pilot control lever, trim and stability and control augmentation system (SCAS) electrical inputs. Essentially, the wing flap system is a "fly-by-wire" configuration in which the electrical commands could be made to drive CCW jet blowing control valves and CCW aft flap hydraulic transfer valves. The current QSRA asymmetric outboard flap lateral trim (for engine-out compensation) and SCAS lift-drag control functions could be maintained with the CCW system.

## Engine Fan/Core Bleed Air System

The original QSRA configuration utilized BLC blowing on the entire wing leading edge and on the upper aileron surfaces (ref. 10). The array of ducts, valves and BLC nozzles is shown in figure 14. Currently the QSRA retains the aileron BLC system but the leading edge BLC system has been replaced with a fixed leading edge slat. Removal of the aileron droop, a function of double-slotted flap extension through a mechanical linkage, would negate the need for aileron BLC blowing. Thus, the original BLC system on all four Lycoming YF-102 engines could be used for the CCW jet blowing requirements. Figure 15 shows the mixed flow BLC system components. A fan "S"-duct bleeds approximately 3% of the fan air flow and an engine compressor bleed band allows up to 10% high pressure compressor bleed. A fixed-geometry ejector pump mixes fan and compressor bleed air with an associated pressure rise relative to fan pressure. An ejector bleed air control valve senses and controls exit pressure to a constant value which can be set at the valve. Figure 16 shows the net blowing thrust from the existing aileron BLC nozzles as a function of engine thrust. The ejector bleed air control valve allows a constant 100 pound blowing thrust at a constant BLC pressure of 4.9 psig. The pressure control feature provides for adjustment of BLC levels from 4 to 11 psig on the airplane for research flexibility.

In the event that the required CCW jet blowing requirements cannot be met by the maximum engine bleed air available, it would be plausible to install auxiliary air compressors in underwing pods. A detailed design study would be required to ascertain the capacity, placement and control of such auxiliary compressors.

## QSRA: A LOW-RISK USB/CCW PROGRAM

### QSRA Performance and Control

The QSRA was designed to have a high level of performance to provide flight research flexibility and safety. The installed thrust-to-weight ratio at 60,000 pounds maximum gross takeoff weight is 0.39; at 45,000 pounds, 0.52. The corresponding wing loadings are 100 psf and 75 psf. Both the STOL and CTOL capabilities of the QSRA have been shown to be superior to other powered-lift aircraft (ref. 11 and 12). Likewise, excess control power, especially in the lateral control axis, was designed into the QSRA to assure safety when performing simulated engine-out flight research. Figure 17 shows the QSRA's lateral control power in terms of roll acceleration versus pilot wheel input. Previous STOL aircraft studies (ref. 13) recommended a minimum roll acceleration capability of 0.4 radians per second squared. The QSRA design team elected to double this goal for the airplane: 0.8 radians per second squared. Figure 17 shows that this goal was exceeded by use of the ailerons and spoilers collectively. The spoilers provide 58% of the maximum lateral control power. These same spoilers, and their use for lateral control, would be maintained for the USB/CCW modification. Therefore, even if CCW lateral control concepts did not prove as effective as the existing ailerons, adequate lateral control would still be available.

### Failure Modes Assessment

A very detailed flight simulation was performed during the QSRA design to develop the flight control laws and SCAS and to investigate the risk of various systems failure modes. References 14 and 15 provide the simulation mathematical model and the results of the simulation investigations. The mathematical model used a 40 by 80 ft. wind tunnel, 55% scale QSRA model aerodynamic data base. Failure modes, such as flap and aileron hardovers and asymmetries, were investigated to determine pilot recognition and ability to counter the uncommanded upset.

A USB/CCW aerodynamic performance and control data base has been acquired by the Lockheed-Georgia Company using a 12-foot span model in their low-speed wind tunnel (reference 6). Figure 18 shows how the USB/CCW aerodynamics could be related to the baseline QSRA simulation results. The USB baseline aerodynamic data, combined with the QSRA control laws, provided a failure mode analysis tool. Flap and aileron hardovers and asymmetries demand sufficient pilot recognition, control power and response times to counter the uncommanded upsets. The baseline USB aerodynamic coefficients can be directly compared to the USB/CCW coefficients. For example, an uncommanded USB flap panel retraction would be expected to generate nearly the same rolling moment coefficient as the loss of CCW jet blowing behind one engine. The pilot reaction and corrective response requirements would be expected to be approximately the same. If certain CCW jet failures caused aerodynamic forces which were found uncontrollable for the baseline configuration, system redundancies would be required to assure a fail safe operation. A new USB/CCW configuration flight simulation would not be required using this analysis technique.

## QSRA Instrumentation

The QSRA has a digital data system which processes, records and telemeters approximately 300 discrete items (ref. 7). In conjunction with the NASA ground station many of these parameters can be monitored real-time by the ground test engineer. Real-time computations of items such as corrected lift coefficient can also be monitored. All of the required USB/CCW unique performance, control surface movement, jet blowing and system health monitors can be added to the existing data system for real-time observation and/or post-test analysis.

## Phased Modification Program

A phased flight program to study USB/CCW performance and control characteristics would be conducted so as to reduce risk. Three modification phases are shown in figure 19: Phases A, B and C. Phase A would replace the USB Coanda flap panels with the CCW jet/flap configuration behind the turbofan engines. The outboard section of the wing (double-slotted flap, aileron and spoilers) would remain unchanged. Initial takeoffs and landings would be performed in a CTOL configuration, using double-slotted flaps and drooped ailerons as the only lift enhancers, as has been demonstrated numerous times during the QSRA's flight history. Evaluations of performance, control and simulated CCW jet failures (loss of partial blowing) would be performed at a safe altitude. Once the control limitations and airspeed and angle-of-attack margins were firmly established, the USB/CCW system would be employed during takeoffs and landings. A flight data base would be developed which would compare the USB Coanda flap to the USB/CCW configuration for overall performance and control capability.

Phase B would replace the double-slotted flap with the CCW jet/flap configuration. This would increase the percentage of the wing that would be subject to circulation lift augmentation. Initial takeoffs and landings would be performed in a clean-wing CTOL configuration with the CCW jet turned off. As with Phase A, the Phase B modification would be fully explored at a safe altitude before conducting takeoffs and landings.

Phase C would replace the existing aileron with a CCW trailing edge configuration, providing circulation lift augmentation across the entire wing span. Differential CCW jet blowing, in conjunction with the QSRA's lateral control spoiler panel function, would be studied as a means of roll control and engine-out roll trim. Again, the initial assessments would be performed at altitude using conservative CTOL takeoffs and landings. The use of the phased modification approach would not only minimize risk but would provide a three-tiered data base to allow assessment of the gains from each modification phase.

## CONCLUSIONS AND RECOMMENDATIONS

The QSRA static USB/CCW ground tests conducted for the U.S. Navy and the low-speed USB/CCW wind-tunnel tests conducted by the Lockheed-Georgia Company have shown the aerodynamic potentials of the combination of USB with CCW. A flight verification is required to assess the overall performance and control characteristics with a fully integrated airframe, propulsion and control system.

The extensive QSRA USB Coanda flap wind-tunnel, flight-simulation and flight research data base can be combined with the USB/CCW wind-tunnel data base to determine and resolve potential performance or control problems during early design. The comparison of the aerodynamics of the two systems will allow, without further wind-tunnel testing or flight simulations, the determination of risks and pilot operational procedures. The phased modification concept will further reduce risks.

The QSRA allows a low-cost approach to USB/CCW flight research by providing a proven, fully instrumented flight facility. The relative simplicity of the QSRA wing structure and flight controls allows maximum modification flexibility. The existence of a fully developed engine air bleed system and associated ducts and valves will further minimize modification costs.

This program will provide a valuable flight data base to assess the USB/CCW performance and STOL control characteristics for comparison to the USB Coanda flap configuration. Many claims have been made for potential improvement over the mechanical flap system. This program will provide a quantitative evaluation. The USB/CCW concept has a strong potential for two-engine powered lift aircraft. The CCW jet assures the continuance of the circulation lift augmentation following the loss of one engine, thus reducing the lateral upset and required corrective action.

NASA-Ames Research Center has been approached by both the U.S. Navy and the Lockheed-Georgia Company to consider a USB/CCW flight research program using the QSRA facility. At the present time there is no defined funding for such a program. The first step, beyond this feasibility report, would be to develop a cost estimate for the USB/CCW modification. It is recommended that NASA, DOD and industry work together to determine the approximate costs and, if reasonable, then to advocate the funding for the program. A NASA project engineering and technical support team exists for specifying and supervising the QSRA modifications and flight testing.

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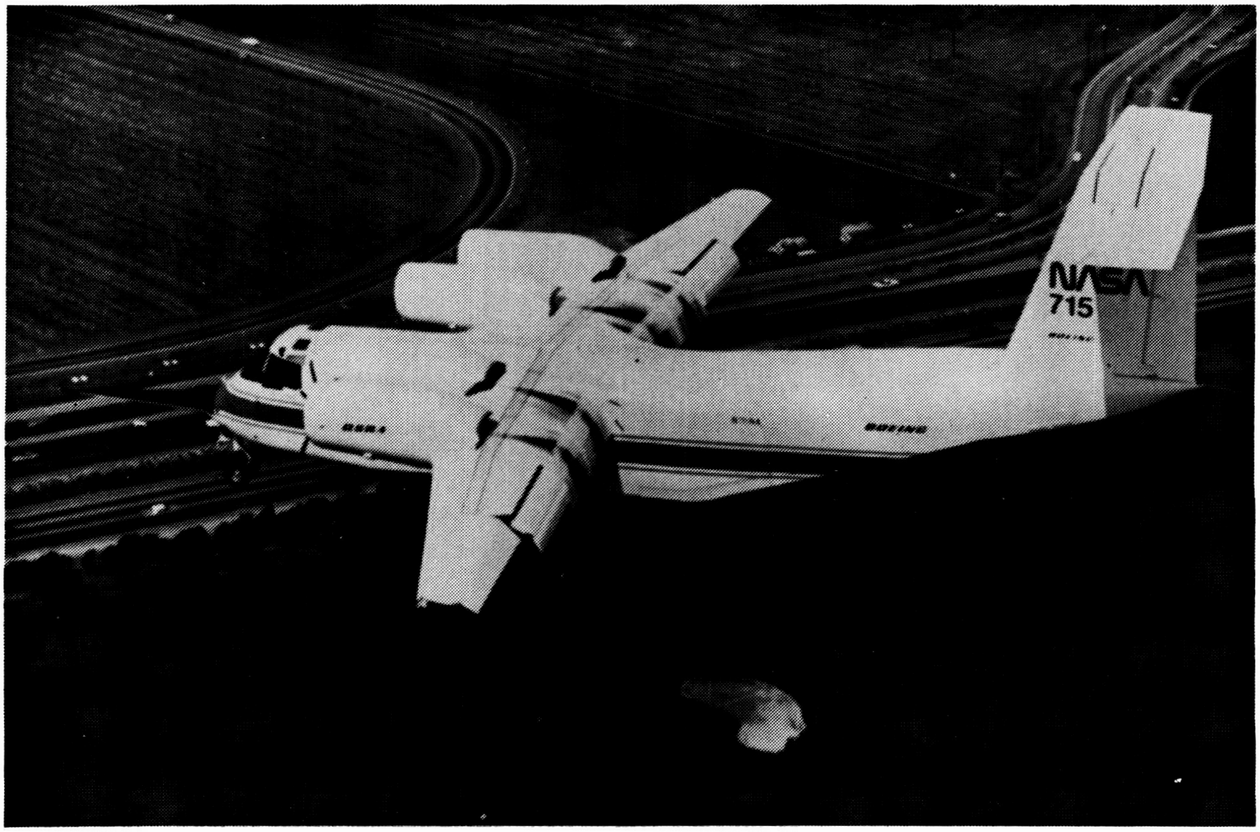


Figure 1. NASA's Quiet Short-Haul Research Aircraft (QSRA).


Figure 2. Navy/Grumman A-6 CCW Flight Demonstration Aircraft.

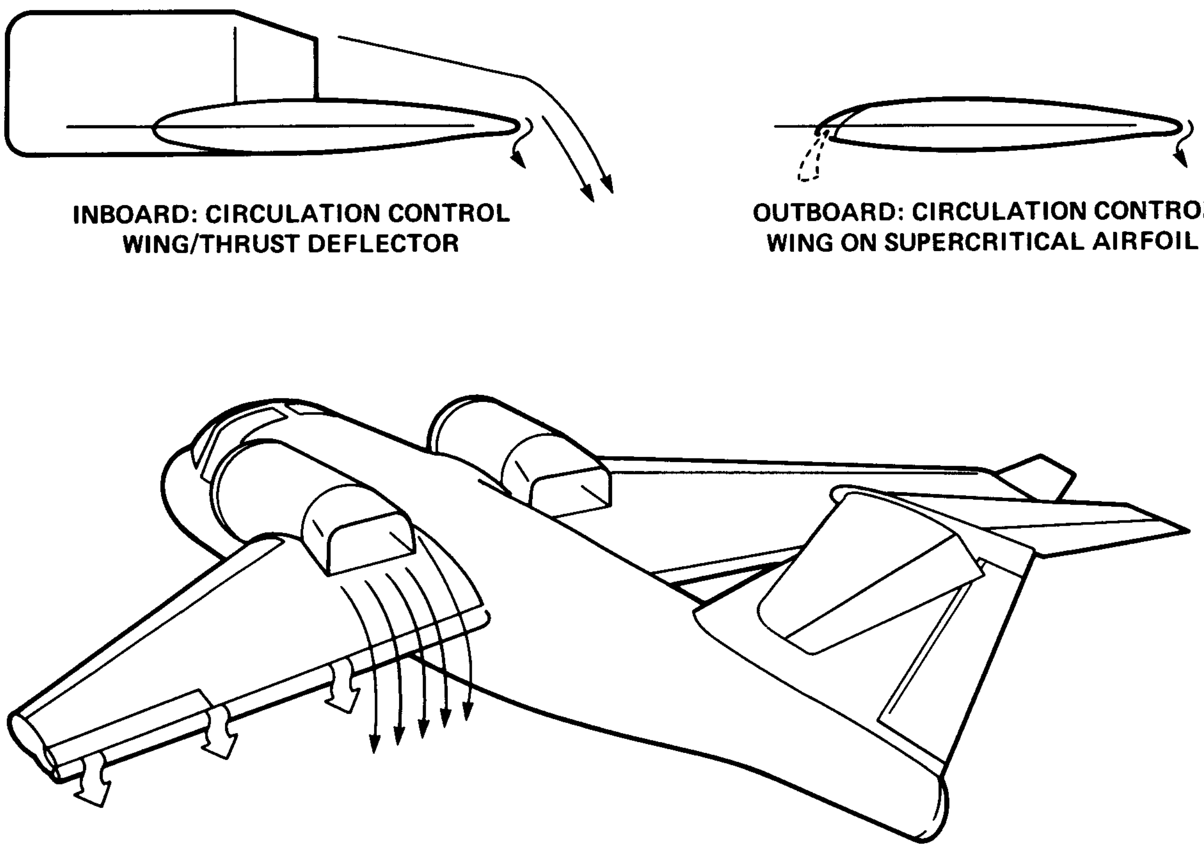


Figure 3. DTNSRDC conceptual USB/CCW aircraft configuration.

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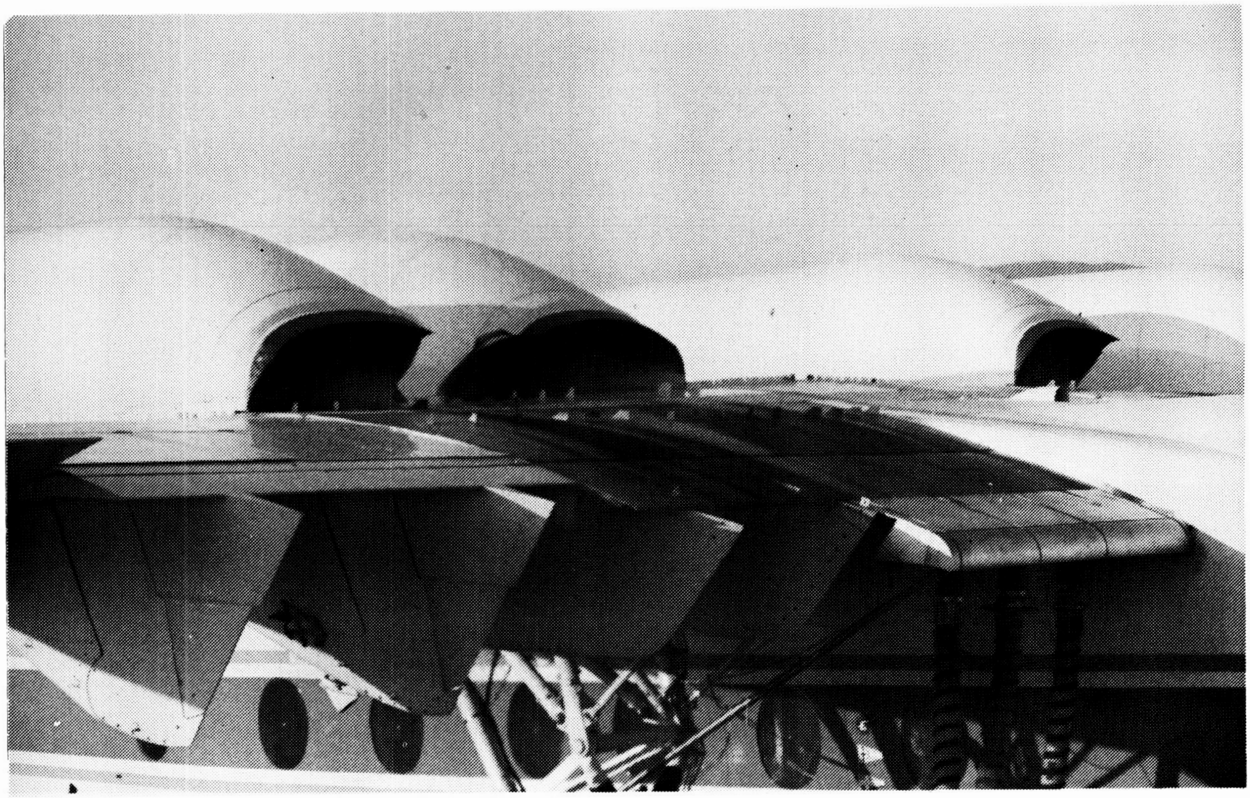


Figure 4. NASA/Navy QSRA USB/CCW static ground test setup.

**AERODYNAMIC DATA**

| | WING | HORIZ | VERT |
|---|---|---|---|
| AREA (TRAP), $ft^2$ | 600.0 | 233.0 | 152.0 |
| SPAN, ft | 73.5 | 32.0 | 14.0 |
| ASPECT RATIO | 9.0 | 4.4 | 1.22 |
| TAPER RATIO | 0.30 | 0.75 | 0.60 |
| SWEEP, C4, deg | 15.0 | 3.0 | 18.0 |
| M.A.C., in. | 107.4 | 88.0 | 137.0 |
| CHORD ROOT, in. | 150.7 | 100.0 | 168.0 |
| CHORD TIP, in. | 45.2 | 75.0 | 100.0 |
| T/C BODY SIDE, % | 18.54 | 14.0 | 14.0 |
| T/C TIP, % | 15.12 | 12.0 | 14.0 |
| INCIDENCE, deg | 4.5 | – | – |
| DIHEDRAL, deg | 0.0 | – | – |
| TAIL ARM, in. | – | 525.0 in. | 488.0 in. |
| VOL COEFF V | – | 1.898 | 0.1402 |

**CONTROL SURFACES**

| | $ft^2$ | BLOWN |
|---|---|---|
| AILERON | 32.2 | BLC |
| FLAPS INBD | 105.0 | USB |
| FLAPS OUTBD | 40.2 | NONE |
| SPOILERS | 33.7 | NONE |
| L.E. FLAPS | 54.3 | NONE |
| ELEVATOR | 81.6 | NONE |
| RUDDER | 60.8 | NONE |

*THEORETICAL RETRACTED AREA

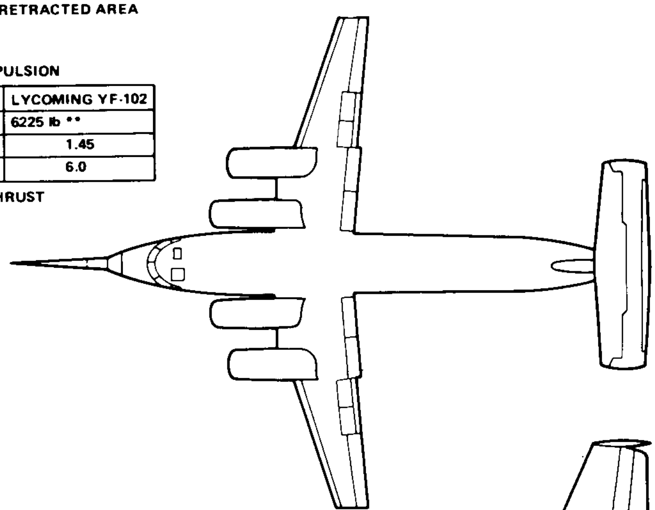
**PROPULSION**

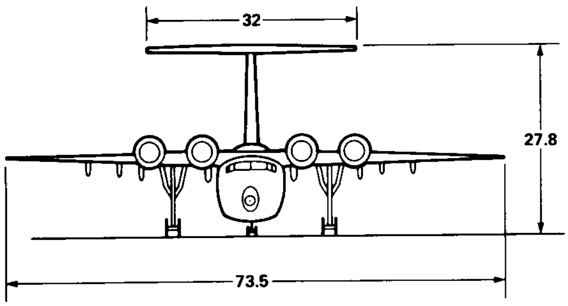
| | |
|---|---|
| ENGINE | LYCOMING YF-102 |
| STATIC THRUST | 6225 lb ** |
| FAN P.R. | 1.45 |
| BY-PASS RATIO | 6.0 |

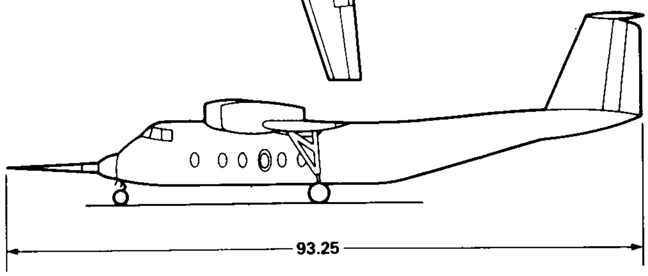
**MEASURED THRUST

**LANDING GEAR**

| GEAR | STROKE | TIRE | TIRE O.D. | ROLLING R. |
|---|---|---|---|---|
| MLG, in. | 21.0 | 11.5-15 NEW DESIGN | 32.0 | 13.5 |
| NLG, in. | 17.5 | 8.90-12.50 TYPE III | 27.5 | 12.0 |






DIMENSIONS IN ft

10/81

Figure 5. QSRA configuration and dimensional details.

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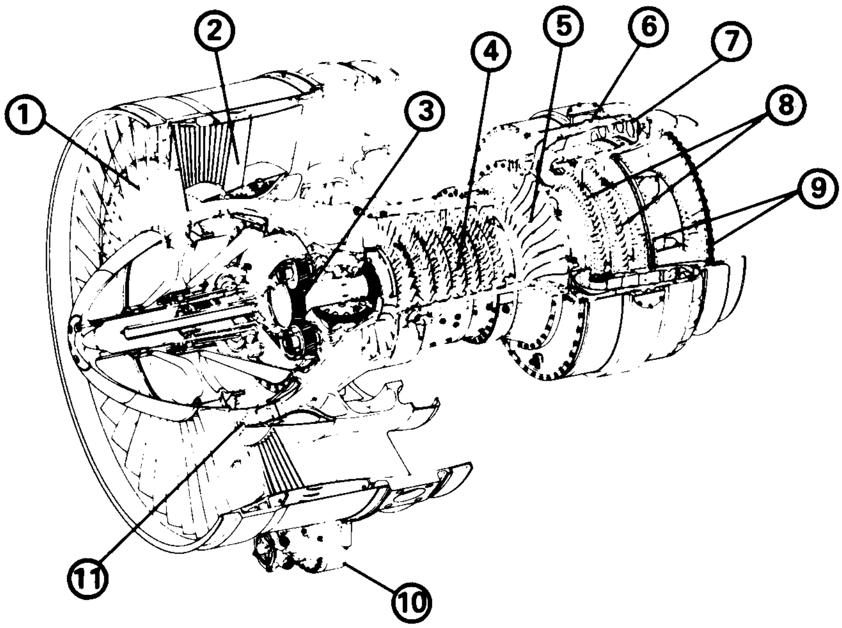


1. FAN STAGE
2. FAN STATOR
3. REDUCTION GEAR ASSEMBLY
4. CORE AXIAL COMPRESSOR
5. CORE CENTRIFUGAL COMPRESSOR
6. CUSTOMER BLEED PORTS
7. COMBUSTOR
8. GAS PRODUCER TURBINES
9. POWER TURBINES
10. ACCESSORY GEARBOX
11. SUPERCHARGER

Figure 6. AVCO-Lycoming YF-102 turbofan engine details.

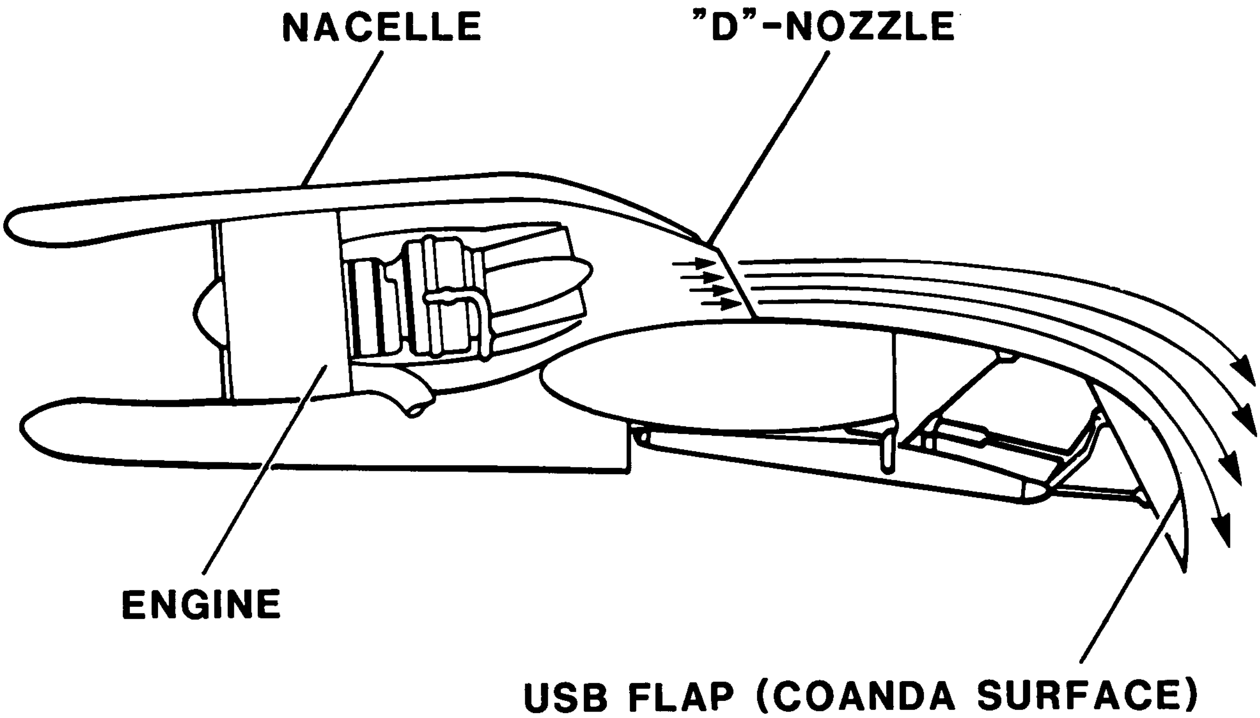


Figure 7. QSRA wing-engine USB configuration.

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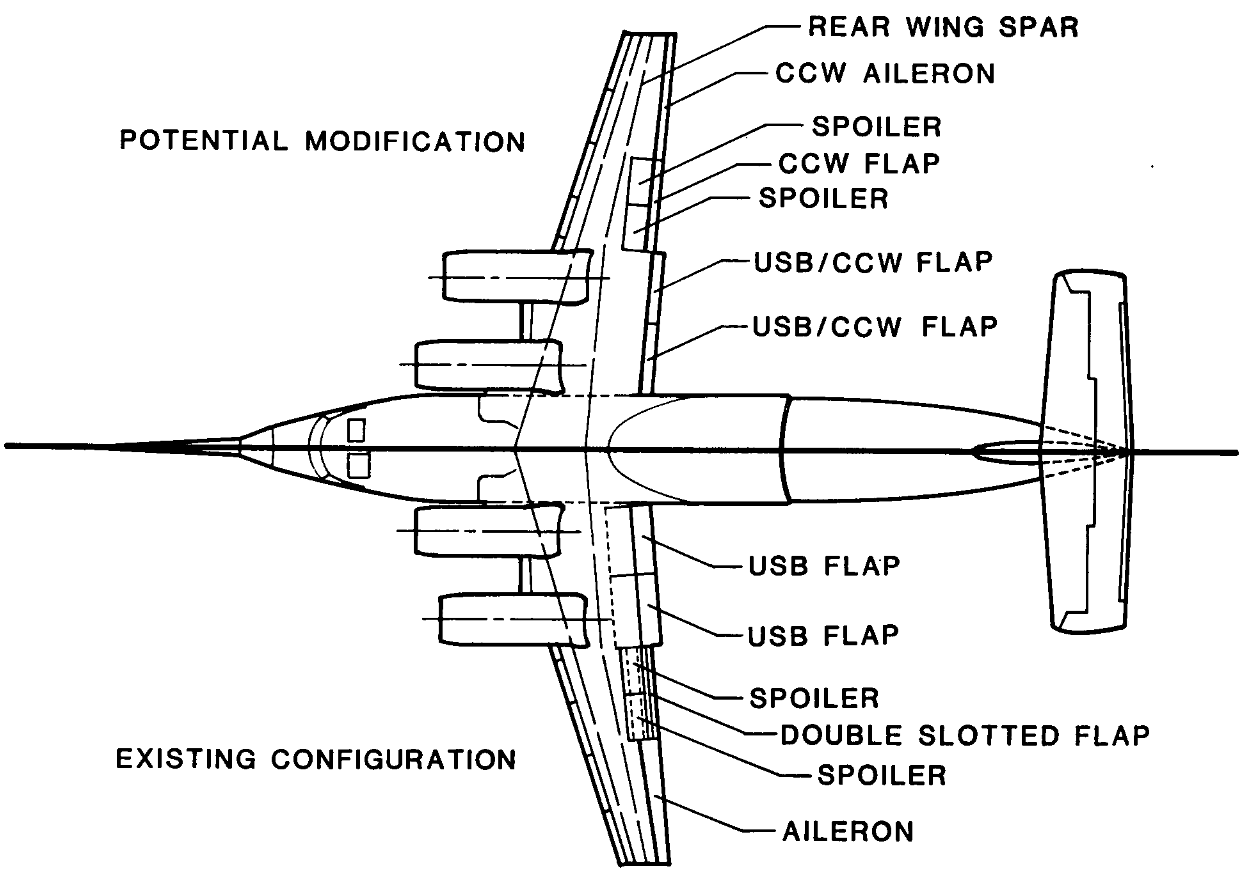


Figure 8. Comparison of existing QSRA wing to a potential USB/CCW modification.

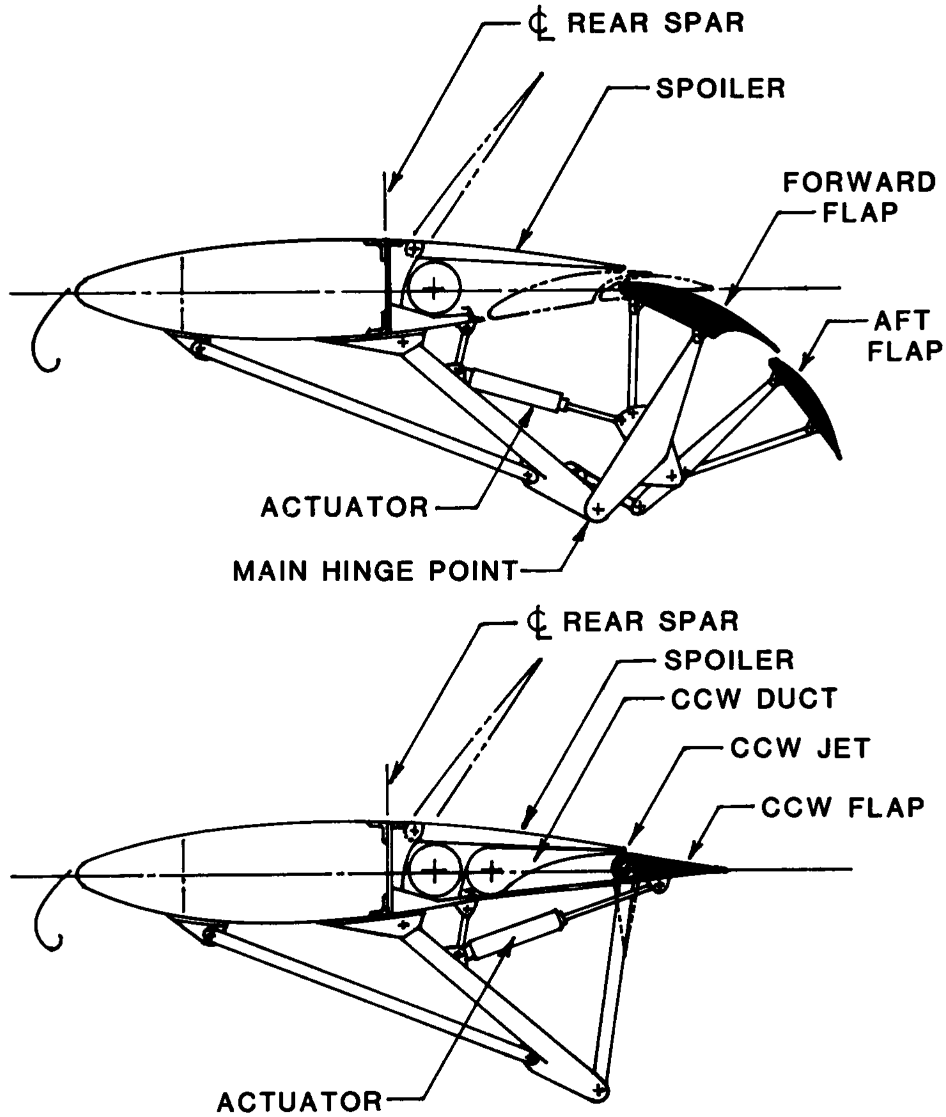


Figure 10. Comparison of existing double-slotted flap to a potential CCW trailing edge modification.

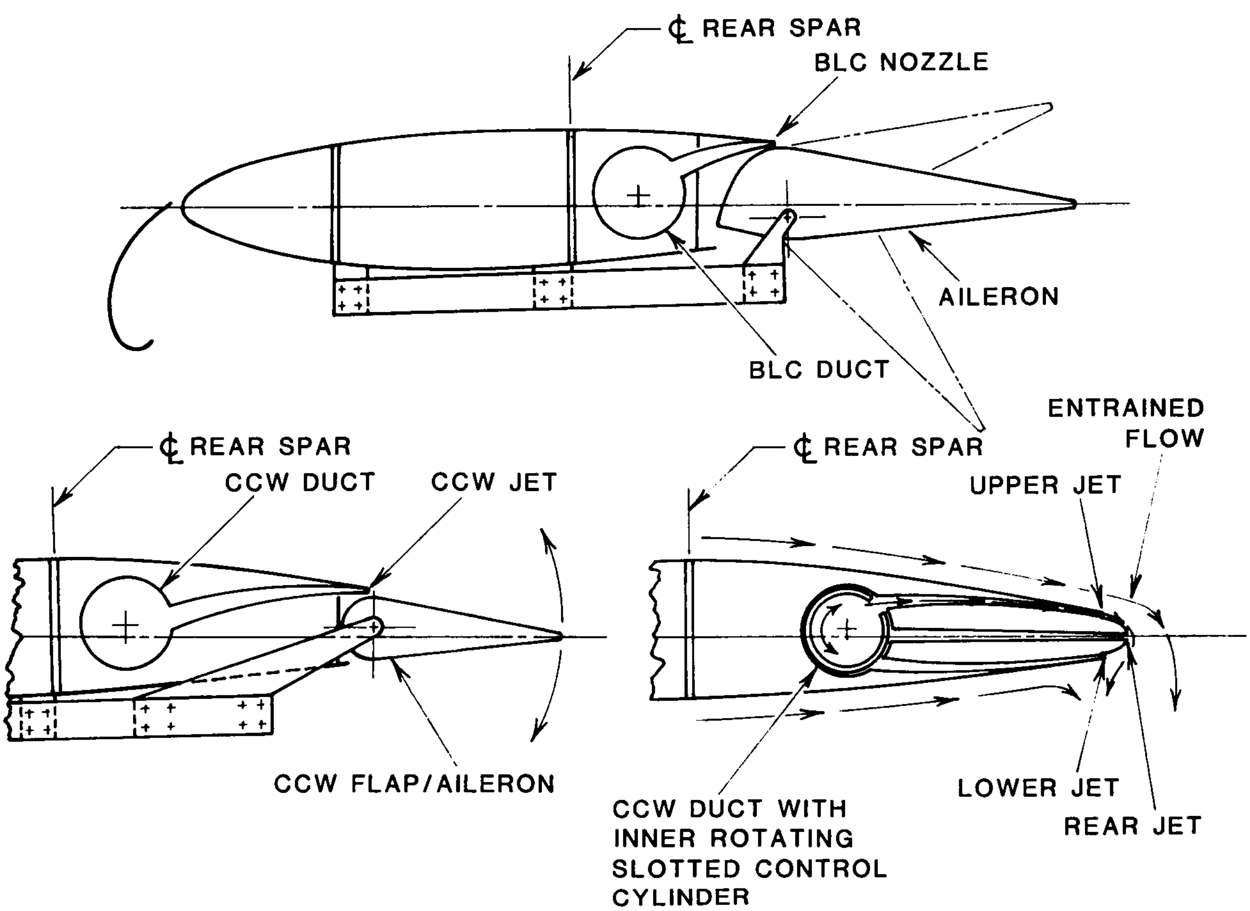


Figure 11. Comparison of existing BLC aileron to two potential CCW trailing edge modifications.

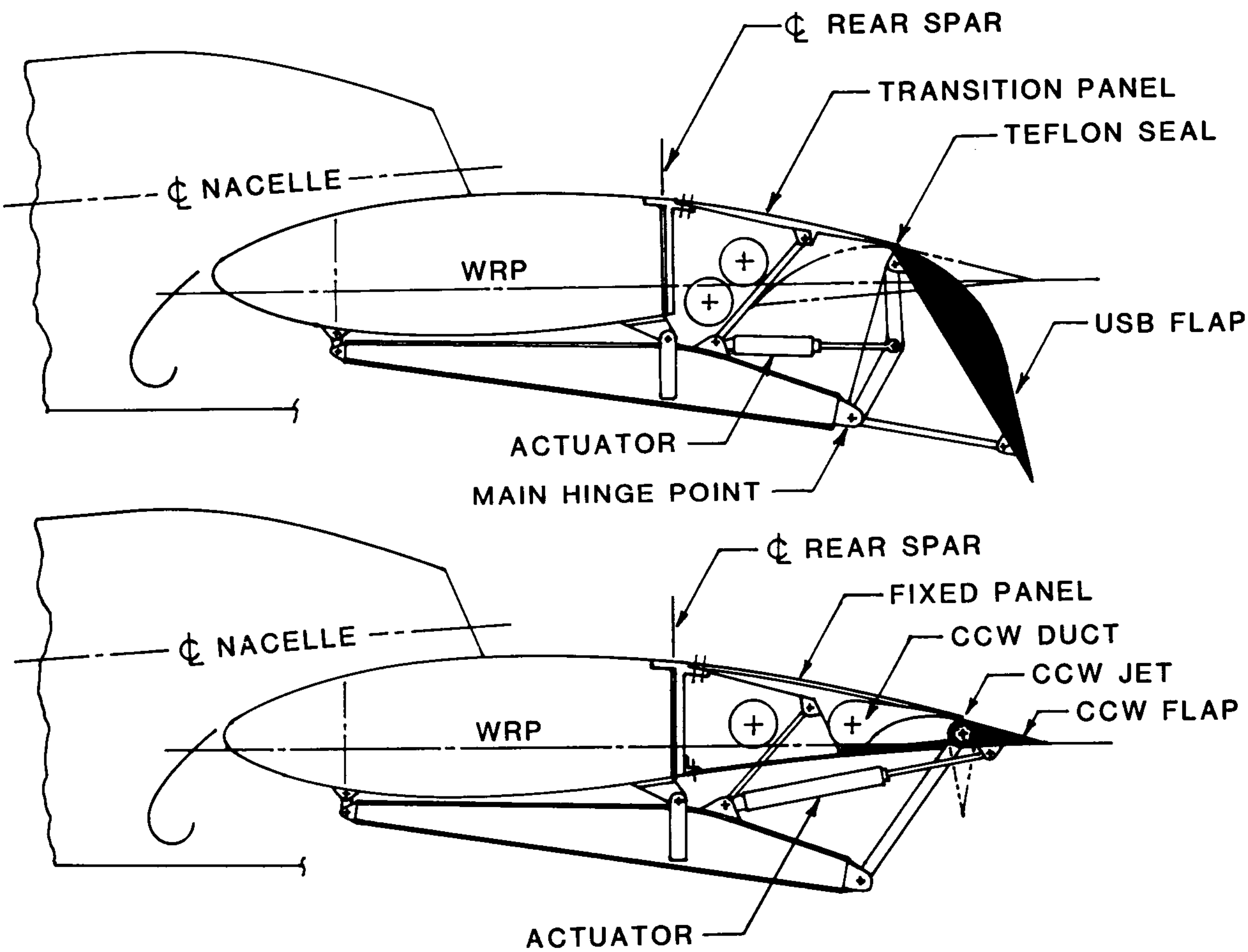


Figure 9. Comparison of existing USB Coanda flap to a potential USB/CCW modification.

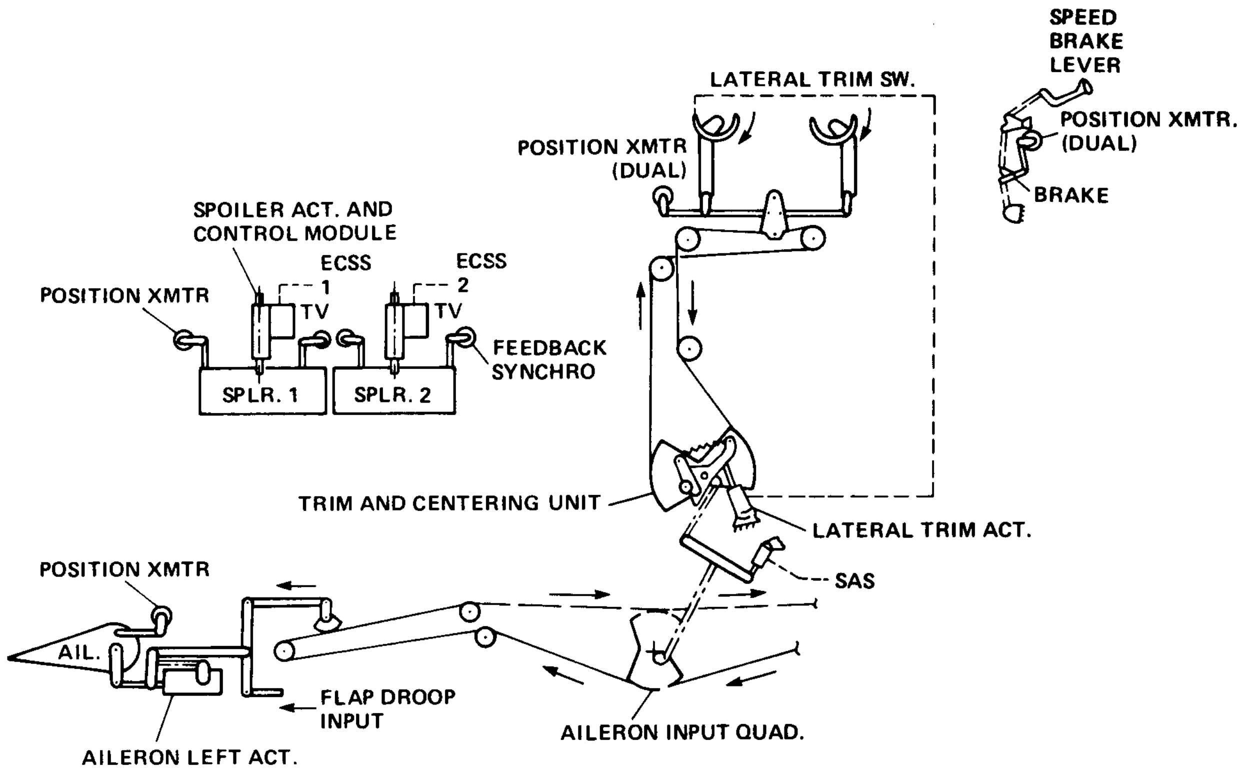


Figure 12. Existing QSRA lateral control system.

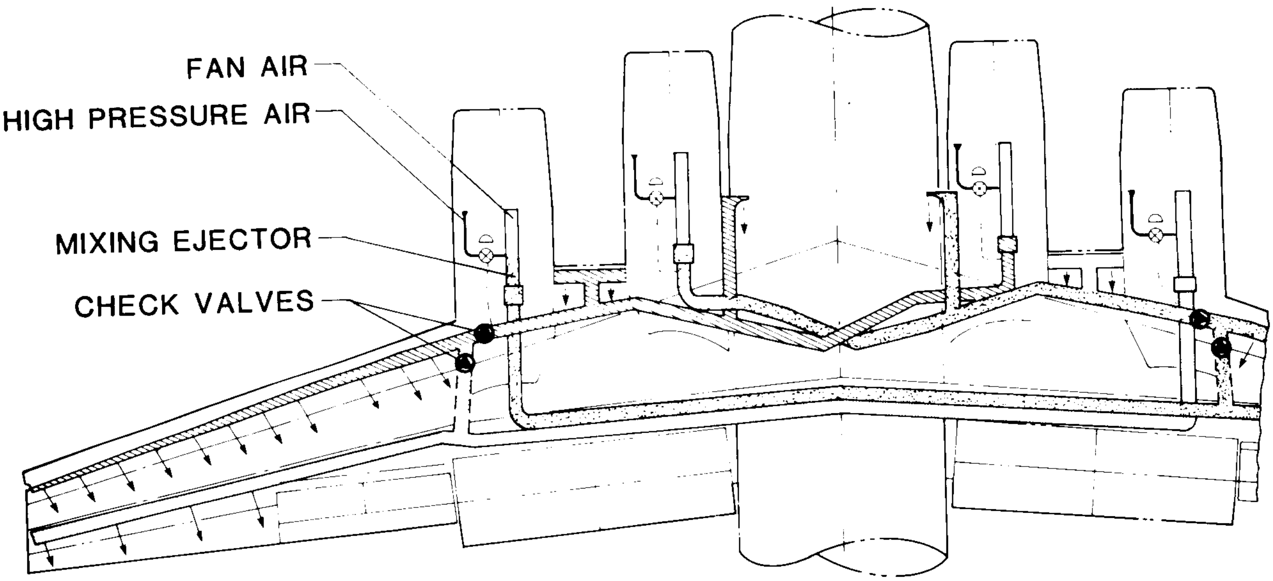


Figure 14. Original QSRA boundary layer control (BLC) system.

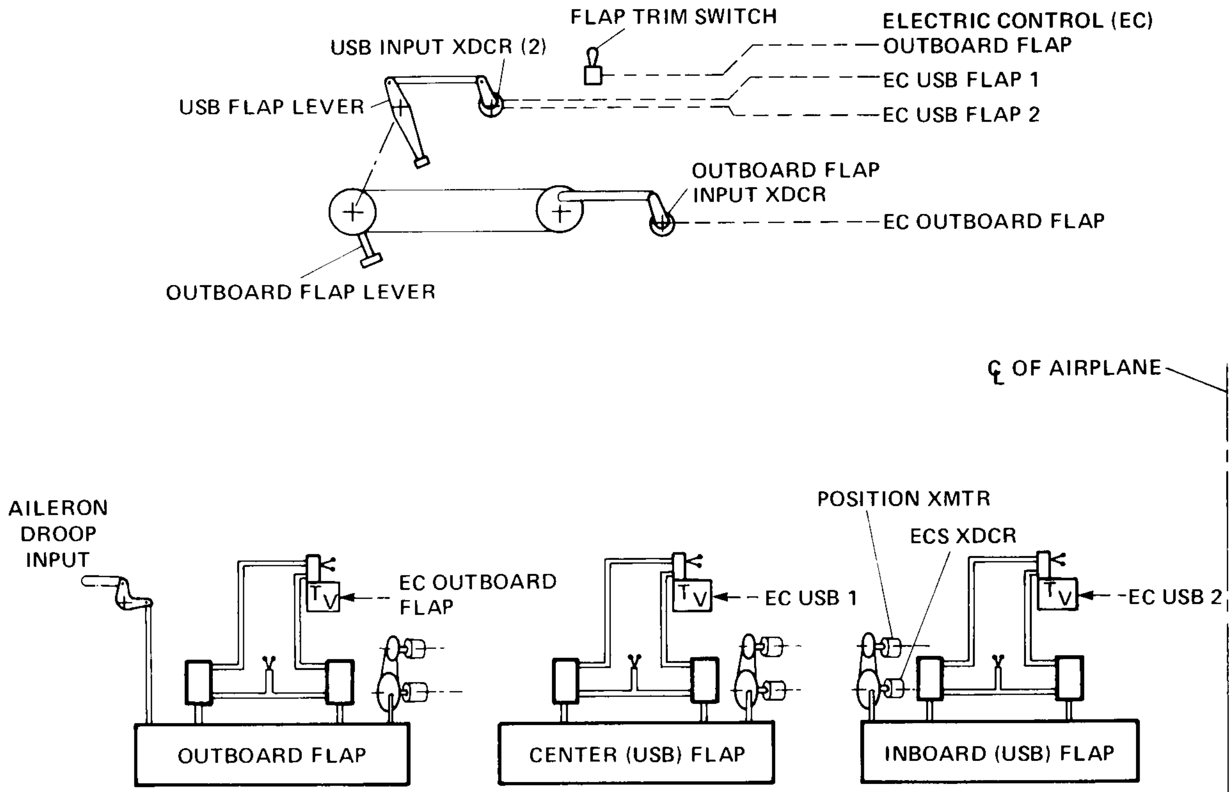


Figure 13. Existing QSRA flap control system.

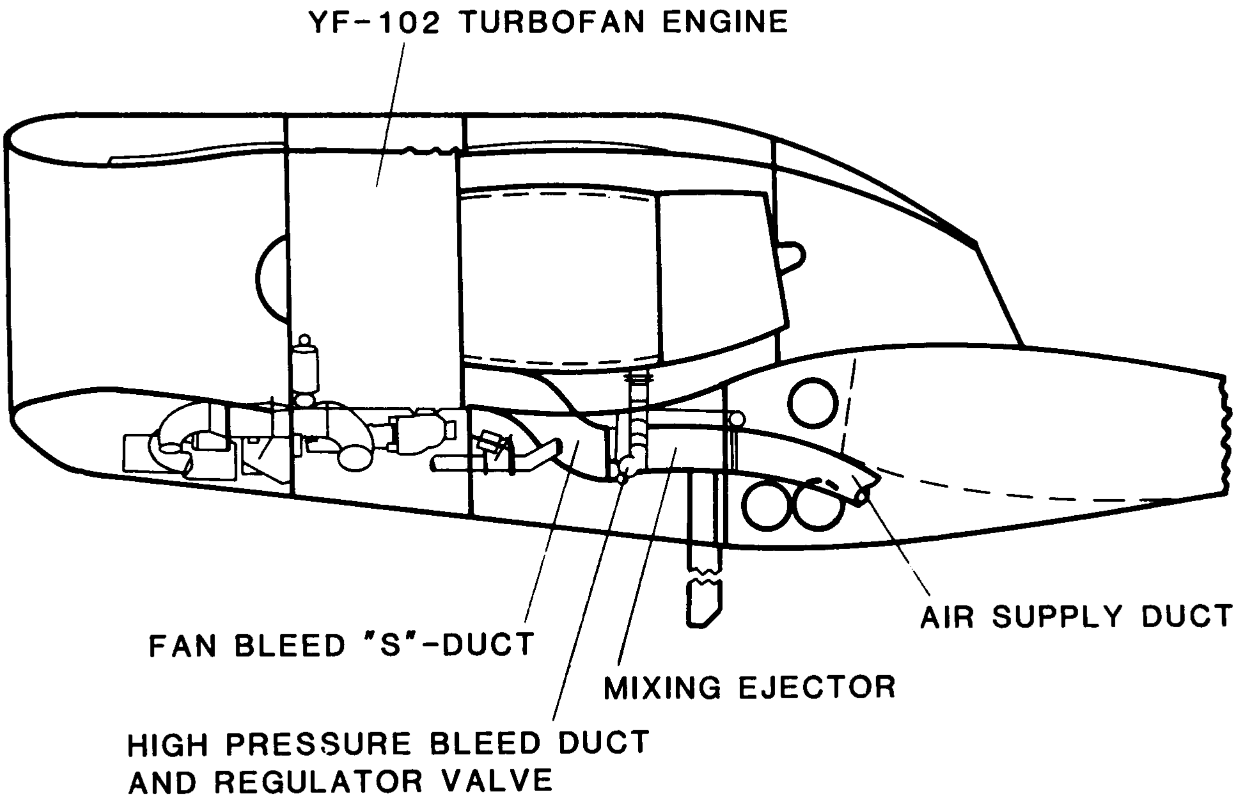


Figure 15. QSRA mixed fan and core bleed air supply system.

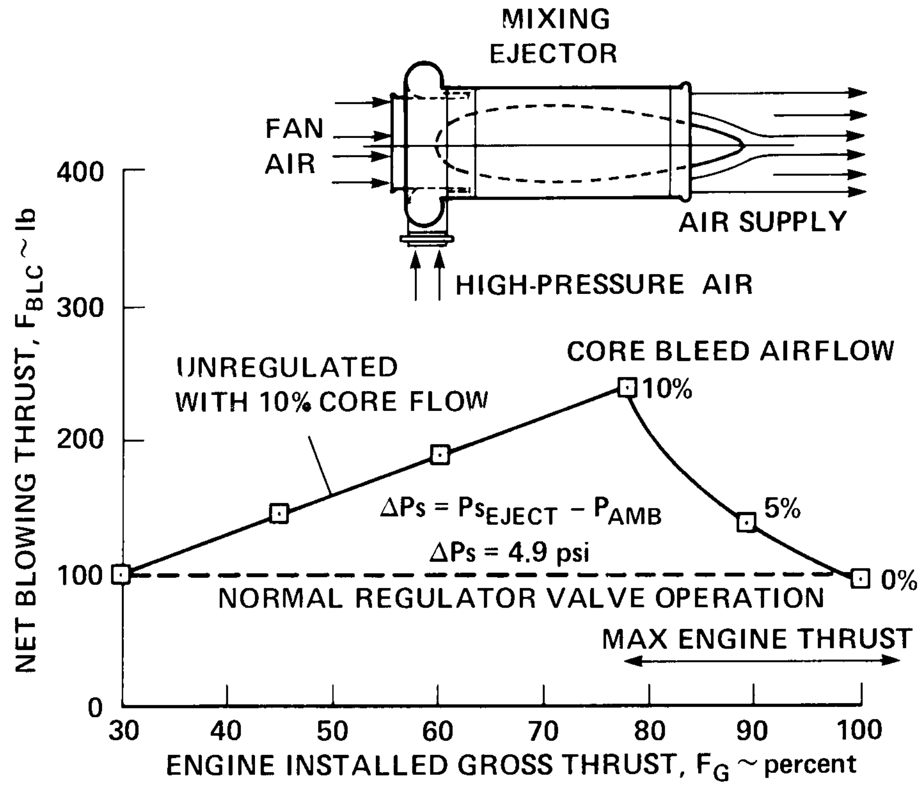


Figure 16. QSRA BLC net blowing momentum characteristics.

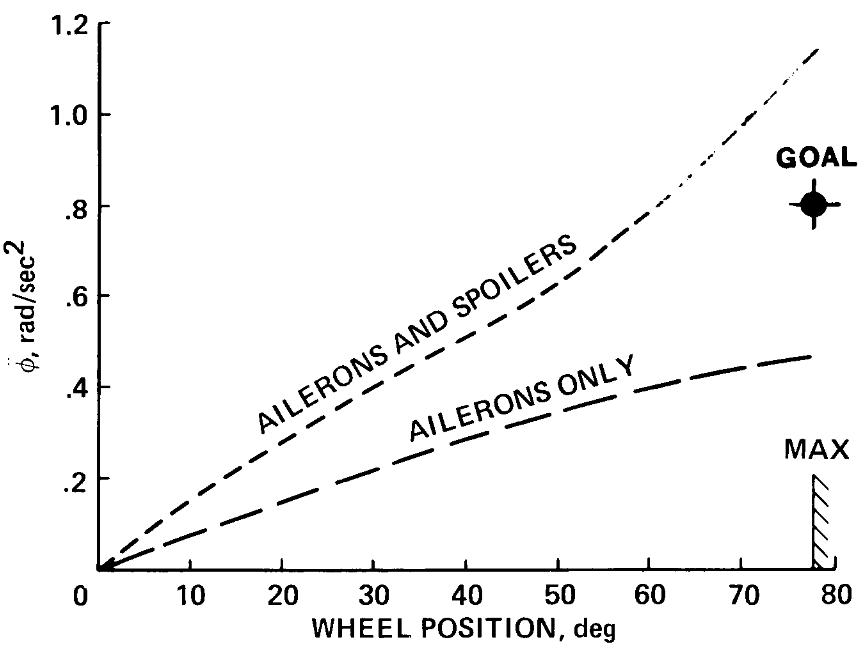


Figure 17. QSRA roll acceleration ($C_L$=4.6, weight = 48,000 lb).

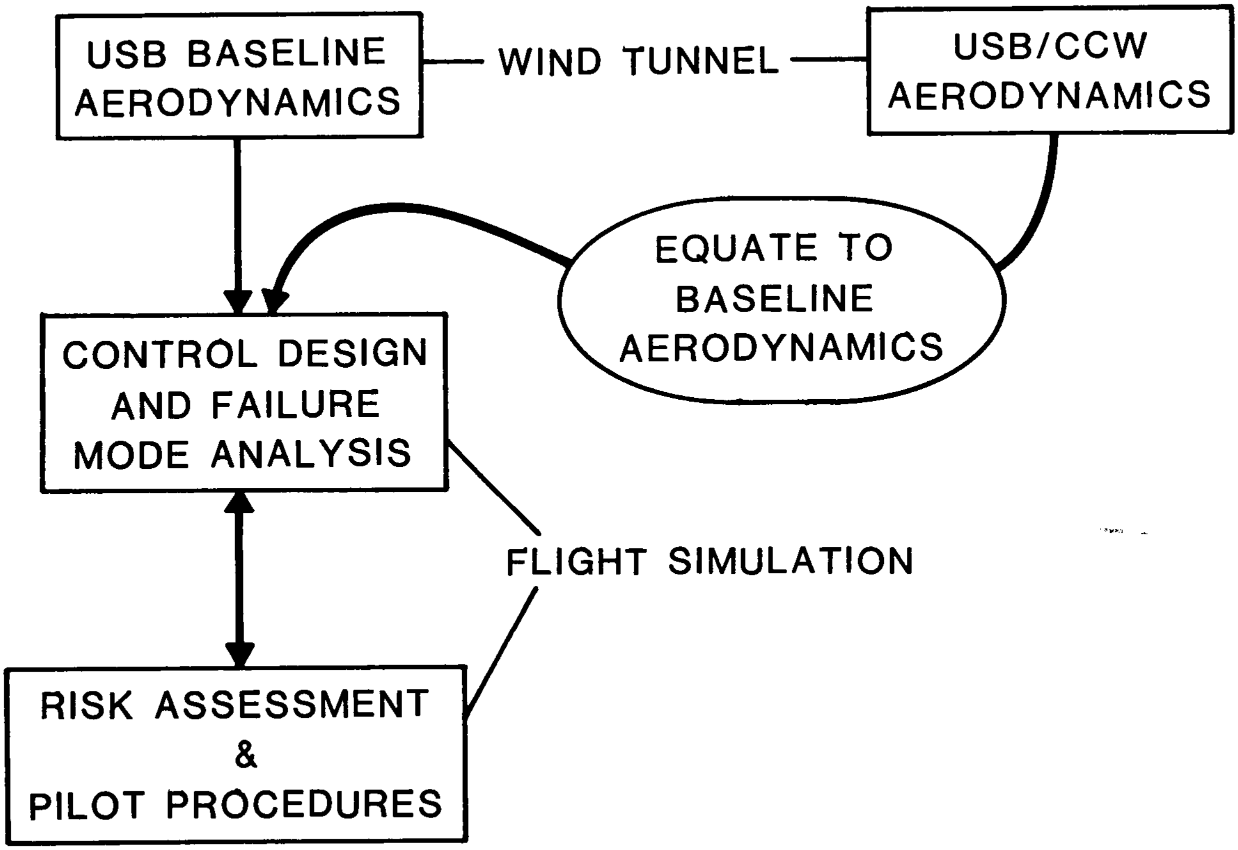


Figure 18. Utilization of USB/CCW aerodynamic data as input to QSRA risk assessment and pilot procedures.



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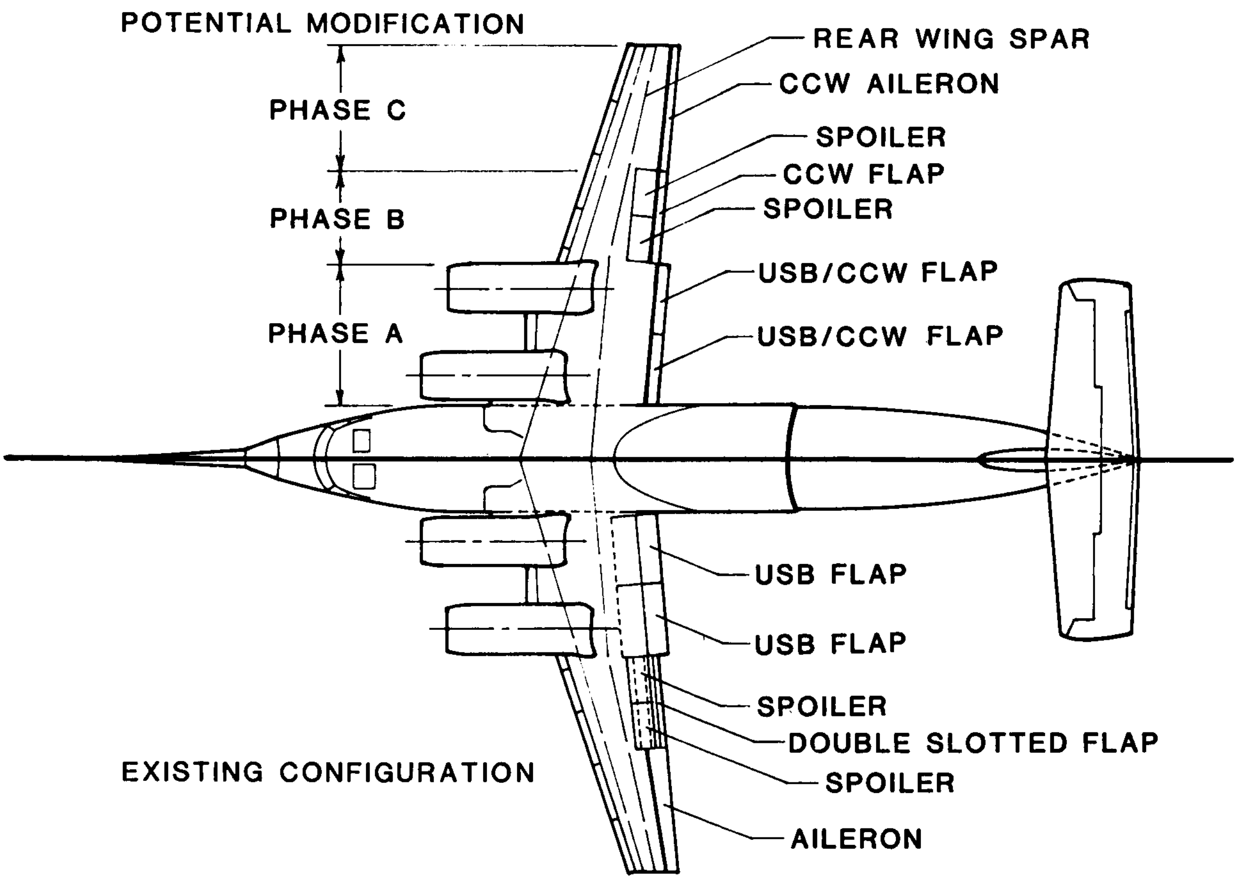


Figure 19. Three phase approach to the potential USB/CCW modification.