BENEFITS OF SPANWISE BLOWING AT TRANSONIC SPEEDS

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Abstract

This paper presents the results of an exploratory wind tunnel investigation demonstrating the beneficial effects of spanwise blowing at transonic speeds. A semi-span model with a basic wing geometry of $\Lambda_{LE} = 40^\circ$, $AR = 4$ and $\lambda = 0.3$ was tested at velocities up to a Mach number of 0.9. Spanwise directed nozzles, located on the wing, provided control of the shock induced separation (occurring at $M = 0.9$). Blowing momentum coefficients, C_μ, of less than 0.005 produced significantly improved longitudinal aerodynamic characteristics at attitudes where shock induced separation predominated. Such benefits are exemplified by the 16% improvement in the lift coefficient for axial force break afforded by a modest blowing level, $C_\mu = 0.002$.

The multi-color flow visualization technique developed by O.N.E.R.A. was used to provide a visual description of the nature of the flow separation and the control afforded by spanwise blowing. An indication of the buffet characteristics was provided by recordings of the trailing edge fluctuating pressures at several stations along the span of the wing. The dynamic characteristics of the root bending moment were also recorded to illustrate the integrated effect of fluctuations in wing loading. Both root mean square and power spectral density type information from the above recordings show the large increase in buffetting caused by the shock induced separation existing over a wide range of attitudes. In this range of angle of attack the blowing dramatically reduces the level of the pressure fluctuations and the vibrations at the wing root.

I. Introduction

Background

Eight years ago at the Seventh International Congress of the ICAS, M. Poisson-Quinton of O.N.E.R.A. and Dr. J. J. Cornish III of Lockheed-Georgia presented separate papers(1) (2) describing the use of a spanwise directed air jet to control the flow over lifting surfaces. A year earlier, at a joint AIAA/AHS meeting on VTOL Research, Design and Operation, C. J. Dixon of Lockheed described (3) some of the pioneering work related to this concept, termed spanwise blowing (SWB). These works, followed closely by publication of a study sponsored by the United States Naval Air System Command (4), provided a basis for international interest. Since that time period, and especially in the last five years, government agencies and airframe manufacturers in several countries have investigated the concept. Almost all of these investigations have been concerned with operations in the low speed regime. Typical studies (5) (6) (7) have demonstrated the feasibility and potential benefits to be gained from blowing from fuselage locations to stabilize the vortex resulting from the separation on sharp leading edge wings. This mode of application provides significant increases in lift at a given attitude as well as increased maximum lift capability.

The benefits of spanwise blowing are evidenced in other modes of application, as well. Typical of other applications are the results shown in Figure 1 of large scale tests (8) in the Lockheed-Georgia Low Speed Wind Tunnel.

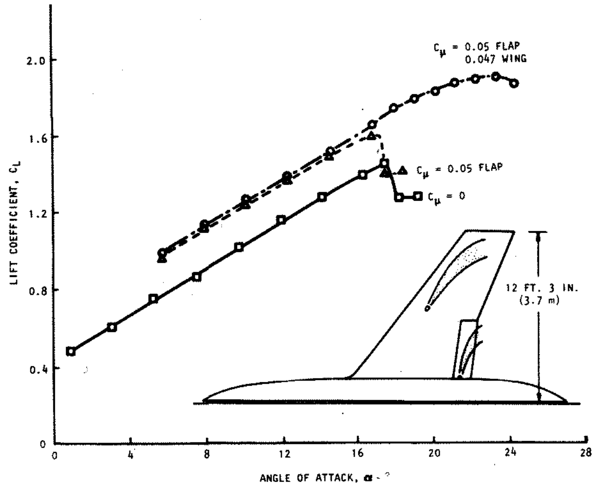


FIGURE 1 LARGE SCALE FLAP AND WING BLOWING

Here spanwise blowing is used to increase trailing edge flap effectiveness as well as provide greater lift capability of the main lifting surface by judiciously placing the nozzle to control the leading edge separation. Recent flight experiments with a jet powered Caproni sailplane have demonstrated the effectiveness of SWB as a lateral control device at conditions near stall (9). A view of this configuration is shown in Figure 2. The above are examples of more localized flow control that can be achieved by proper nozzle placement.

Transonic Applications

The need for increasing the maximum usable lift coefficient at high subsonic speeds is evidenced by the development of devices such as leading edge slats, strakes and variable camber techniques. When compared to the weight and complexity of such systems, the simplistic design approach of spanwise blowing is very attractive.

Demonstration of the feasibility of using spanwise blowing to control various types of flow separation at low speeds thus raises the logical question "Can SWB be also used effectively at transonic speeds to solve buffet or other high speed problems?". Limited tests (10) showed that control of the leading edge vortex could be achieved at high subsonic speeds ($M = 0.75$) with blowing momentum coefficient levels comparable to that used at low speeds. At these higher speeds, such a momentum coefficient implies a level of blowing that is impractically high relative to that available from typical propulsion systems. That the more global control can be achieved at high speeds was encouraging, however.

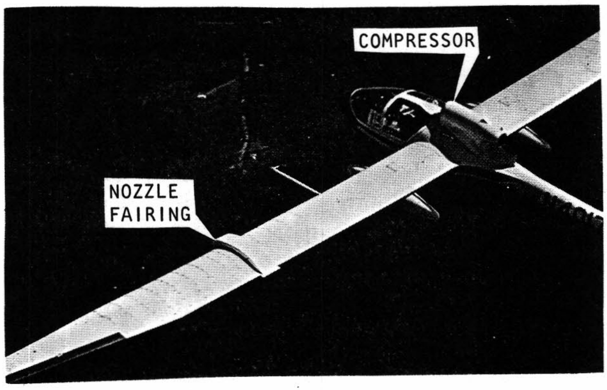


FIGURE 2 CAPRONI FLIGHT RESEARCH VEHICLE

Several years ago data from flight and wind tunnel tests of a fighter aircraft indicated that buffet/flutter problems might be caused by localized intermittent shedding of vortices. It was surmized that small amounts of blowing from properly located nozzles could stabilize this behavior. A brief feasibility experiment was conducted in the Lockheed-Georgia Compressible Flow Wind Tunnel (CFWT) using a modified semi-span wing and limited pressure instrumentation(11). As shown in Figure 3, blowing at a very low momentum coefficient reduced the magnitude of the fluctuating pressure, especially that of the broad band peak which occurred near the Strouhal frequency. Simple calculations also indicated that SWB could increase the effective sweep causing a delay in shock induced separation as well as reduced buffet intensity. While these results were not conclusive, they were encouraging in that they indicated that small amounts of blowing could influence unsteady flow at transonic speeds.

Concept of Present Study Program

From the above background evolved the concept of an exploratory test to further evaluate the feasibility of using SWB at high subsonic speeds. The general features of the program, as originally formulated, are shown below:

OBJECTIVE

- o Determine Effectiveness at High Subsonic Speeds
  - Low C_μ
  - Representative Configuration
- o Determine Best Mode of Application

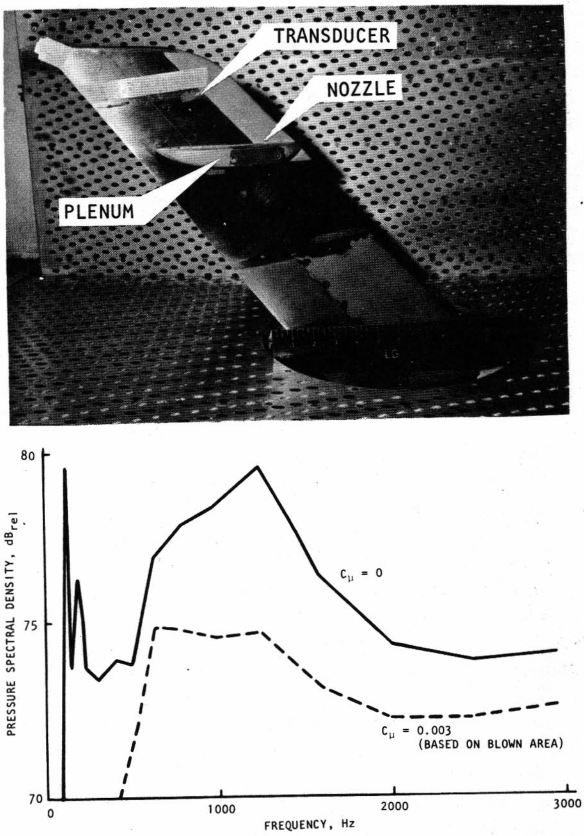


FIGURE 3 PRELIMINARY TRANSONIC STUDY

APPROACH

- o Exploratory Experiment
  - O.N.E.R.A. S3MA
  - $M = 0.6$ TO $M = 0.9$
- o Balance Data
- o Buffet Instrumentation
- o Two-Phase Test
  - Phase I: November 1976
  - Phase II: June 1977

The main objectives were to determine the effect of small, practical levels of blowing on separation related flow characteristics and to establish the mode of application having the highest potential. The compatible interests of the O.N.E.R.A. and the Lockheed-Georgia Company led to the formulation of a cooperative program using the combined expertise and facilities of both organizations. O.N.E.R.A. facilities at the Modane-Avrieux test center were used with O.N.E.R.A. personnel responsible for conducting the tests, instrumenting the model and reducing the data. The model, on-site test direction and data analysis were supplied by Lockheed-Georgia as a part of Lockheed's Independent Research and Development Program.

II. Experimental Program

All aspects of the experimental program were developed with consideration for the exploratory nature and basic objectives of the program as defined above.

Model Characteristics

The nature of the program directed the design of a model having certain necessary features.

- Aerodynamic characteristics representative of current configurations
- Size and strength to permit high Reynolds number testing
- Sized to test in available, economic wind tunnels
- Ability to vary nozzle configuration and placement
- Ability to instrument for buffet characteristics
- Flow visualization capability

The above features, together with the desire for economy of construction and test, led to the semispan design shown in Figure 4. The model was sized to permit testing in the Lockheed-Georgia CFWT, a 0.71 by 0.51 m blow-down wind tunnel, which also made it ideal for installation in the O.N.E.R.A. 0.78 by 0.56 m S3MA blowdown facility. There was no attempt to match any particular wing design: the particular planform and airfoil were selected to provide representative behavior over the subsonic speed range. The basic wing was tested during the first series of tests; the strake, flap and spoiler (cross-hatch in Figure 4) were tested during the second series. Twist and camber were not deemed necessary nor advisable for this type of exploratory testing.

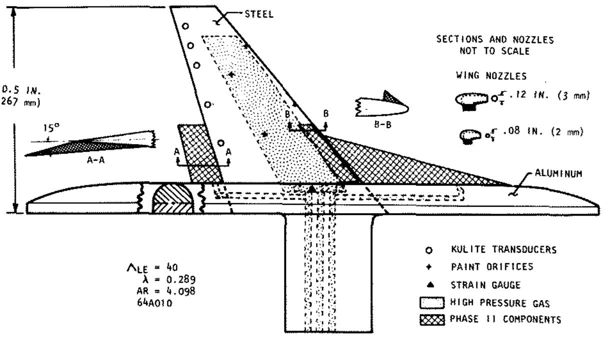


FIGURE 4 SEMI-SPAN WIND TUNNEL MODEL

The use of the plenum, which permitted a large region for possible nozzle locations, dictated the 10-percent thick airfoil. As shown in Figure 4, two sizes of wing nozzles were constructed with a screw-in design which permitted drilling and tapping the wing plenum to provide a wide range of nozzle arrangements. Plugs were used to seal these holes when not in use. Since the primary use of the nozzles was in the presence of separated flow, no special effort was made to streamline or otherwise minimize their drag. In addition to the wing nozzles, provisions were also made for larger fuselage nozzles at 20, 30, and 50 percent of the wing chord at the fuselage juncture. These nozzles were also of the screw-in variety. The provisions for blowing the removable strake and flap permitted small adjustments in location and orientation.

Instrumentation

In order to utilize flow visualization in an effective manner, the colored fluid techniques developed by O.N.E.R.A. were used. A tough white coating was applied to the wing and tubes were provided for ejection of the kerosene-diphenyl tetrachloride-colorant fluid at the surface of the wing as shown in Figure 4. The pattern was selected to provide a definition of the surface flow with a minimum of tubes.

The primary instrumentation for determining the buffet characteristics were Kulite XCQL-087-5 dynamic pressure transducers located along the trailing edge as shown in Figure 4. These pressure pickups were used during force runs to obtain root mean square (RMS) values of the local fluctuating pressures and, at selected attitudes, sufficient data to define the power spectral density of the unsteady pressures.

A 4-unit strain gauge system was installed on the lower surface of the wing near the fuselage juncture and was used to obtain root bending moment RMS and spectral data.

Test Facility

As stated previously, the S3MA blow-down wind tunnel at the O.N.E.R.A. test center at Modane-Avrieux was used for both test series. Figure 5 provides an illustration of the test section pertinent characteristics. The model is attached to a moving side wall that opens to permit easy access to the model, most desirable due to the number of nozzle changes made during the tests. The transparent side wall of the opposite sides of the test section permitted visual and photographic observation of the surface flow during the test that complemented the 35mm still photographs taken from a camera mounted above the model in the plenum. Automatic Mach number control provided, in general, a Mach number ±0.003 of that specified.

An air bridge across the 6-component balance prevented the high-pressure lines for the nozzles from influenceing the balance reading. Compressed nitrogen was used for the blowing gas. The nozzle flow was calibrated against a plenum pressure reading and this pressure was used to establish the blowing level with pressures up to 12 bars used during the course of the tests.

The force data and RMS values were recorded on tape and computer reduced and plotted, providing the rapid turnaround necessary in the study. No wall type corrections were used and all testing was with natural transition. All balance data were reduced to the same reference area.

Conduct of Tests

Exploratory programs which are heuristic in nature can often be inefficient from a viewpoint of tunnel occupancy time. In order to minimize such inefficiency, a special cooperative effort was required between Lockheed and O.N.E.R.A. personnel in the scheduling of the different type of runs, data reduction and evaluation.

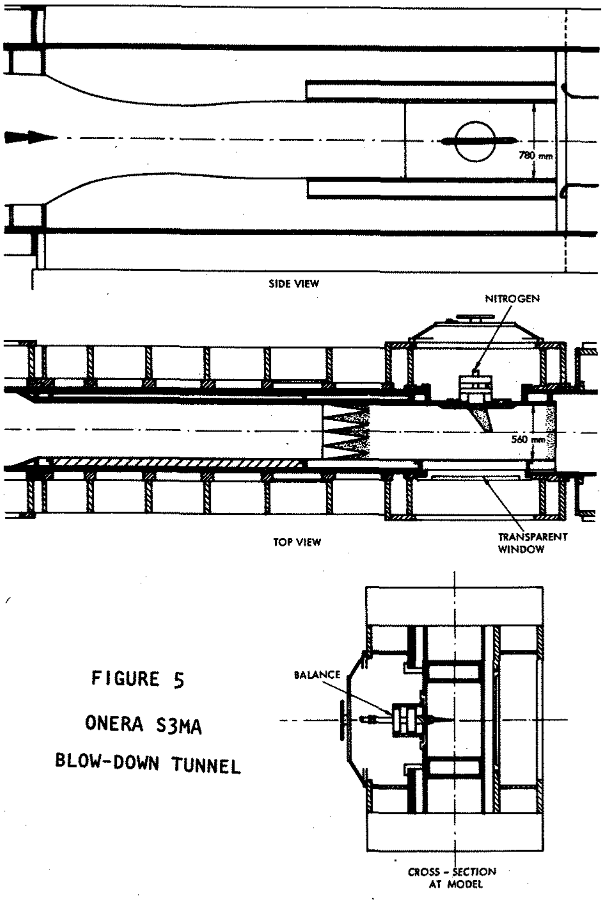


FIGURE 5

ONERA S3MA

BLOW-DOWN TUNNEL

DOWNSTREAM VIEW

The first portion of each series of tests was to establish the characteristics of the model without blowing. This consisted of obtaining force data at the desired Mach numbers throughout the angle of attack range. From an evaluation of the force data, certain angles of attack were selected for power density spectral data and flow visualizations. Since the flow visualizations required special model setup, the scheduling was organized to recognize pump-up time, model change time and data turn-around time. In order to maximize the amount of information from the flow visualization, a color video system was used that permitted playback and detailed observation of shock and separation patterns. It was from these flow visualization studies that the initial location of the nozzles was derived.

An indication of the number and type of tests conducted in the two series of tests is shown in the following:

o CONDITIONS

M	$R_N \times 10^{-6}$	α	C_μ
0.9	3.3	0 → 16,30	0 → 0.005
0.8	3.6	0 → 18,30	0 → 0.005
0.6	3.9	0 → 30	0 → 0.005
0.3	1.3	0 → 40	0 → 0.035

Free Transition

o CONFIGURATIONS

Phase I: Basic Wing, Nozzle Arrangements

Phase II: Wing Plus Strake, Nozzle Arrangements
Spoiler (Basic)
Flap (Basic, Strake)

o DATA

Balance:

6-Component with Air Bridge
Phase I: Continuous Pitch
(1°/Sec)

Phase II: Pitch/Pause
(2 Sec)

No Wall Corrections

Transducer and Root Strain Gauge:

Rms - 2 Sec, All Runs
Spectral - 15 Sec, Selected α

Flow Visualization

Five-color Technique - Video, 16mm movie, 35mm Still

Selected α

In addition to model configurational differences, there were certain other differences in the conduct of the two series brought about, in part, by the learning process associated with the first phase. An existing force balance was used for the Phase I tests. A new balance, with better resolution, especially in drag, was constructed for the Phase II tests. Repeatability was good for both series of tests, however. The tunnel floor perforation pattern also differed for the two tests. Such differences are not considered of consequence in the accomplishment of the objectives of the investigation.

During Phase I, force and RMS data were taken with continuous pitch at about 1°/sec. with data acquisition at about 3 points per second. RMS values were based on use of the data taken 2 seconds before and 1/2 second after each data point. While the force data appears accurate, the RMS data is difficult to evaluate using this technique. During Phase II, therefore, a pitch-pause technique was used with both force and dynamic data taken while pausing at specific angles of attack for a period of about two seconds.

Special runs were made to obtain spectral data during Phase I. This type of data recording was incorporated with the force runs in Phase II. For both series of tests a limited number of attitudes were specified for such data and each data point required 15 seconds acquisition time.

III. Test Results

The results of this investigation show that spanwise blowing can indeed be used effectively at transonic speeds. The primary mode of application is in the control of shock induced separation. Low, practical levels of jet momentum provide this control which results in the delay of the onset of separation, significant reduction in buffet intensity and favorable effects on longitudinal characteristics.

The dominance of shock induced separation was established early in the Phase I tests. The control of this form of separation was, therefore, emphasized during subsequent tests and other modes of application of SWB were investigated in only a limited manner. Some of these other modes considered strake and leading edge vortex control, but nozzle location and blowing quantities were inadequate for the high speed vortex control. Control of the flow behind the spoiler was also ineffective. The flap showed high effectiveness without blowing, indicating a minimal separation, and blowing thus showed no improvement. The results of these limited investigations should be considered inconclusive rather than completely negative, however.

A number of nozzle arrangements were investigated as part of the evolutionary process to establish an effective configuration for control of shock induced separation at $M = 0.9$. For the sake of brevity the results of these investigations will not be discussed in detail but a few words are appropriate for the sake of completeness.

The effectivity of the jet is, in part, determined by its velocity characteristics. Tentative criteria, using jet centerline velocity decay calculated by the method of Abramovich $^{(12)}$, indicate that the jet velocity should be approximately equal to the velocity normal to the jet axis. The extent of the effectiveness of a given jet can thus be estimated. This approach explains the fact that a dual nozzle arrangement was shown to be more effective than a single nozzle. At the same total C_μ, the extent of the wing affected by a dual nozzle is about 50% greater than that influenced by a single nozzle. While substantial improvements were provided by the single nozzle, all subsequent data were obtained using two of the approximately 3mm diameter nozzles. While the location on the wing differed for the basic and straked wing the direction of all nozzles was swept about 10° aft the local wing element line -- an orientation that allows for the jet expansion. One test was conducted with the nozzles pointed directly aft with an effectiveness similar to that of a single nozzle - positive, but not as beneficial as the spanwise-directed dual nozzle arrangement.

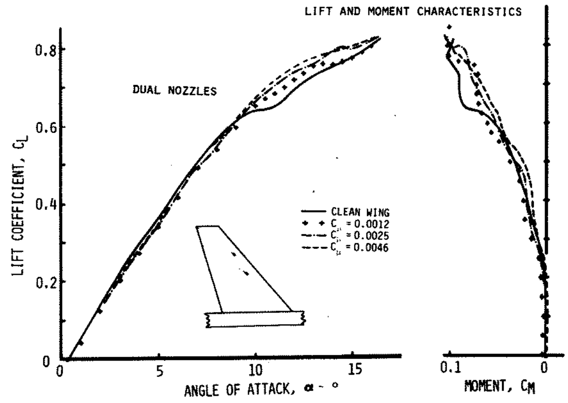
The following data will present the effectiveness of spanwise blowing for the nozzle configuration shown most effective for the $M = 0.9$ condition. This condition will be emphasized although benefits at other speeds will be demonstrated. In all discussions the blowing momentum coefficient, C_μ, is the total of the two nozzles and is calculated by

$$C_\mu = \frac{m_i V_i}{q S}$$

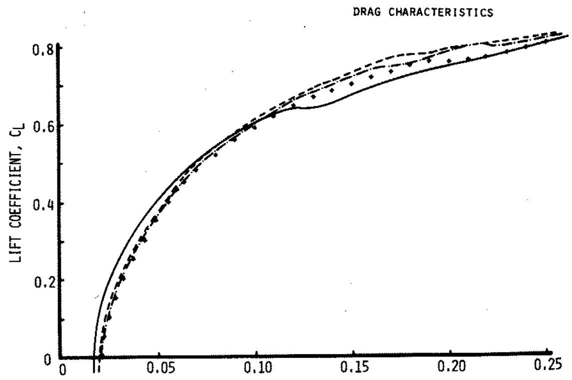
where m_i = Total mass flow
V_i = theoretical isentropically expanded
q = freestream dynamic pressure, $1/2 \rho V^2$
S = wing reference area (same for all configurations)

Longitudinal Characteristics

Figures 6 through 10 show the longitudinal characteristics at $M = 0.9$, 0.8, 0.6 and 0.3 for the 40° swept wing with and without blowing. As stated before, the nozzle configuration is that determined as best at $M = 0.9$. The configuration consists of the two smaller nozzles; both are located at the 25% chord location with one at 50% span, the other at 70%. These positions are not necessarily the optimum even for $M = 0.9$, but represent the best of those tested during the allotted test period.



a. LIFT AND PITCHING MOMENT



b. DRAG CHARACTERISTICS

FIGURE 6 BASIC WING LONGITUDINAL CHARACTERISTICS $M = 0.9$

At M = 0.9 (Figures 6 and 10), the improved flow generated by the blowing is reflected in increased lift at angle of attack and reduced drag at a given lift over a fairly significant range of attitudes. The lift (or attitude) for the pitching moment break is also substantially increased. The most dramatic effect is that illustrated in Figure 10 by the increase of the angle of attack at which the axial force break occurs. An indication of the onset of separation is provided by this break in the axial force characteristics. At the lower angles of attack where separation is minimal, interference effects of the nozzles are obvious especially in the axial force. Since the primary concern is at conditions where separation has occurred and the nozzle is immersed in at least partially separated flow, no attempt was made to fair the nozzle or otherwise minimize the interference effects. Tests conducted with the nozzle in place and no blowing showed little difference at the higher attitudes where separation exists. In an actual application, fairing, pop-up or possibly swiveling nozzles could be utilized once the location had been finalized.

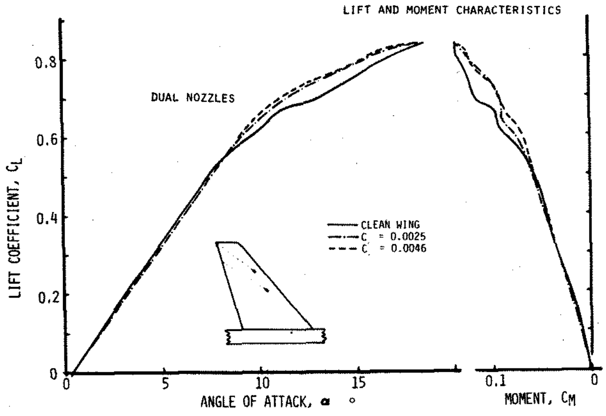


FIGURE 7 BASIC WING LONGITUDINAL CHARACTERISTICS, M = 0.8 LIFT AND PITCHING MOMENT

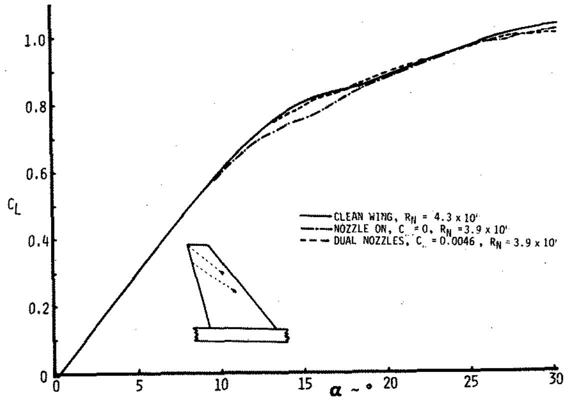


FIGURE 8 BASIC WING LONGITUDINAL CHARACTERISTICS, M = 0.6 LIFT

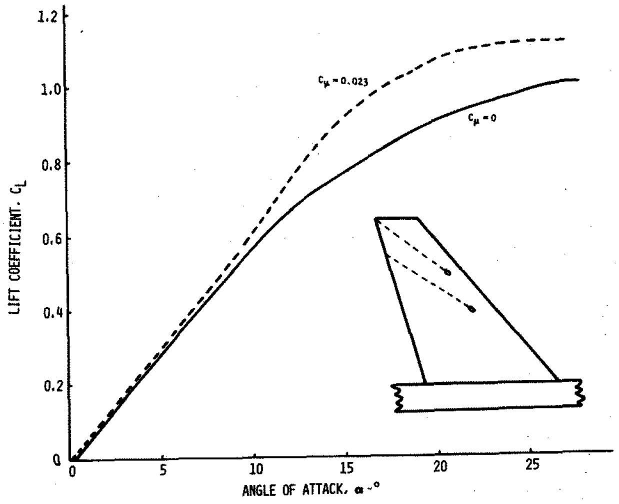


FIGURE 9 BASIC WING LONGITUDINAL CHARACTERISTICS, M = 0.3 LIFT

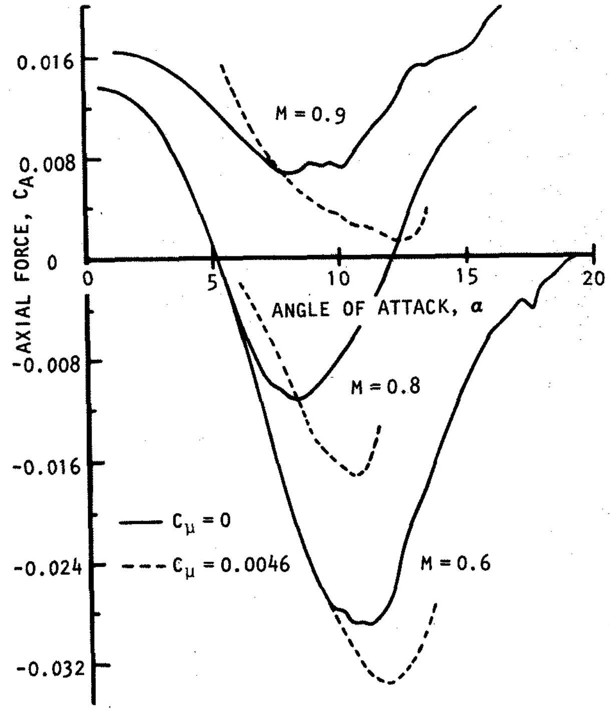


FIGURE 10 BASIC WING AXIAL FORCE CHARACTERISTICS

Figure 7 illustrates similar effects at M = 0.8 but with a somewhat reduced blowing effectiveness. As stated earlier, no attempt was made to optimize the nozzle arrangement for effectiveness at other than M = 0.9. Even though the nozzle location is best for M = 0.9 the same low blowing momentum gives substantial improvement in the low speed maneuver at these low Mach numbers of 0.3 and 0.6. No shock-induced separation exists at M = 0.6 (Figure 8), but when comparing the M=0.6 results at the same Reynolds number, there is minimal, but significant, control over the large vortex caused by leading edge separation. It must also be noted that increasing Reynolds number does delay the angle of attack for which vortex lift starts, but the amount of vortex lift is nearly independent of Reynolds number. Vortex control is more obvious for the M = 0.3 conditions shown in Figure 9.

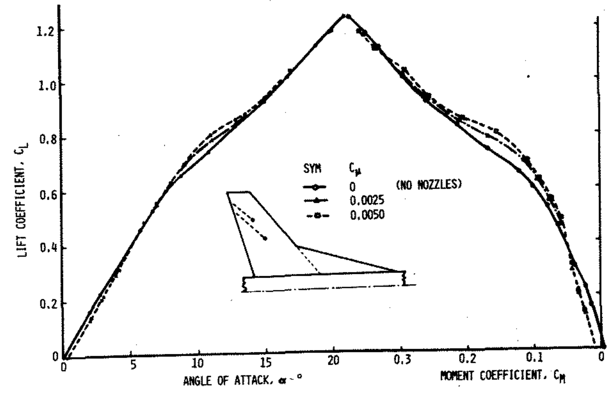
The shock pattern at M = 0.9 for the straked configuration was similar to that of the basic wing. The best location for the nozzles was different, however, indicating that the strake had influenced shock position and strength. The spanwise nozzle locations for the straked wing were the same as those for the basic, 50% and 70%, but located at 50% and 55% chord location, respectively. Figure 11 illustrates that the influence of blowing on the straked configuration was quite similar to that for the basic wing. Again, improvements in all aspects of the longitudinal characteristics show the beneficial effects of blowing.

Flow Visualization

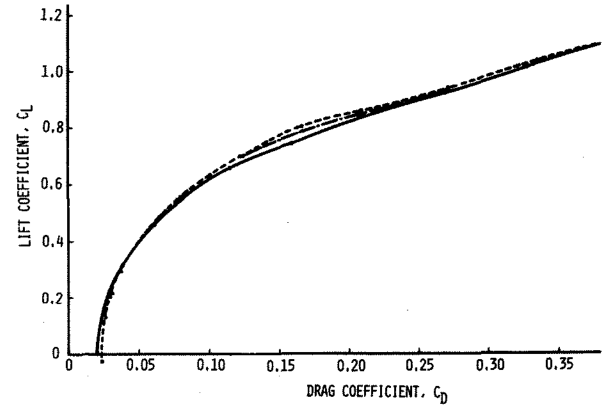
The multi-color flow visualization technique developed by O.N.E.R.A. and discussed previously was used to determine the separation patterns and hence provide guidance to nozzle placement. The use of the color video system was invaluable and permitted such decisions to be made almost immediately after a test run. The 35mm color slides permitted more detailed study during later stages of the test program. Interpretation of the effects and apparent anomalies shown by the fluctuation pressure measurements demonstrated the desirability of the surface flow visualization. Some of the more pertinent surface flows are shown here to illustrate the flow behavior as well as the usefulness of this type of information.

Of the many photographs obtained during this investigation, those depicting the flow at M = 0.9 and $\alpha = 9^\circ$ are the most interesting and informative. At these conditions both wing configurations exhibit strong shock-induced separation without blowing and demonstrate a pronounced effect of the blowing.

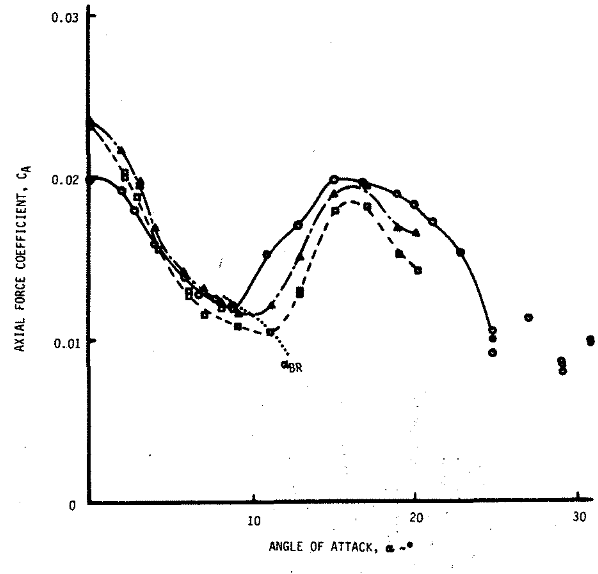
At other attitudes and conditions the visualization was useful in defining the shock and, at the higher angles of attack, the large vortex eminating from the fuselage-wing and fuselage-strake juncture. This form of vortex flow was the dominant feature at angles of attack greater than about 11 degrees.



a. LIFT AND PITCHING MOMENT



b. DRAG



c. AXIAL FORCE

FIGURE 11 STRAKED WING LONGITUDINAL CHARACTERISTICS, M = 0.9

The upper portion of Figure 12 shows the basic wing without blowing with the outboard 50 percent of the wing indicating both leading edge and shock-induced separation. The flow appears highly three-dimensional with one, and possibly two, vortices being emitted with their axes perpendicular to the wing. The addition of blowing radically changes this pattern (bottom photograph of Figure 12). While at least one vortex still appears to emerge from the wing, its location and apparent strength is altered. Little separation is indicated outboard of the outboard jet, although the absence of a paint orifice in this region hampers the observation. The photograph also indicates a shock ahead of the inboard nozzle and jet that is similar to that observed at lower attitudes.

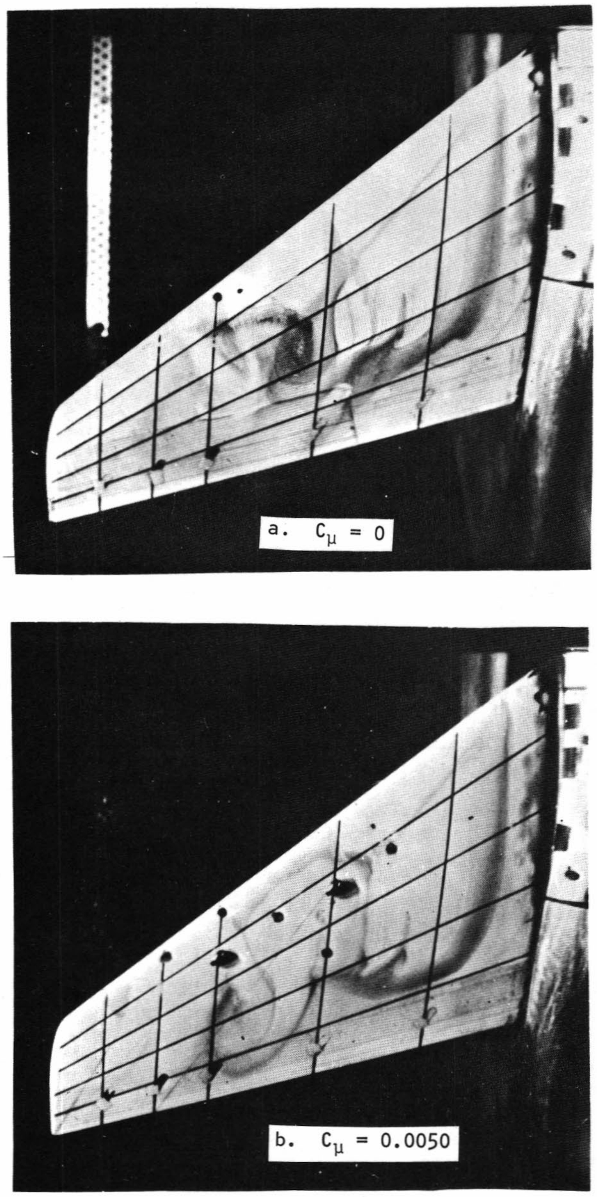


FIGURE 12 BASIC WING SURFACE FLOW
$M = 0.9$, $\alpha = 9^\circ$

The same condition ($M = 0.9$, $\alpha = 9^\circ$) is shown in Figure 13 for the wing-strake combination. While the shock pattern is somewhat different from that of the basic wing, the predominant feature is still the strong outboard shock with both shock-induced and leading edge separation. The vortex emitting from the wing is also indicated. The outboard "paint" orifice is functioning in this test and adds to the description of the flow patterns. The blowing is seen to move the separation quite far out the span of the wing. The aft-placed nozzles (relative to the basic wing location) are in the flow behind the shock and appear to penetrate further than the jets on the basic wing. Two small vortices, one behind the inboard jet and one between the tip and the outboard nozzle, are also indicated.

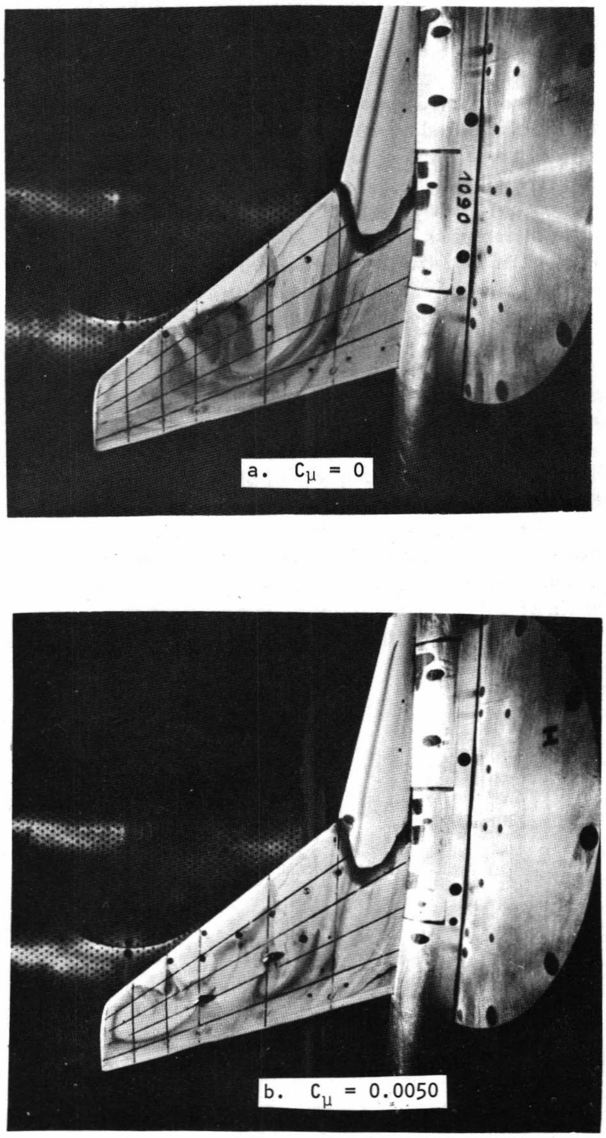


FIGURE 13 STRAKED WING SURFACE FLOW
$M = 0.9$, $\alpha = 9^\circ$

Buffet

One of the principle objectives of this investigation was to determine effect of spanwise blowing on the onset and magnitude of buffet. Although a precise determination of buffet characteristics requires an aero-structural analysis, various aerodynamic quantities can be used as indicators of both absolute and relative effects of configuration perturbations. The use of such indicators is also more appropriate due to the exploratory nature of the study and the representative, rather than specific, nature of the model.

The behavior of the balance measured forces and moments is descriptive of the separation (hence buffet) and the manner in which the axial (chord) force varies with the angle of attack is often used as an indication of buffet onset. The use of this latter criteria is admittedly subjective but does permit quantifying the effects of configurational perturbations on separation characteristics of a global nature.

A more fundamental insight into the nature of the buffet is provided by measurements of the unsteady aerodynamic forcing functions and their effect on the model. The five Kulite transducers provide more localized information concerning the fluctuating flow while the strain gage indicates an integrated effect at the root. During Phases I and II, the Kulites and strain gage provided spectral data at selected angles of attack, while RMS data were obtained at all angles during Phase II.

An overview of the relationship of the above criteria and the effect of blowing on these indicators of buffet is provided by the next series of figures.

Figure 14 shows the effect of blowing on the axial force characteristics of the basic wing at M = 0.9. Superimposed on this figure are spectral data obtained from the Kulite at the 90% span location. The favorable impact of blowing is obvious as indicated by the increased angle of attack for the axial force break and the reduced magnitude of the fluctuating pressures at the 90% span location.

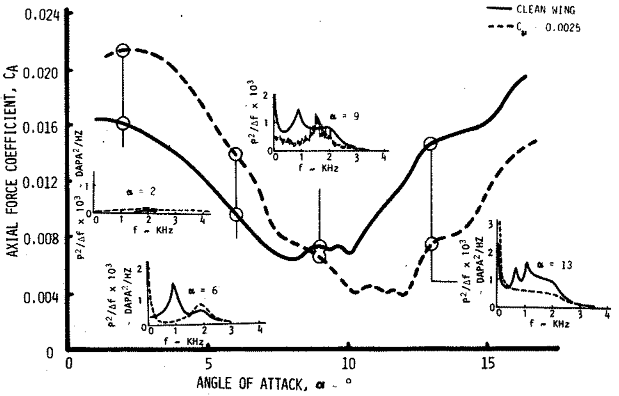


FIGURE 14 BASIC WING BUFFET INDICATORS, M = 0.9

The relationship of several aerodynamic separation/buffet indicators are shown in Figure 15 for the straked wing at M = 0.9. While the combined use of flow visualization and the complex Kulite RMS and spectral data are required to fully interpret the data and explain some of the apparent anomalies, the summary type data of Figure 15 corroborates the favorable effects of blowing. Several noteworthy observations are indicated by the data.

- The favorable effects of blowing are evident over a range of angles of attack from about 6 to 14 degrees.
- The angle of attack where spanwise blowing provides the greatest benefit is about 11° as shown by all four types of indicators.

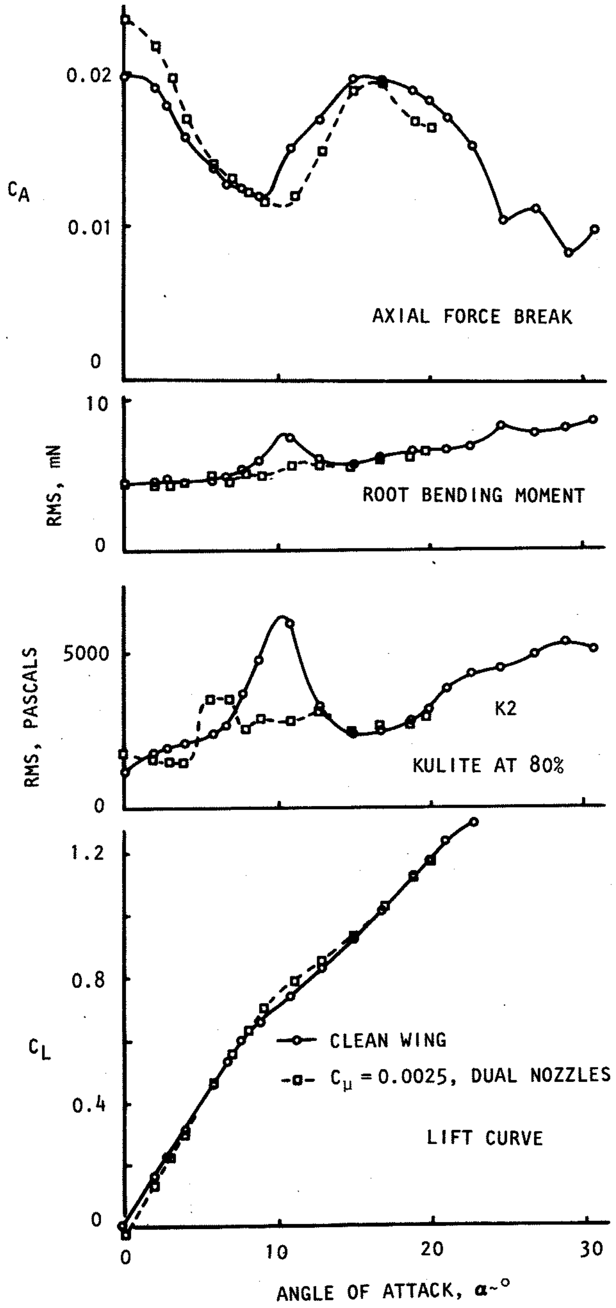


FIGURE 15 COMPARISON OF STRAKED WING BUFFET INDICATORS, M = 0.9

Root Mean Square Data. An indication of the fluctuating flow characteristics over the span of the wing is indicated by the RMS data shown in Figure 16 for the configuration and Mach number described above. Some of the more important information obtained from these data are as follows:

- Flow at the outboard Kulites (70, 80, 90%) is dominated by the location and strength of the outboard shock up to an angle of attack of about 11°. Spanwise blowing reduces the magnitude of the generally broad frequency band fluctuations caused by this shock.
- Above 11°, vortical flow begins to predominate and the magnitude of the fluctuations are less than that for the shock. The level and type of blowing used in these tests did not appreciably influence this type of flow.
- At low angles of attack, where the nozzle and jet are in attached flow, the magnitude of the fluctuations is increased at Kulite stations directly behind the nozzles (50% and 70%).

Power Spectral Density. Figure 17 presents power spectral data for the strake configuration at $M = 0.9$, $\alpha = 9^\circ$. By comparing the characteristics of the outboard transducers to the spectra shown in the $\alpha = 9^\circ$ inset of Figure 14, the similarity between the spectral content of the unblown basic and straked wing can be seen. Figure 17 shows the effect of blowing at the outboard three transducer locations to be a broadband reduction in the magnitude. The increase in the magnitude at K4, also indicated by the RMS data in Figure 16, appears due to the vortex location shown by the flow visualizations. The effect of blowing on the basic wing (see inset, Fig. 14) is somewhat different. While there is a reduction in the average or effective value, the blowing causes a peak in magnitude to occur at about 1500 Hz. This effect is also noted at K2, K3, and K4. Judging from high coherence factors between K1 and K2 and K3 and K4 at this frequency, vortex shedding exists along the span of the wing. This vortex shedding probably originates from the vortex shown just aft of the outboard nozzle in Figure 12b. A similar disturbance is noted in Figure 17 but is limited to K4, which is just behind the inboard nozzle and in the proximity of the vortex shown in Figure 13b. The frequency of this disturbance is considerably higher, 3600 Hz.

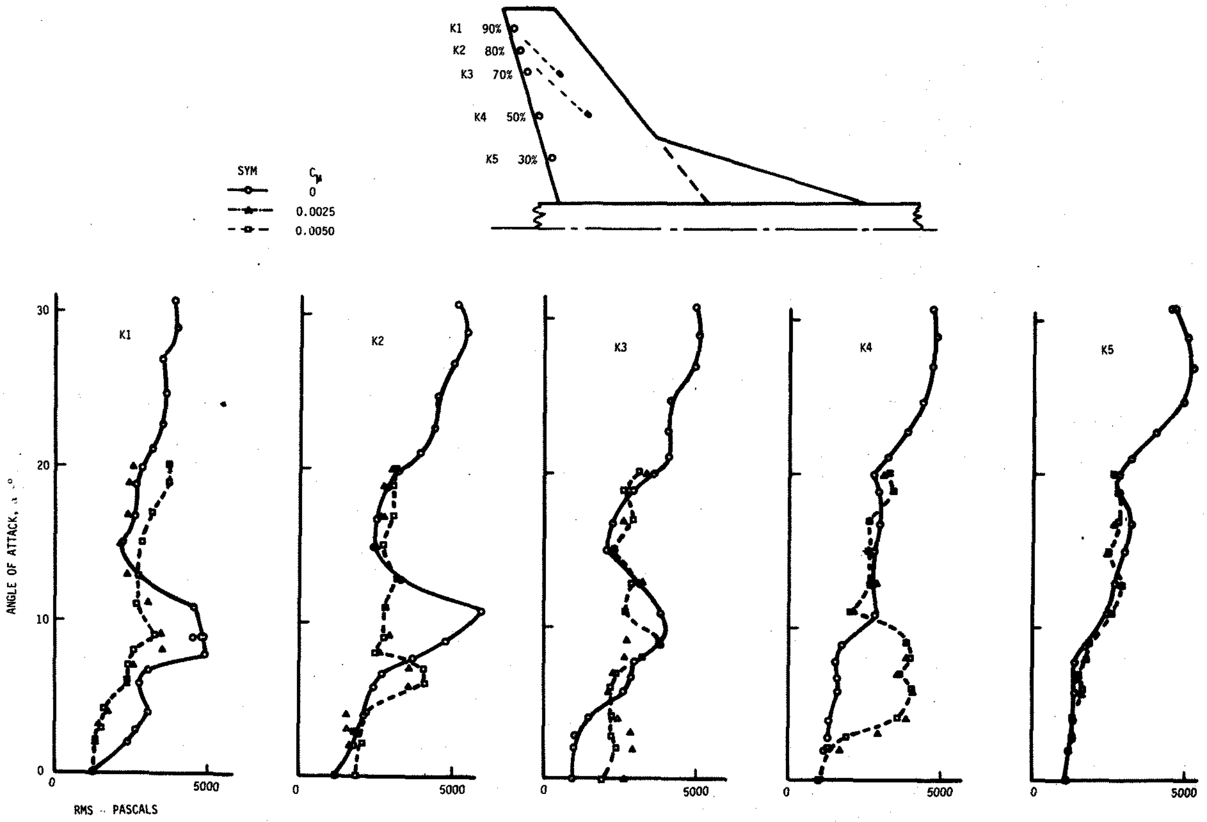


FIGURE 16 TRAILING EDGE RMS PRESSURES, STRAKED WING, M = 0.9

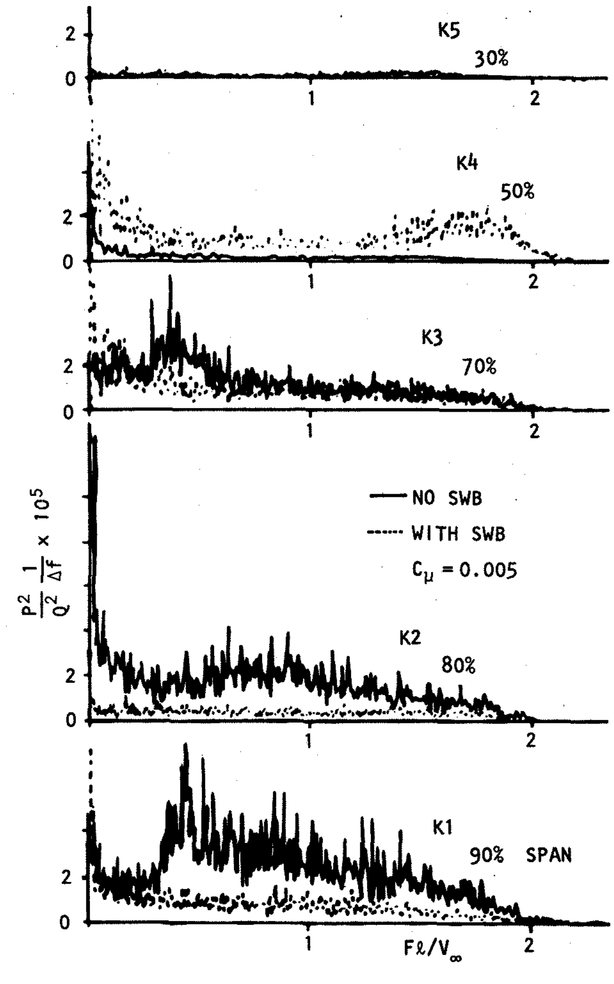


FIGURE 17 TRAILING EDGE PRESSURES, POWER SPECTRAL DENSITY, STRAKED WING, $M = 0.9$, $\alpha = 9°$

The more detailed analysis afforded by combining all of the flow visualization, RMS and spectral data correlates the preliminary evaluation of the favorable effects of blowing on buffet intensity. This study also indicates that, for the present model configurations, further improvements could be made by minor relocations of the nozzles. Such refinements are more appropriate, however, to the refinement of the application to a specific configuration.

IV. Application

The maneuver capability of an aircraft depends upon many factors: thrust and drag relationships, stability and controllability and structural characteristics, to name a few. The extent to which buffet can limit this capability in either transient or sustained maneuvers can be determined only through a detailed study of a specific configuration. It was not the purpose of this study to quantify the effects of spanwise blowing on the maneuver capability of any specific aircraft. This investigation has, however, illustrated that amounts of blowing consistent with the bleed capability of many engines can favorably affect both the buffet and steady state characteristics of configurations exhibiting shock-induced separation.

While data is not available for a direct comparison of spanwise blowing to other techniques for buffet suppression, an indirect comparison can be made as shown in Figure 18. Here the results of an extensive high speed slat development study (13) are compared to those of the current exploratory effort. Only the lift characteristics are presented to simplify the comparison, but the effects of SWB are shown to compare favorably with the results achieved by an optimized slat system.

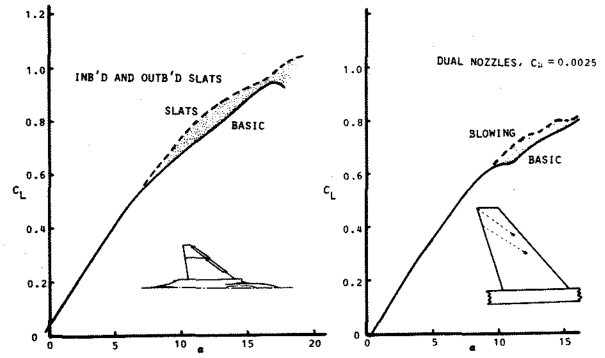


FIGURE 18 COMPARISON OF SLATS AND SPANWISE BLOWING

The results of the tests have demonstrated significant reductions in buffet intensity as measured by fluctuating pressures on the wing and the resulting effects on wing vibration as measured at the root. Figure 19 presents the effect of SWB on the wing lift coefficient for axial force break for both the basic and the straked configuration using the same reference area. Since the application of the blowing is to control the shock-induced separation, similar for both configurations, it is not surprising that the curves are essentially parallel. While the intent of this figure is to show that both types of wings are benefitted by the blowing, it also illustrates that SWB can be used to accomplish improvements in performance achieved by the addition of a strake. (This facet has also been demonstrated by low speed studies at higher, yet practical, blowing coefficients.) A C_μ level of 0.002 is all that is required to match the lift level (without blowing) of the straked configuration. This corresponds to a lift increment of $\Delta C_{L_B} = 0.09$ or a 16% increase in the lift for axial force break. From an effectivity viewpoint, this amounts to a $\Delta C_{L_{BR}}/C_\mu = 45$.

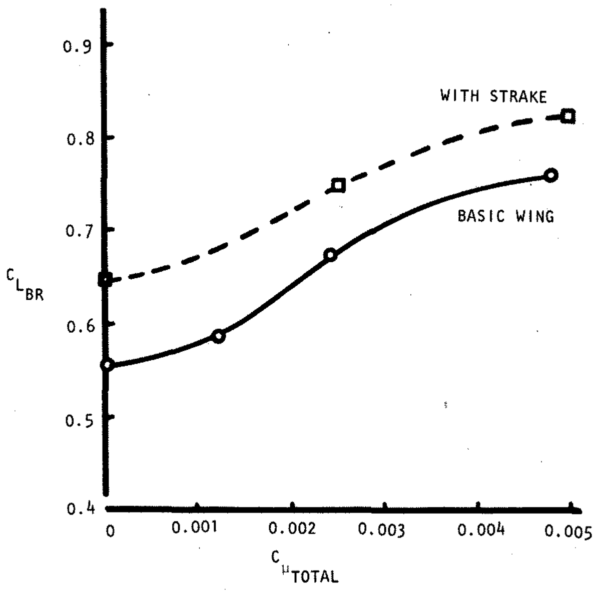


FIGURE 19 EFFECT OF BLOWING ON LIFT COEFFICIENT FOR AXIAL FORCE BREAK

Not only has the lift coefficient for buffet onset increased, but the suppression of separation results in a lift increase at constant angle of attack and a reduction in drag at a constant lift coefficient. This latter aspect counteracts any losses in available engine thrust due to bleed from the propulsion system. The basic wing data shows that blowing at a constant angle of attack (in buffet without blowing) can provide a 7.5% increase in load factor with a 2% increase in effective L/D and with no buffet. (In this context, effective L/D includes a thrust degradation equal to twice the value of the blowing momentum, $\Delta C_T = \Delta C_{D_{EFF}} = 2C_\mu$.) Depending on the nature of the separation that may limit the usable flight regime, it appears possible that benefits of SWB at both high and low speeds may be used to improve the capabilities of more conventional aircraft. There is also the challenging possibility that by properly designing the wing to recognize the effects of SWB even greater benefits can be developed. This approach has special meaning as the performance requirements increase for all phases of multimission, trisonic aircraft and the unfavorable effects of design compromises must be minimized.

V. Conclusions

Despite the exploratory and necessarily time-limited nature of this investigation, results demonstrate the potential for use of spanwise blowing at transonic speeds. The most important general conclusions from these tests can be summarized as follows:

1. Practical, low levels of blowing ($C_\mu \equiv 0.003$) can provide significant control of shock-induced separation.

2. This separation control results in reduced buffet intensity and improved lift, drag and pitching moment characteristics.

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