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Evolution from 'Tabs' to 'Chevron Technology' – a Review

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Abstract

‘Chevrons’, a sawtooth pattern on the trailing edge of exhaust nozzles, are being implemented on modern jet engines. The technology reduces jet noise for ‘separate-flow’ nozzles used on newer jet aircraft engines. The purpose of this paper is to describe the development of this technology, starting with studies of ‘tabs’ in the 1980’s and 1990’s. The tabs, essentially chevrons with more aggressive penetration, were studied in those early years with a focus on mixing enhancement in jets. Observations from experimentalists in connection with mixing enhancement and plume signature reduction suggested that there might also be a noise benefit. In the mid-nineties, these devices, with mild penetration to minimize thrust loss, were first seriously explored for aircraft engine noise reduction purposes. Prompted by a strong need for jet noise reduction, the study became a joint NASA/industry effort that ultimately matured the chevron technology to production by mid-2000’s. The process is an example of how fundamental studies over decades eventually migrate to application but often take a concerted effort.

1. Introduction

Chevrons are sawtooth-like patterns at the trailing edge of jet engine nozzles that help reduce noise from the ensuing jet. It has been known from past experimental studies with laboratory-scale jets that small protrusions at the nozzle lip, called ‘tabs’, would suppress ‘screech’ tones. In the 1980’s and 1990’s the tabs were explored extensively for mixing enhancement in jets. These studies advanced the understanding of the flow mechanisms and suggested that the technique might have a potential for reduction of ‘turbulent mixing noise’ that is the dominant component of jet noise for most aircraft. Driven by stringent noise regulations, such a potential first received serious attention on an application level in the mid 1990’s. Engine companies expressed interest and some proposed their own concepts for tests. In 1996-97, concepts from General Electric Aircraft Engines (GEAE), Pratt & Whitney (P&W) and others were combined into a test program under NASA’s Advanced Subsonic Technology (AST) Program. Various tab/chevron configurations were evaluated for noise reduction with models of separate-flow nozzles in free-jet tests and encouraging results were obtained. However, skepticism lingered and there was reluctance to embrace the technology primarily out of concerns about thrust penalty. In 1998 the impact on thrust was evaluated and found to be less than 0.25%. This was the turning point in the development of the technology when industry started to invest heavily with product development programs. The effort under AST culminated in flight tests in 2001 on NASA’s Learjet 25 and Honeywell’s Falcon 20 test aircraft proving the noise reduction.

Today, chevrons are implemented on various engines, initially on GE’s CF34 engine for regional jets and now on the GEnx engine for Boeing 787 and 747-8 aircraft. However, as stated, the evolution of the technology can be traced back to decades of fundamental studies with tabs and similar devices at universities, NASA as well as in industry. The concerted NASA / industry studies in the 1990’s eventually led to designs that produced significant noise reduction while keeping the thrust loss within acceptable limits. The objective of this paper is to provide an account of this evolution, starting with a summary of the earlier fundamental studies. In view of the vast number of publications on the subject, the literature review remains far from being complete and we invoke only the ones that to our knowledge have been significantly pertinent to this process. Furthermore, this paper is a perspective from within NASA and our objective is to provide an account of the events as we saw them while emphasizing the fact that fundamental research often takes a long time and concerted efforts to mature into application.

2. Earlier studies on the effect of tabs

It has been known for a long time that tabs, small protrusions placed near the nozzle exit, suppress screech noise (e.g., [1]-[6]). Screech is a phenomenon typical of small, clean, laboratory jets that, under imperfectly expanded supersonic condition, involve a feedback loop to produce a sharp tone. In laboratory experiments the curious suppression effect is readily demonstrated by inserting a small obstacle, such as the tip of a pencil, near the nozzle exit. One of the earliest studies of noise suppression by such devices is that of Westley & Lilley [1]. A picture of the 'teeth' patterns used in their experiment, in the then newly established program of jet noise research at Cranfield, UK, shortly after WWII, is reproduced in Fig. 1; see also [7]. The authors observed large reduction of supersonic jet noise by these devices apparently in part due to suppression of screech. Later experiments usually deployed a single tab or two tabs that were sufficient to suppress screech. Suppression of screech was desired in order to allow a clearer study of other components of jet noise [3]. There were other applications of the tabs, e.g., for suppression of resonant interaction between wind tunnel exhaust and a downstream collector [8]. They were also used in the NASA Glenn Research Center's (GRC) Nozzle Acoustic Test Rig (NATR) located in the Aero-Acoustic Propulsion Laboratory (AAPL), a facility used heavily for NASA's jet noise research. The tabs were used for increasing the 'free jet' ejector efficiency as well as for reducing the background noise level (private communications; facility described in [9,10]).

With regards to the effect of tabs on the jet flowfield, Ref. [11] is perhaps the first to carry out a detailed set of measurements. The authors of this work noted that the insertion of small rectangular tabs into the jet flow on the nozzle perimeter had a profound effect; "…the apparent potential core length was reduced to about two diameters followed by a rapid decay of the centerline mean velocity". Most of the earlier studies involved the use of rectangular tabs inserted perpendicular to the flow at the nozzle exit. Reference [12] studied the flowfield as affected by a 'notch' on the lip of the nozzle. Notches were also effective in suppression of screech and it was generally recognized that these devices disrupted the screech feedback loop while generating streamwise vortices to cause enhanced jet spreading. From flow-field distortion seen in schlieren images the authors of the last reference provided a schematic of the streamwise vortices anticipated in the flow. As described shortly the mechanism of streamwise vorticity generation with the notches and the tabs is thought to be essentially the same.

In the mid-1980's a detailed work was conducted at Lockheed Georgia on mixing enhancement in high-subsonic and supersonic jets using tabs [13]. Later, the work was continued under a NASA grant to study the effect on rectangular jets [14]. Around this time the work of a group of researchers at NASA GRC focused on flow control and mixing enhancement in various shear flows. The results from Lockheed on the effect of tabs were so impressive, relative to other methods of flow control, that the tabs were dubbed within this group as 'super mixers'. In 1990 the topic was picked up for further study at NASA. In collaboration with universities, the knowledge of the flow mechanisms was advanced and reported in several publications [15-19]. A summary of results from this activity is given below with the help of Figs. 2-4.

While in most previous studies the tab was a rectangular protrusion at the nozzle exit, it was soon recognized that a triangular tab with same base width worked just as well. Moreover, when the apex of the triangular tab was tilted downstream it appeared to work even better. The latter configuration, termed 'delta-tab', obviously was preferable from a thrust loss point of view. The enormous effects of the delta-tabs are captured in Figs. 2 and 3. (The term delta-tab was used to specifically denote a triangular tab with an angle of 90° at the apex and with the apex tilted downstream by 45° [17,18]. For brevity mostly the term 'tab' will be used in the following to denote any triangular tab geometry). Figure 2 shows the large increase in jet spreading and mixing at small-scales caused by 4 tabs in a supersonic circular jet; the shock structure is also altered drastically. Figure 3 shows laser-sheet illuminated cross-section of the jet. The visualization was done without any artificial seeding; the laser sheet illuminated naturally condensed moisture particles from the entrained air and thus the mixing layer region. The jet core deformed into 'fingers', each emanating from the region between two adjacent tabs, the number of fingers usually being equal to the number of tabs. When the number was large there was obvious interaction – with six tabs the flow settled back to three fingers. This was a clear indication that the flowfield distortions were due to streamwise vortices. Depending on their strength and size, there was amalgamation and interaction when the flow got crowded with too many of these vortices. These observations prompted further investigations to explain mechanisms, studies that might allow further development beyond cut-and-try.

That each tab produced a pair of streamwise vortices was documented by hot-wire measurements and postulations were made with regards to their origin [17]. Two sources were identified. Source 1 was due to a 'pressure hill' occurring within the nozzle upstream of the tab. The lateral pressure gradient in conjunction with the no-slip condition on the nozzle wall produced the pair of vortices. Source 2 was due to reorientation of the vortex filaments shed from the edges of the tab. As these filaments travelled downstream they were oriented in the streamwise direction by the mean velocity gradient. Thus, the delta-tab yielded stronger vortices since vorticity from the two sources reinforced each other. In contrast, when the apex of a triangular tab was tilted upstream (into the nozzle) the effect was not as pronounced since there was cancellation of vorticity from the two sources.

In subsequent experiments it was inferred that source 1 dominated in most situations. Observations made with overexpanded jets (showing little effect), a tab placed slightly downstream of the nozzle (showing no effect) or placed upstream inside the nozzle (producing vortex pair of opposite sense) could be qualitatively explained based on source 1 [17,18]. The point was further delineated in [20] based on flowfield distortions by cutouts (notches) of various shapes on a rectangular nozzle. The vorticity dynamics were explored and elucidated further in studies at Ohio State University [21] and Michigan State University [22,23]. The latter work discussed the mathematical foundation of the vorticity sources and also advanced the idea of 'sister tabs' – smaller tabs tilted the opposite way between two larger tabs in an array – producing a stronger effect on mixing.

It is worthwhile to note that the upstream pressure gradient (source 1) also explains the streamwise vorticity generation from a notch. Here, a pressure valley is generated that produces a vortex pair of opposite sense relative to that found with a tab. However, with subsonic flow the nozzle has to be convergent in order for the notch to produce the lateral pressure gradient. With parallel flow-lines at the exit a pressure valley may not be generated to produce the streamwise vortices. Similarly, the chevron, a triangular extension of the nozzle wall (the geometry further discussed shortly), is also expected to work only with a convergent nozzle when the flow is subsonic.

Further fundamental experiments were carried out at NASA in 1994-1995 exploring the effect of varying inclination of a single triangular tab as well as the effect of spacing when an array of tabs were employed in a two-stream planar mixing layer [19,24]. A set of data on the tab inclination effect is shown in Fig. 4. Streamwise vorticity distribution at a downstream location is shown as the inclination was varied. It can be seen that a pair of counter-rotating vortices is produced in each case. The sense of the pair changes as θ varies from positive to negative values. What is pertinent here is the fact that even at the smallest inclination of $\theta = 15°$ a vortex pair of substantial strength is generated. These observations, as well as ideas such as the 'sister tabs' developed at Michigan State University, had some bearing in the development of the chevron technology.

There were many other investigations at other institutions around this time frame. Alternative methods of producing streamwise vortices and the resultant impact on the flowfield were studied. For example, swirl generators were used and their effect on mixing characteristics of a supersonic wake was studied in [25]. Reference [26] used half delta-wings and investigated the effect on ejector pumping. Similar devices were used in the interior of a rectangular nozzle to find that the streamwise vortices hastened the jet centerline velocity decay and also impacted the noise [27]. Other studies of note are: the effect of tabs on noise reduction [28], effect in conjunction with ejector flows [29], on molecular mixing [30], on a coaxial jet [31] and on a two-stream planar mixing layer [32]. Reference [33] further explored the effect of notches. Limited CFD studies with the delta-tab configuration were carried out in [34] and [35].

3. The emergence of Chevron technology

In early 1990's most of the jet noise research in NASA was conducted under the High Speed Research (HSR) Program. Primary focus at this time was the 'mixer ejector' nozzle for the High Speed Civil Transport (HSCT) plane. The program also supported lower 'technology readiness level' work such as the fundamental experiments and the university grants described in the previous section. During this period increasing attention was paid to tabs and vortex generators for jet noise reduction. For example, tabs were discussed in a workshop, ‘Enhanced turbulent mixing for HSCT take-off noise reduction’, held at NASA Langley Research Center (LaRC) during October 28-30, 1992 (hosted by J.M. Seiner). In 1992 the Noise Element of the Advanced Subsonic Technology (AST) Program was initiated primarily to address engine fan noise. Upon urging from the industry, elements of subsonic jet noise research were brought under this program by 1994 and these were supported partially by the Federal Aviation Administration (FAA). An in-house experiment was conducted subsequently to explore the effect of mixing chutes as well as tabs, for noise reduction with a model of the P&W ‘JT8D’ nozzle. The results obtained with the tabs in this experiment are summarized shortly in the next subsection.

While tabs were quite effective in mixing enhancement and jet plume reduction their effect on the noise field was mixed. Tabs suppressed screech noise as well as broadband noise at low frequencies but usually there was a penalty at high frequencies. That is, the spectral levels for the tab case became larger relative to the no-tab case at high frequencies. This was of serious concern since the latter frequencies for scaled-up practical nozzles would fall in the sensitive range of human perception, thus, washing out the noise benefit or even making it worse on the effective perceived noise level (EPNL) metric. Nevertheless, the suppression of turbulent mixing noise at lower frequencies was encouraging. It is worth noting that the work of [12] was inspired by an observation of reduced side-line noise from the engine of the Concorde aircraft when the thrust reverser bucket was left in a semi-closed position – a tab-like protrusion into the flow.

3.1 Noise reduction for P&W JT8D nozzle by tabs:

Credible evidence of overall noise reduction with the tabs came from the experiment with a model of the JT8D nozzle [36]. In 1994-95, noise characteristics with various chutes (mixers) with this nozzle were being tested when the idea of trying the tabs in place of the chutes came up. The experiment with the tabs was carried out in March of 1996. Various configurations were tried by placing the tabs on the lip of the internal core nozzle (i.e., the chutes were replaced by the tabs) as well as at the lip of the outer nozzle. A mild but significant noise reduction was noted especially with the tabs on the internal nozzle. This is shown in Fig. 5. A consistent noise reduction was observed, although the reduction with the conventional chutes was better. However, the effect of the tabs was encouraging since it would involve a simpler geometry and less nozzle weight.

The JT8D nozzle involved ‘internal mixing’, i.e., the core flow discharged upstream and mixing occurred within the outer nozzle (see inset in the Fig. 5). The internally mixed nozzle also offered the possibility of adding sound absorbing liners on the interior of the outer nozzle to further suppress high-frequency noise created by the tabs and mixers. However, from weight penalty and performance point of view an externally mixed or separate-flow nozzle, where the core nozzle exit is located downstream of the fan nozzle exit, is preferred in practice. In fact, most modern engines involving higher bypass ratios use the latter type of nozzle. Thus, attention was turned to the separate-flow nozzles. Here, aggressive mixing with the chutes had a bleak prospect since the high frequency noise created outside would radiate unabated and dominate the EPNL. It was felt that tabs with mild penetrations had a chance to provide some benefit.

3.2 The AST Separate-Flow Nozzle Test Program:

By 1995 several engine companies were interested in the tab-like devices for noise reduction. General Electric and Pratt & Whitney submitted proposals for conducting such tests in response to a NASA solicitation under the AST Program. Meetings and workshops were held. Besides GEAE and P&W other participants included Allison Engine (affiliate of Rolls Royce) as well as Boeing. Subsequently, the concepts from the different sources were rolled into the ‘separate-flow nozzle test’ (SFNT) program, (with Naseem Saiyed as the NASA technical team leader and contract monitor). GEAE and P&W were awarded contracts to design and build scale models of the separate-flow nozzle as well as a variety of noise suppression devices.

With regards to the geometry of the noise reduction devices a distinction was made between ‘tabs’ and ‘chevrons’. The term ‘chevron’ seemed to first appear in connection with the mixer-ejector nozzle studies under the HSR Program and later in the 1995 GEAE proposal to the AST Program. Chevrons were basically extensions of the nozzle wall into a continuous serrated edge. In contrast, the tabs were to have 'hard breaks' and more aggressive penetration into the flow; they were spaced intermittently around the perimeter. Later, mild penetration of the chevrons was allowed. For the SFNT program five nozzle models were chosen: (1) coplanar exits for fan and core nozzles with (bypass ratio) BPR = 5, (2) internal plug with BPR = 5, (3) external plug with BPR = 5, (4) internal plug with BPR = 8 and (5) external plug with BPR = 8. In cases 2-5, the fan nozzle exit was located upstream relative to the exit of the core nozzle. Internal and external plug refers to configurations where the tip of the center plug was located upstream or downstream of the core nozzle exit, respectively. GEAE provided designs for eleven suppression devices consisting of various chevron configurations as well as other vortex generators and mixers. P&W provided nine designs with various combinations of tabs, an offset centerline fan nozzle, a 'scarfed' fan nozzle and other mixers [37, 38].

The design of the tabs and chevrons were aided by computational fluid dynamics (CFD) simulations. Due to a lack of understanding of the noise generation mechanisms, the difficulty in choosing suitable criteria to correlate the simulation results to noise reduction is reflected in the following statement from [38]. "…A great difficulty with postprocessing the CFD results was interpreting the acoustic benefit of the chevrons. More rapid plume decay should reduce the strength of noise sources located far downstream and thus reduce low-frequency noise. However, higher turbulence near the nozzle exit could increase high-frequency noise". The trends in turbulent kinetic energy (TKE) profiles were eventually used as guidelines. The reader is reminded that the energy in the radiated noise represents only a minute fraction of the TKE in the flow; thus, there could be pitfalls in such guidelines. In any case, accumulated evidence suggests that this may be a sound choice as turbulence and noise seem to correlate well in these flows. This is discussed further in the following. Based on the GEAE CFD studies as well as past experience subtle modifications were incorporated in the penetration and geometries of the chevrons. Later on, GEAE obtained a US patent on some of the chevron designs [39].

It is worthwhile to explain some terminologies used in the SFNT program since these appear extensively in various reports. The BPR = 5 case with external plug is referred to as the '3BB' nozzle; '3' represents the number in the list of five mentioned earlier, the first 'B' designates baseline (no modification) for the core nozzle and the second 'B' designates baseline for the fan nozzle. Most promising noise reduction with the suppression devices was observed with this nozzle and it became the focus of the program. In this paper, the discussion will also be limited to data only from this model. For identification purposes, each of the two B's (in 3BB) was replaced by other letters according to the type of suppression devices used. The letter 'C' stood for chevrons, 'T' for tabs, 'I' for chevrons with an inward bend and 'A' for chevrons alternately bent inward and outward. Thus, '3C12B' would denote the case with 12 chevrons on the core nozzle with no modification on the fan nozzle, model '3I12C24' for 12 inward-bent-chevrons on the core nozzle and 24 regular chevrons on the fan nozzle, etc. Pictures of the 3BB, 3I12B, 3I12C24 and 3T24C24 cases are shown in Fig. 6. (Note: in some of the cited reports the numbers from the notations were dropped, e.g., '3IB' stood for '3I12B', '3AC' for '3A12C24', etc.)

The noise tests were carried out during March – June of 1997 in the AAPL at NASA GRC (then Lewis Research Center). A SFNT status workshop was held in September 1997, as documented in [40]. The results obtained with some of the suppression devices were quite encouraging. Noise data for cases 3BB, 3C12B and 3I12B are shown in Fig. 7, as examples [39, 41]. The abscissa represents the 'mixed jet velocity' normalized by the ambient speed of sound, and a consistent noise reduction is observed throughout. Note that the two chevron cases in this figure are essentially identical except in the latter case where the chevrons had an additional inward bend by about 6°. This slight extra penetration made a significant difference in the result – the noise reduction improved from 1.2 to 2.1 EPNdB. The latter numbers are quoted for an abscissa value of 1.07 representing the takeoff condition. Corresponding data for a few other configurations are discussed shortly.

Overall, the noise results from the SFNT tests were quite encouraging. However, the question of thrust penalty loomed large. In the mean time, Aero Systems

Engineering (ASE) won the bid to conduct thrust measurements. Only a few cases showing significant noise benefit were considered for testing. NASA knew that the ASE FluiDyne facility was trusted by the industry and would be a way to convince their aerodynamicists who would ultimately be responsible for integrating the chevron nozzles into their engines. To everyone's pleasant surprise the thrust losses turned out to be quite small.

The static thrust measurements (without simulated flight effect) were first done for cases with chevrons only on the core nozzle. Results for four chevron/tab cases are listed in Table 1, as examples. NPRC and NPRF represent nozzle pressure ratios for the core and the fan flows, respectively. Data for six combinations of NPRC and NPRF ('cycle points') are listed. ASE FluiDyne quotes precision in the thrust coefficient data of about ±0.15% for static measurements and ±0.25% with simulated flight effect [41]. For differences (yielding the loss values), it is possible that some bias errors cancel out. It appears that the uncertainty in the loss values, obtained from measurements in the same series of tests, might be smaller. This is reflected, for example, by the small loss values, well under 0.1%, recorded consistently for various cycle points for the 3C12B case.

Table 1 Static thrust coefficient data.

Nom. NPRC	Nom. NPRF	Coeff for 3BB	Loss (%) 3C12B	Loss (%) 3I12B	Loss (%) 3T24B	Loss (%) 3T48B
2.0	2.0	0.9908	0.06	0.10	0.54	0.33
1.79	1.89	0.9903	0.07	0.09	0.54	0.32
1.68	1.83	0.9901	0.03	0.18	0.54	0.34
1.51	1.73	0.9893	0.04	0.18	0.56	0.30
1.34	1.60	0.9891	0.03	0.21	062	0.35
1.27	1.51	0.9882	0.04	0.17	0.57	0.33

With simulated flight effect (i.e., with a surrounding outer flow at M=0.8), representing cruise condition, the losses generally increased. The cruise thrust loss data are listed in Table 2 for several cases together with the estimated noise benefit data. The noise data is for the take-off condition and adjusted on an equal thrust basis. (Thrust for all cases was not measured; thus, the noise data could not be adjusted for some of the cases and hence not shown). One finds that with the simulated flight the thrust performance degrades considerably for the chevron cases; compare static loss of about 0.06% (Table 1) with cruise loss of 0.55% (Table 2) for the 3C12B case. Similar increases can be noted for cases 3I12B (0.10% to 0.32%), 3T24B (0.54% to 0.99%) and 3T48B (0.33% to 0.77%). Paradoxically, when chevrons were added to the fan nozzle there was improvement in cruise losses for most cases. For example, compare, from Table 2, 0.99% loss for 3T24B case with 0.43% for 3T24C24 case. The 3I12C24 case turned out to be the best configuration with only 0.06% cruise thrust loss while yielding 2.7 EPNdB benefit.

Table 2 Noise benefit and cruise thrust loss data

Configuration	Noise benefit EPNdB	%Loss in thrust coefficient at cruise
3C12B	1.36	0.55
3I12B	2.18	0.32
3I12C24	2.71	0.06
3T24B	2.37	0.99
3T48B	2.09	0.77
3T24C24	--	0.43
3T48C24	--	0.51
3A12B	--	0.34
3A12C24	--	0.49

In summary, the losses in thrust coefficient were small for some of the chevron cases. Configurations yielding less than 0.5% loss and over 2.5 EPNdB benefit were proposed for further verification via engine tests on static stands as well as flight tests [41]. Historically, jet noise reduction concepts that worked statically had reduced benefits in flight. It was important to properly account for forward flight and installation effects on the noise. Actual flight tests were the ultimate answer and this was the next critical task. Before describing those tests some comments may be in order regarding the flow and noise mechanisms of these devices based on past and concurrent fundamental studies.

3.3 Concurrent fundamental studies with chevron nozzles:

We have seen how a slight difference in the chevron geometry makes a large difference in the noise benefit as well as the thrust penalty. The difference between the 3C12B and 3I12B cases (Figs. 6, 7) was an additional 6° penetration by the tips of the chevrons in the latter case. This improved the cruise noise benefit from 1.36 to 2.18 EPNdB while the cruise thrust penalty actually dropped from 0.55% to 0.32% (Table 2). We have noted in the previous section how the addition of chevrons on the fan nozzle reduced the thrust penalty incurred by the tabs/chevrons when placed only on the core nozzle. It suffices to comment at the outset that the interactions of these devices are subtle and a lot remains unknown about their aerodynamics and acoustics. Thus, it is important to carry out fundamental studies towards a better understanding of the mechanisms. This has been an emphasis in NASA's jet noise research programs.

It is apparent that some penetration by the chevrons is necessary to achieve good noise benefit. On the other hand, it is also clear that too aggressive penetration would reverse the benefit due to increased high-frequency noise. A series of experiments were conducted at the University of Cincinnati, in collaboration with GEAE [42, 43]. Chevron penetration was identified as the primary factor controlling the trade-off between low-frequency reduction and high-frequency increases in SPL. Thus, for a given chevron geometry, there should be an optimum penetration. Perhaps, this should translate to an optimum ratio between the peaks of streamwise vorticity generated by the chevrons and the azimuthal vorticity. However, there are little data to allow further comment.

One way of understanding the chevron nozzle flow is in terms of vorticity distributions. It is amply clear that introduction of streamwise vortex pairs is necessary. These vortices appear to have a 'calming effect' reducing the overall turbulence in the shear layers. With the baseline nozzles, the vorticity in the shear layer is primarily composed of the azimuthal component. Such vorticity concentrates into the discrete ring-like (or helical) coherent structures. These structures go through contortions and interactions while propagating downstream. Their dynamics are unsteady and vigorous giving rise to high turbulence intensities. In contrast, the streamwise vortices are part of the steady flow feature and have a 'time-averaged definition'. They persist long distances and do not involve as vigorous dynamics as do the coherent azimuthal structures. Furthermore, the only source of vorticity in the flow is the efflux boundary layer of the nozzle. The chevrons simply redistribute part of it into the streamwise component at the expense of the azimuthal component. Thus, the chevrons arrest the vigorous activity of the azimuthal coherent structures to some extent via introduction of the streamwise vortices. The result often is a reduction in the turbulence intensities that correlates with the noise reduction.

Until complex vortex motions can be directly linked to sound generation, the reduced turbulence intensity is the most direct connection to the noise reduction as far as one can tell. A set of Particle Image Velocimetry data from [44], shown in Figs. 8 and 9, corroborates this (see, also [45]). Data for the 3A12B configuration are compared with the baseline 3BB case. For the former case, data at two azimuthal planes (through the tip and valley of the chevrons) are shown. A reduction in the mean velocity gradients is obvious from Fig. 8. This is accompanied by a significant decrease in turbulent kinetic energy as evident in Fig. 9. Peak value of TKE has reduced from about 3500 m^2/s^2 to 2500 m^2/s^2. This chevron configuration yielded approximately 2.6 EPNdB noise reduction. That a reduction in noise directly follows a reduction in turbulence has been observed with other flows, e.g., with a lobed nozzle as reported in [46].

Efforts to further understand the mechanisms of these flows continued both at NASA and at many other institutions. Unpublished results from a pressure-sensitive-paint experiment conducted in the AAPL in October, 2000, by Timothy Bencic and James Bridges, provided some insight why the cruise thrust improved when the chevrons were added on the fan nozzle. Recall the comparison between cases 3I12B and 3I12C24 in Table 2. With the addition of the fan chevrons the surface pressure distributions were seen to change favorably, as shown in Fig. 10, resulting in less nozzle base drag. Overall, the pressures became more positive on the core nozzle cowl as well as on the center plug. The higher pressures, especially on the core cowl on the left in Fig. 10 (involving larger surface area), qualitatively explain the improvement in the thrust. The increased base pressures must be a result of the streamwise vortices from the fan chevrons. However, more study will be needed to fully understand the subtle interactions between the vortices from the core and fan chevrons.

Recent work at P&W and United Technologies Research Center has tied 2-point space-time correlation data on jet near-field pressure to far-field noise. It has been noted that the 'wave packet' amplitude reduces considerably with the chevrons yielding lower far-field noise (R.E. Schlinker, private communication; see [47-49]). Numerical studies have the potential to significantly advance the understanding of the flow and noise mechanisms. We have mentioned the CFD work aiding the design of the chevrons in the early stages of the SFNT program. Several other CFD studies were done concurrently with the SFNT program and later [50-52]. Reference [53] reported results of a RANS based noise prediction and noted that the streamwise vortices caused a rapid increase of the width of the mixing layer with a resultant reduction in turbulence production. There have been several other efforts recently; to the authors' knowledge, [54-57] are some examples. Further development in the chevron technology is covered in §3.5.

3.4 Flight tests with the Learjet 25 and the Falcon 20 test planes:

Flight tests were done during the Spring of 2001 with NASA's Learjet 25 research aircraft as well as Honeywell's Falcon 20 test aircraft. The two tests were coordinated and performed in sequence at the Estrella Sailport near Phoenix, AZ. The acoustic data acquisition crew consisted of personnel from Wyle Laboratories Inc., based at LaRC as well as Honeywell Engines with observers from NASA. Two ground based microphone arrays were independently operated by Wyle and Honeywell [58]. For the tests, each aircraft was fitted with a baseline nozzle on one engine and the chevron nozzle on the other. The reader is reminded that in the actual aircraft effects due to the proximity of the fuselage, pylon, etc come into play all of which can influence the radiated noise which is why the flight test is so imperative. Before sending out to Estrella, a 'quick and dirty' test was conducted with the Learjet at the Lorain County Airport in Ohio on March 15, 2001.

In the Lorain test, data were acquired with a single microphone on the ground and a hand-held spectrum analyzer. The test was run with 500-ft altitude flyovers alternating power between the left and right engines (chevron versus baseline). The aim was to obtain an idea if indeed there would be a noise reduction. It suffices to say that after all the efforts of the past years the result of this test was a matter of great anticipation. Eleven flyovers were conducted before complaints came in from the surrounding community about high noise. (This was a rural community airport not used to turbojet planes making repeated flyovers at full throttle. For the record, personnel participating in this test were Cliff Brown, James Bridges, Carol Quinn, two observers and three generations of Huffs: Ronald, Dennis and Kevin. Naseem Saiyed provided support in the planning and coordination of the test and the plane was flown by William Rieke).The results did show 1-2 dB noise reduction. Estimates in EPNdB will be compared with the Estrella test data in the following. It was a relatively simple test that provided a great deal of confidence. However, only the elaborate measurements at Estrella would provide a reliable answer on the noise reduction.

The flight test at Estrella with the Learjet was done during March 26 to 29, 2001. This plane involves two turbojet engines each having a single exhaust with no fan bypass flow. Thus, the nozzle was not the same as the separate-flow nozzles tested in the SFNT program. (Part of the motivation for using the turbojet was to explore benefits of the chevrons for higher nozzle pressure ratios and higher exhaust temperatures. By this time the military was interested in finding ways to decrease jet noise for tactical aircraft. This test served as a feasibility study and the results were presented at a Navy-sponsored workshop in October, 2001. It should also be noted that tests had been performed in the AAPL with the Learjet nozzle; the results provided the confidence to go forward with the flight test.)

Two configurations with 6 and 12 chevrons were tested. A picture of the Learjet together with a close-up view of the 12 chevron configuration is shown in Fig. 11. The engines were alternated during the flyover passes, with one engine set to idle and the other one set at the desired engine pressure ratio (EPR). EPR was varied as 2.3, 2.2, 2.0, 1.8 and 1.6. The flaps and gear were deployed in all but the last EPR when the gear was retracted. The flyover altitude for all runs was 500 feet. Atmospheric data were recorded on the ground and at various altitudes using weather balloons. A set of noise data as a function of EPR is shown in Fig. 12; also shown in this figure is the estimate of corresponding noise data from the Lorain test. For the 12-chevron case consistent noise reduction was noted throughout the EPR range, the maximum was 2.1

EPNdB at the highest EPR. The Lorain data agreed quite well with the trend.

Typical observations during the tests were as follows. To a fixed observer on the ground, the chevrons had no effect on the noise as the aircraft approached. A clear reduction in the noise was heard in the aft as the aircraft flew by. (The difference was clear in a post-processed video clip from Honeywell where the records from the baseline and the chevron cases were alternated.) On the sideline, at 90° emission angle, the noise was reduced by 3 to 5 dB up to 2 kHz. There was a 'cross-over' in the spectral amplitudes by a fraction of a dB at higher frequencies. A full description of the Learjet test including details of noise spectra can be found in [59]. (For the record, participants in the Estrella test included, among others, Odilyn Santa Maria of Wyle laboratories, Donald Weir of Honeywell and James Bridges of NASA; Carol Quinn oversaw the effort as Project engineer, and William Rieke and Kurt Blankenship piloted the planes.)

The Falcon 20 test plane had the separate-flow nozzle on its engine (TFE731-60). Three configurations were tested: baseline, chevrons on core nozzle and chevrons on both core and fan nozzle. The last configuration was similar to the 3A12C24 case of SFNT. Figure 13 shows a picture of the aircraft and a close-up view of the chevron (in both fan and core streams) configuration. The experiments with this plane were completed over a few weeks following the Learjet test. The results essentially confirmed the observations made in the SFNT program and subsequent engine static tests. A bar-chart taken from [58], on the overall noise reduction results, is presented in Fig. 14. These results were first reported by the author of the cited reference in an AST working group meeting on September 18, 2001. Note that the dominant effect comes from the chevrons on the core nozzle (3AB case). In fact, addition of chevrons on the fan nozzle (3AC case) slightly reverses the noise benefit (more so at the lowest power setting for reasons remaining unknown). However, the thrust loss is improved significantly with the latter configuration, as discussed in §3.2. Overall, noise reduction exceeding 2 EPNdB was demonstrated.

3.5 Continued development and application of the technology:

Prior to the flight tests, engine companies had conducted further static measurements. A description of the static test on the Falcon 20 engine by Honeywell can be found in [58]. GEAE conducted tests on their engines. Figure 15 is included to show a picture of the GE CF34 engine with chevrons undergoing static test, in (a); this chevron engine was the first to fly commercially on a CRJ900 aircraft, shown in (b).

Meanwhile, Boeing conducted tests under the Quiet Technology Demonstrator (QTD) program, in collaboration with other industry partners and NASA. The first of these tests (QTD1) was carried out in 2001-2002 followed by a series of tests (QTD2) in 2005-2006 (see [60]). Installation effects, e.g., effects due to the pylon, struts as well as proximity of the wing and fuselage, were given considerations in the design of the QTD2 'fixed' chevrons. This led to azimuthally varying geometry of the chevrons on the fan nozzle. In particular, larger chevrons for aggressive mixing near the pylon with progressively smaller ones towards the keel on the fan nozzle proved to be superior. The noise reduction was confirmed in the flight tests and for some configurations thrust coefficient loss was reported to be less than 0.05%. The chevrons not only reduced jet noise ('community noise') but also broadband shock associated noise at cruise ('cabin noise'). These results have been presented in a series of papers notably at the 12th AIAA Aeroacoustics Conference in 2006 [60-65].

The chevron technology has potential for possible spin-offs. Because even a small fraction of a percent of thrust loss is of concern, there have been efforts to develop 'smart chevrons' where the penetration can be reduced during cruise [66]. In a collaborative effort in 2005, Boeing, Goodrich and NASA successfully tested individually controlled 'variable geometry' chevrons on the fan nozzle of a GE90 engine with a 777-300ER aircraft. This is perhaps the first known application of morphing structure technology to a commercial application. It has the potential for use in other flow control applications. Chevron-like serrated trailing edge on blades is also being explored for fan noise reduction. The latter effort started with NASA's Quiet Aircraft Technology (QAT) Project and continues to date. Similar blade geometry is also being considered for reduction of noise from wind turbines.

4. Concluding remarks

The chevrons were first applied with the GE CF34-8C5 engine flown on the Bombardier CRJ900 aircraft in 2003. Today, there are several aircraft in production with the chevron nozzles, e.g,, a new version of Boeing's 747-8 as well as the new 787. As evident from this paper, maturing the technology followed a long and arduous path with multiple dead-ends and parallel efforts. Seedling observations from laboratory-scale experiments eventually migrated to applications, a process that required prodding from noise regulations, inspired tests and finally a concerted NASA/ industry effort. It is emphasized that jet noise remains a major component of aircraft noise for moderate to low bypass ratio engines. Chevron technology has provided a modest relief. Unfortunately, a complete understanding of jet noise mechanisms is still not in our grasp. The insight of fundamental experiments coupled with application of CFD allowed the development of the subject technology with tools slightly better than cut-and-try. Hope for further control and reduction of jet noise hinges on advancement of our understanding of the relevant mechanisms. This has been and will continue to be an emphasis of NASA's noise related projects.

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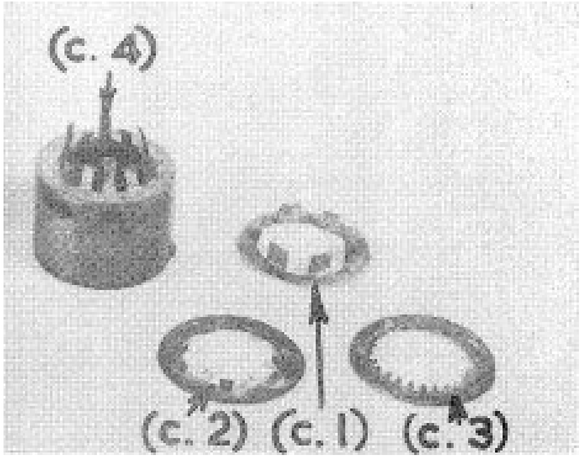


Figure 1 Noise reduction ‘teeth’ used by Westley and Lilley 1952, [1].

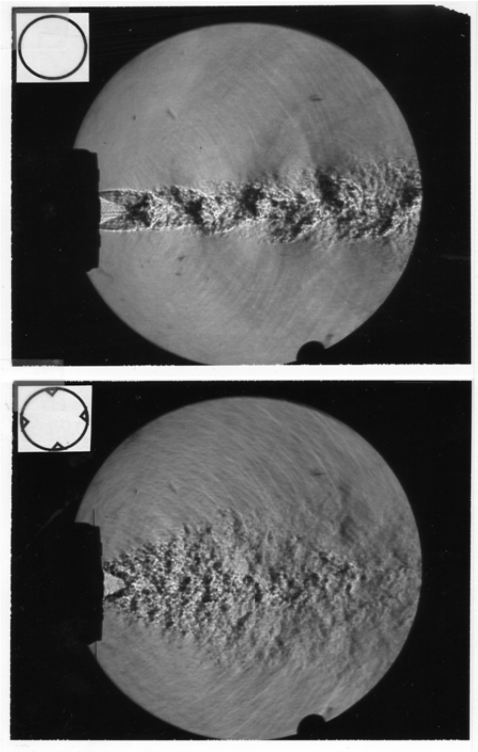


Figure 2 Schlieren images on the effect of four delta-tabs on a convergent circular jet at fully expanded jet Mach number, M_j=1.63.

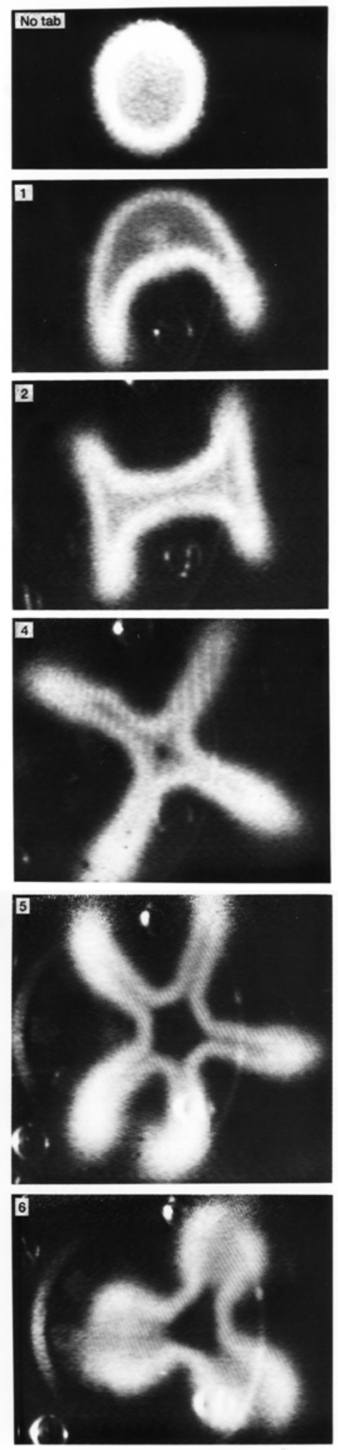


Figure 3 Laser-sheet illuminated cross-section of a round jet two jet diameters downstream, at M_j=1.63, for indicated number of (equally spaced) delta-tabs, [17].

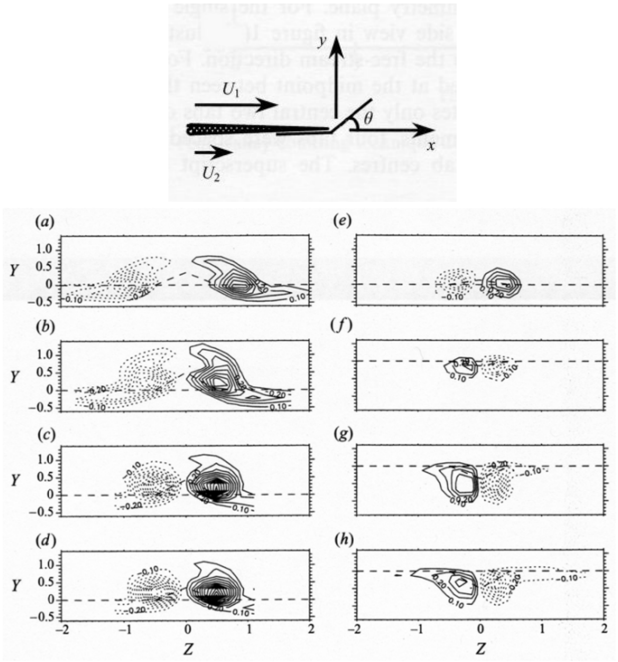


Figure 4 Streamwise vorticity contours in a 2-stream mixing layer generated by a triangular tab, at *x/b*=2, where *b* is base width of the tab. Data in (a)-(h) are for tab inclination θ = 135, 90, 60, 45, 15, -15, -45 and -90 degrees, respectively [19].

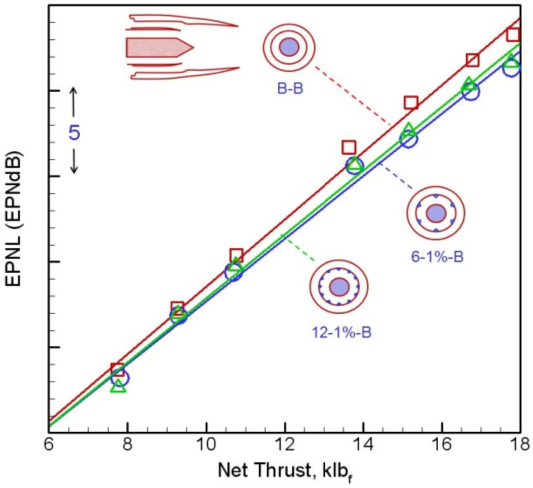


Figure 5 Noise reduction with a model of P&W JT8D nozzle. B-B: baseline nozzle; 6-1%-B: 6 delta-tabs on core nozzle having a total core area blockage of 1%; 12-1%-B: 12 delta-tabs on core nozzle having a total core area blockage of 1%, [36].

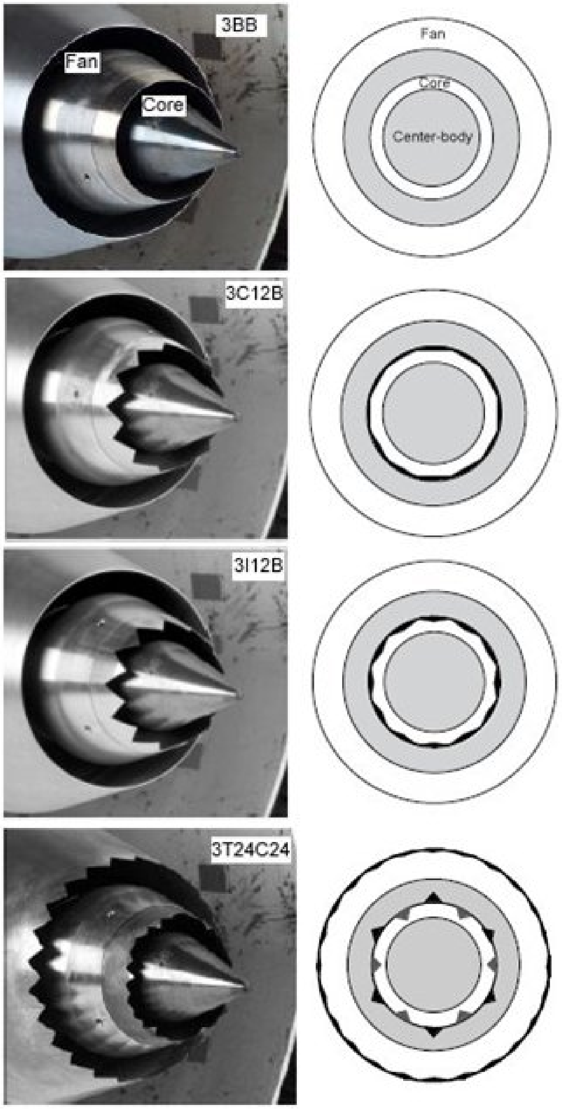


Figure 6 Baseline nozzle (‘3BB’) and examples of chevron and tab configurations (‘3C12B’, ‘3I12B’ and ‘3T24C24’); [41].

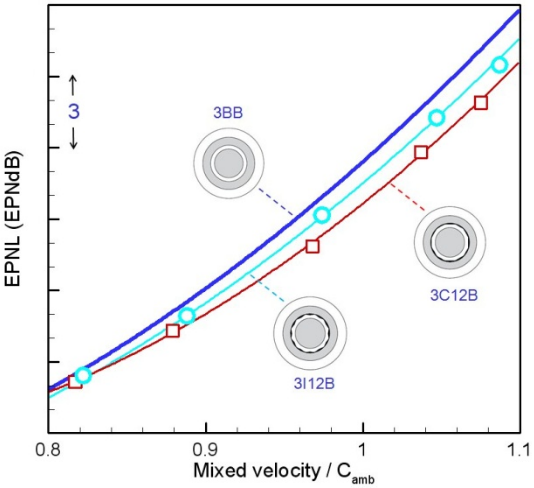


Figure 7 Noise reduction with two chevron configurations (3C12B and 3I12B) compared to baseline (3BB) case, [41].

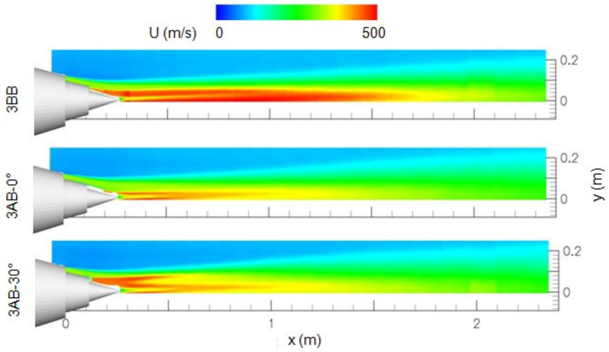


Figure 8 Mean velocity contours. Top graph is for baseline (3BB) case; two lower graphs are for the 3A12B configuration at indicated azimuthal angles (0 and 30 degrees relative to the chevron tip), [44].

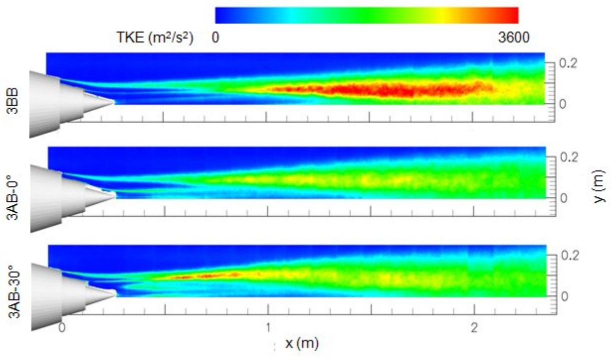


Figure 9 TKE contours corresponding to Fig. 8.

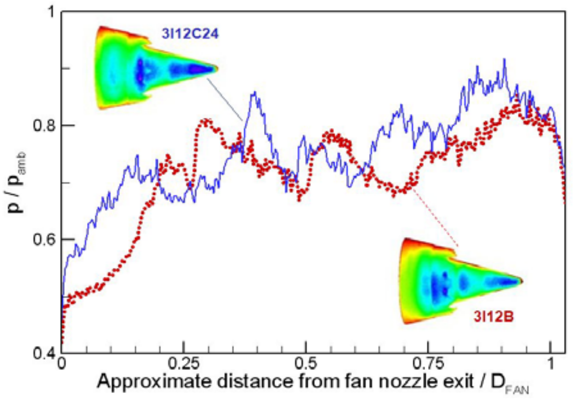
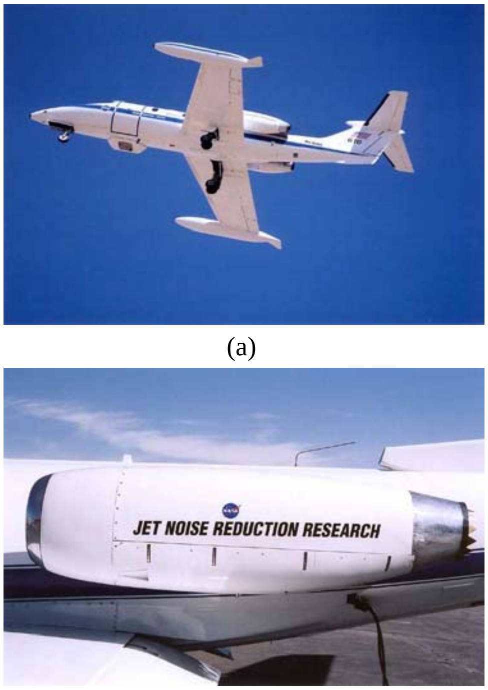


Figure 10 Surface pressure distribution obtained by pressure-sensitive-paint experiment for indicated nozzles.



(a)

(b)

Figure 11 Chevron nozzle flight test with NASA's Learjet: (a) during flyover, (b) close-up view of engine and nozzle.

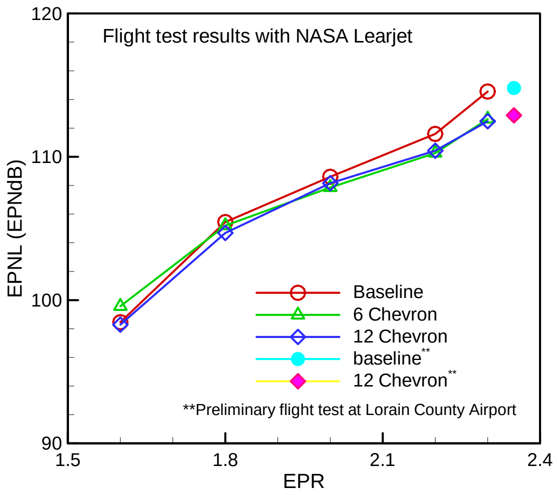
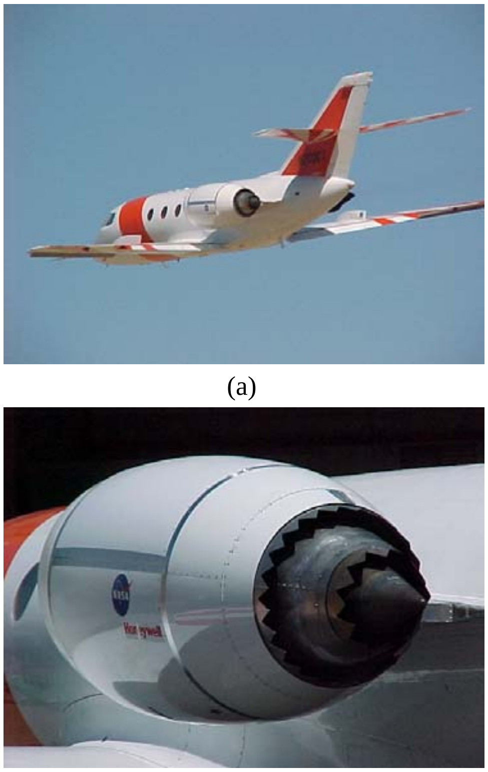


Figure 12 Flight test results with the Learjet; two solid data points are from preliminary tests at Lorain.



(a)

(b)

Figure 13 Chevron nozzle flight test with Honeywell's Falcon 20 test plane: (a) during flyover, (b) close-up view of engine and nozzle.

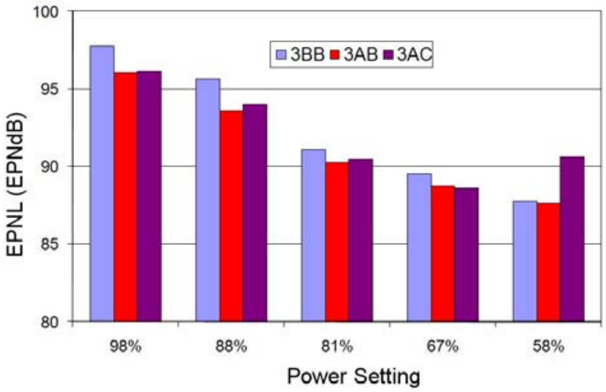


Figure 14 Falcon 20 flight test results on noise reduction [58].

(a)

(b)

Figure 15 GE's CF34 Engine with chevrons: (a) undergoing static test, (b) used on a CRJ900 aircraft.