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COMMERCIAL AIRCRAFT NOISE

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Abstract

Commercial aircraft engine manufacturers have responded well to the public and legislative demands for reduced noise. Over the past decade noise levels have fallen close to those prevailing in the pre-jet all-propeller era. A technology plateau has now been reached, where no single engine noise source can be regarded as dominant, and further progress will be possible only if significant improvement is made on all fronts.

This paper reviews the state-of-the-art in the industry, highlighting areas where progress is likely and the work in hand to ensure that the environmental situation of the 1960's is not repeated. Particular reference is made to the work in the UK on turbomachinery and exhaust noise areas, the use of advanced signal detection and source location techniques, and installation effects.

Introduction

Aircraft noise, the industry's problem child of the 1960's, is now widely assumed to be mature enough to take care of itself. Governments around the world have reduced both their own research efforts and contract funding for industrial research. The UK position, typical of the situation worldwide, now shows investment in noise research to be less than a quarter of that during the peak activity period around 1970.

In support of this position, some published airport noise exposure patterns are showing a decided improvement - London's Heathrow Airport NNI (Noise and Number Index) contours have almost halved in area in a decade[1] - but industry is depressed, and activity is low. New aircraft orders are at minimum levels and up to 10% of the airline fleet, particularly the older, noisier types, are now 'tied down' or up for sale, and are likely to remain inactive until the world economy and airline business improves. When it does, their return to active service coupled with new airline purchases may cause some concern, particularly if the ongoing noise improvement is halted; if so, is the industry technically equipped to deal with the issue? Let us examine the history, status of the technology and attempt to forecast the future position.

Background

Until the late 1950's the world's commercial fleet of around 2,000 aircraft was almost uniquely propeller powered. Whilst the number of propeller aircraft has remained almost constant since then, the revolutionary changes brought about by the application of the jet engine, allied to the availability of cheap energy, saw the fleet double in one decade and treble in two. Today there are over 6,000 jets in the commercial fleet, and a similar number in the business and general aviation sectors, and the impact of number of operations is a powerful factor in noise exposure indices.

Early jets were noisy - very noisy - and their impact on the communities near to major airports was dramatic and sustained as the jet fleet grew in the early 1960's. Multiple lawsuits and vociferous lobbying eventually led to governments around the world introducing controls on the industry in the form of Noise Certification[2] - a requirement to meet noise standards before the granting of a ticket to operate.

Consequently, supported by substantial government funding under the environmental ticket, industry stepped up its noise control activity, and by the time the modern turbofan emerged in the B747, DC10, L1011 and A300 it was able to capitalise on the inherent advantage of its low jet velocities. This benefit is now working its way into airport noise exposures as the turbofan powers an increasing proportion of the fleet. However, since turbofan power aircraft are generally twice as large as their predecessors, the beneficial effects have not been as great or as quickly appreciated as might be hoped. Even at busy airports, where the major airlines utilise their new equipment most frequently, the shrinking of noise exposure contours only represents an absolute benefit of around 5dB, or a 25% reduction in annoyance.

As the fleet gradually becomes dominated by turbofan aircraft the noise situation will continue to improve. But all comparisons are relative and, as Fig. 1 shows, it will be almost 10 years before

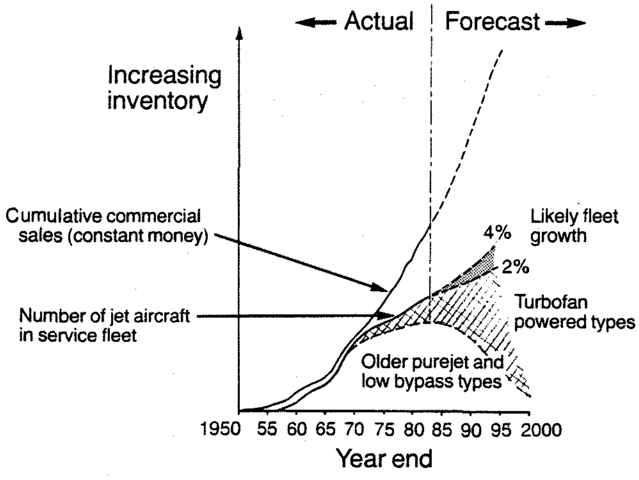

Figure 1. Historic and Projected Airline Fleet

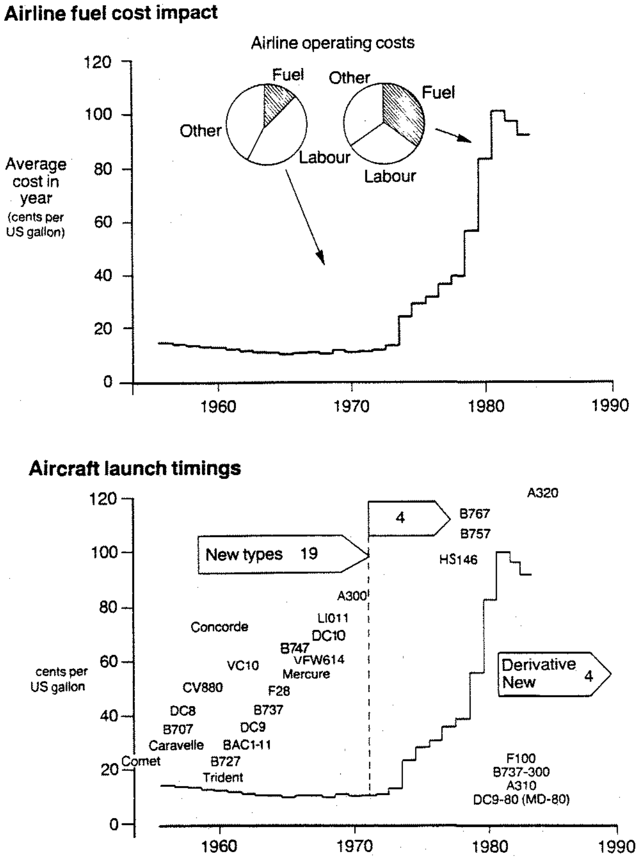

Figure 2. Effect of Aviation Fuel Price Changes on Aircraft Development

the number of turbofans exceed the older jets, and even then there will be as many older jets still in service as there were in the 1960's, the time period of the original problem. So what does the future hold?

Future Trends

The future trend in airport noise exposure hinges upon two factors - the rate of growth of the fleet and the rate at which the older types are retired through antiquity or economic pressures. Both these factors are influenced by the world economy and the proportion of operating costs taken up by the fuel bill. Throughout the 1950's and the 1960's fuel prices fell - some 40% in cash terms or around 70% in real terms. In the 1970's, as Fig. 2 shows, the situation changed as oil producing nations exerted their power. The price rose tenfold, or three to four-fold in real terms, and now accounts for around $\frac{1}{3}$ of airline operating costs. This eroded profits even further than the world-wide recessionary spiral, and delayed the launch and purchase of completely new aircraft that offered all the advantages of the state-of-the-art technology; lower fuel consumption became of paramount importance. As a result, whereas 19 new jet aircraft types were launched before 1970, only 4 have emerged since. These, and the equal number of fairly radical "derivatives" rely in the main on developments of engines launched in the 1960's. Only one all-new powerplant has been developed in the past 10 years, and low fuel consumption has been the primary goal, not noise control.

Consequently, bearing in mind the time-scales for new engine/aircraft development, airport exposure patterns to the end of the century are likely to be dictated by

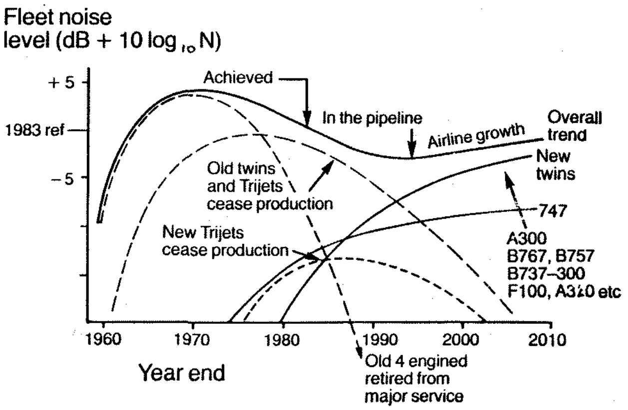

Figure 3. Historic and 25 Year Projected Noise Exposure Trends

the noise from aircraft with the current breed of turbofans. Based upon the fleet projection of Fig. 1, these will foster a further slow noise improvement until reducing source noise level becomes offset by the "number of movements" element as the fleet grows. Most noise exposure indices add a factor of $10\log_{10}N$ to account for the effect of multiple disturbances and, because of this factor, Fig. 3 indicates a possible upturn in exposure patterns to occur in around 10 years time. Since this is the order of time it takes to establish new technology in the airline fleet, the state of today's technology will dictate for how long and to what degree the public appreciate the improvements of recent years.

Technology Status

The engine manufacturing industry has reduced noise levels progressively over the past 20 years - from the early pure jet to the modern turbofan around 20dB per unit of thrust, or a hundredfold reduction of energy. Unfortunately, the ear senses this as only a fourfold reduction - but that is enough to noticeably counter the rapid escalation in noise that occurred in the 1960's. This reduction has resulted from two developments - the emergence of the high bypass ratio turbofan in the late 1960's, and the application of research findings to the engine turbomachinery throughout the 1970's. Consider the cycle trends.

The earliest civil jet engines converted an airflow of some 40kg/sec into 50KN thrust by exhausting it at high temperatures around 600-700m/sec velocity. Jet noise was by far the dominant feature, but it was reduced slightly with the step forwards in thermodynamic efficiency afforded by the bypass engine, where twice the airflow was utilised at a lower exhaust velocity. However, it was not until the turbofan further utilised yet more air and reduced exhaust velocities to around 400-500m/sec that the effect on jet noise became widely appreciated, and coupled with action within the engine led to the 20dB reduction referred to earlier (Fig. 4).

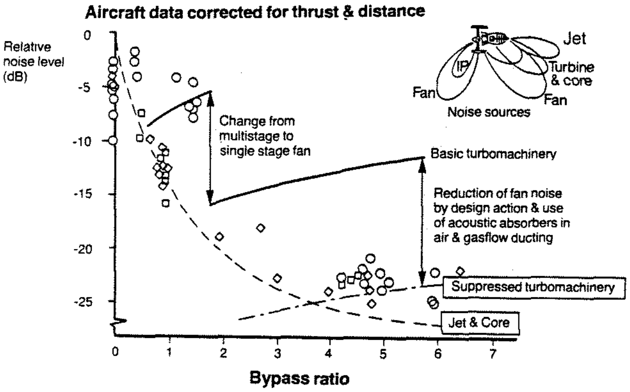

Figure 4. Source Noise Variation With Bypass Ratio

The question before us today is whether we can further improve the situation, for we are no longer concerned with just one predominant source. The curve of noise against bypass ratio is substantially flat across the current bypass ratio range of 3-6, and many sources contribute in varying degrees. R & D will have to be approached on a broad front if a general improvement is demanded, and this will necessitate action on all the sources now discussed.

(a) Jet Noise

For over a quarter of a century the quest for a fully effective jet noise silencer has been notably unsuccessful. The early jet silencers - if silencer is an appropriate name - were largely frequency-raising devices which in part relied upon the sound absorption properties of the atmosphere to make them effective. Such effect was limited to high jet velocities, and they were heavy and also lossy; but fuel consumption increases which would not be entertained today were accepted as a natural penalty of early jet operations. These multitube, multilobe and multichute nozzles all had one objective; rapid mixing of the jet by subdivision into several small elements to promote lower mean velocities in a shorter turbulent mixing region. Importantly, this subdivision also disturbed the organised shock pattern that caused a characteristic high frequency "tearing" noise at supercritical exhaust velocities.

Today, with the engine cycle benefit of lower exhaust velocities already taken, the need for a genuine exhaust suppressor is still there, although the problems are different. With twin nozzle assemblies of large diameter, low frequency noise is enhanced, and engine growth potential is limited by the need to contain core velocities so as not to infringe the more stringent certification requirements at full thrust. A traditional "suppressor", fitted to the core flow as shown in Fig. 5, although demonstrated to be effective[3], causes unacceptable scrubbing drag losses in the bypass flow over the convoluted core structure. The alternative, mixing the core and bypass flows before they are discharged through a single nozzle, is being studied in great depth. Already the RB211-535E4 for the Boeing 757 aircraft uses a single discharge nozzle to good effect, but mixing is a natural process as a result of the core nozzle being "buried" in the secondary flow upstream of the main nozzle. Forced mixing of the two flows holds potential of some 2-3dB jet noise reduction, if it can be accomplished efficiently.

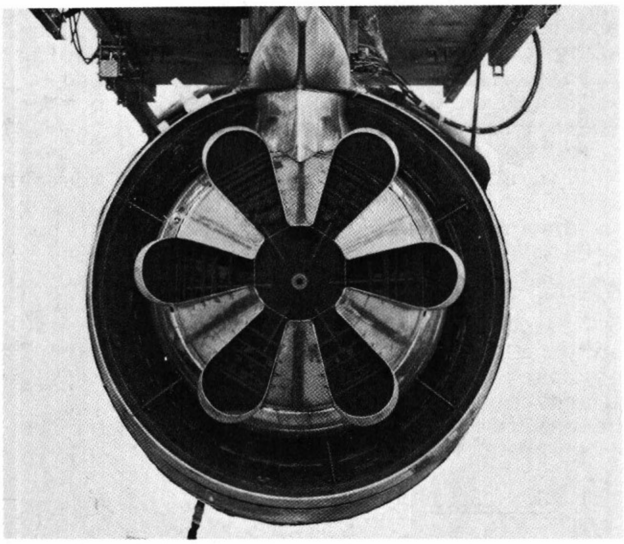

Figure 5. Lobed Jet Suppressor Fitted to Core Nozzle of an RB211

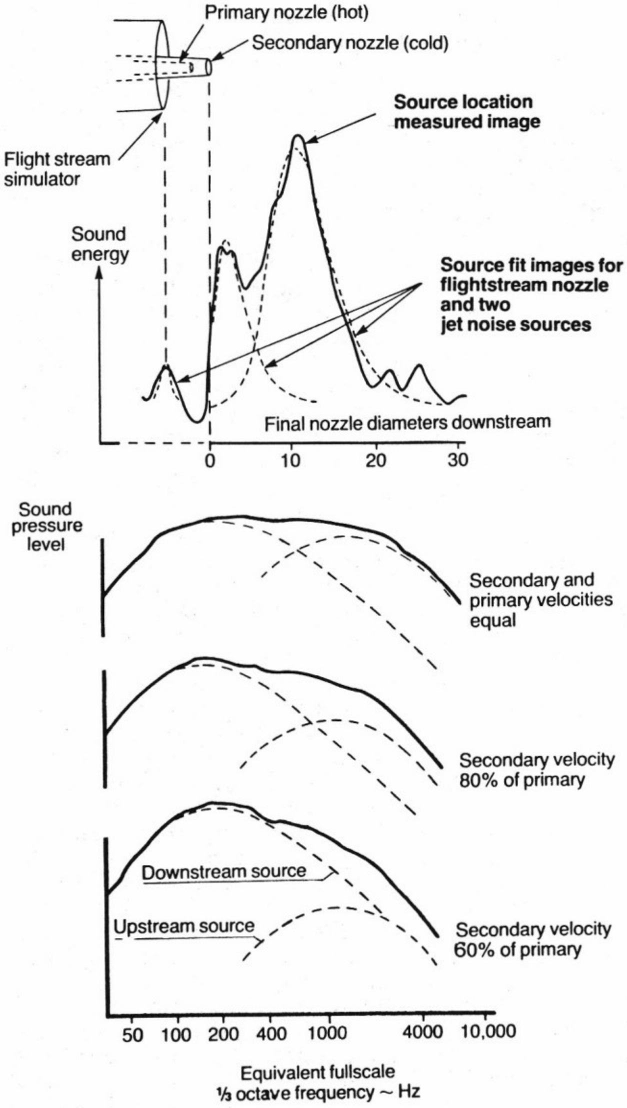

Figure 6. Detection of Two Jet Sources and Their Variation with Flow Conditions

The UK mixer research programme is being conducted at RAE Pyestock. It has been found that some mixers exhibit the same features as jet suppressors did - a frequency shifting (or high frequency augmentation) which can negate the beneficial effects at low frequency. The problem has come full circle, the differences being in lower velocities and the complexity of interaction between three flows; airflow around the nacelle in flight and the two engine exhaust flows.

The structure of the jet mixing process has long intrigued researchers, in the belief that a full understanding will lead to noise control mechanisms. The turbofan exhaust is complex, but recent source location findings[4] have confirmed an earlier hypothesis of two noise producing regions; one close to the nozzle exit and the other distributed downstream. These two sources appear to vary in strength according to the ratio of the primary to secondary jet velocities (Fig. 6), and it remains to be seen whether this information will lead to the understanding necessary to produce substantial jet noise reductions. An important element in the process may be the possible augmentive effect on jet mixing noise of other acoustic sources within the engine[5].

(b) Fan Noise

Until the late 1960's fan noise research was somewhat limited. Pure jet and low bypass engine compressor noise was, in the main, submerged beneath jet mixing noise at all but approach power settings. The two-stage fan on the JT3D engine changed the picture, and prior to the appearance of the high bypass turbofan considerable research had taken place. Theoretical and experimental work on multistage and single rotors[6,7,8] had identified the complex criteria in the generation of discrete tones and indicated design parameters to control these and broadband sources. To this day they still form the background to fan design methods and have promoted basic features of the modern engine. As Fig. 7 indicates, these include the absence of flow disturbances upstream of the single rotor, maintenance of healthy gaps between rotating and stationary stages, choice of rotor and stator blade numbers to ensure "cut-off" of significant modes, and the provision of liberal quantities of sound absorbent material in the airflow ducting.

Research today concentrates on detailed examination of the fan sources to enable practical changes to be made at appropriate points in engine development programmes, and more comprehensive new-design rules to be developed. Examples of advances in recent years are available in the areas of supersonic tipspeed "buzz" noise, interaction tone control, reduction of broadband sources and in development of acoustic liner technology.

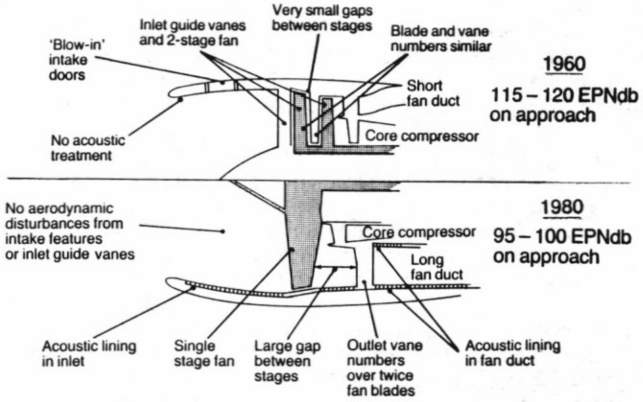

Figure 7. Evolution of the Quiet Fan

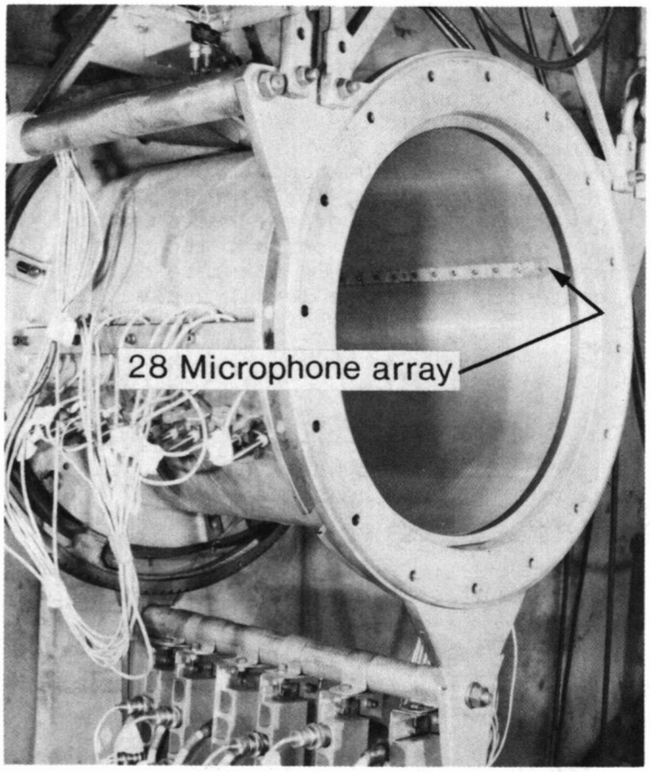

Figure 8. Rotating Duct with 28 Microphone Array for Duct Mode Analysis

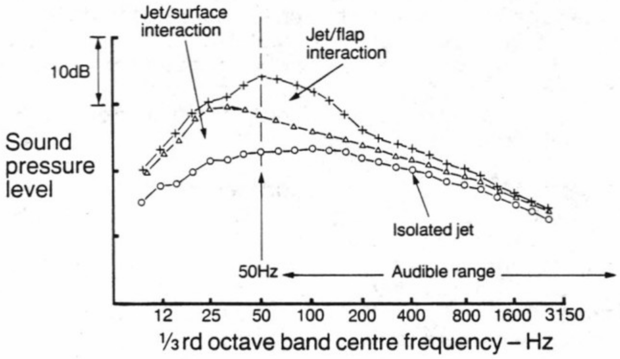

Figure 9. Significance of Installation Effects

The structure of tone generation and propagation is complex, and advances in source detection techniques are being pursued. To this end Rolls-Royce has designed a special rotating intake section, containing 28 microphones, which maps the modal pressure patterns ahead of research fans run in the Rolls-Royce Ansty Compressor Noise Test Facility (Fig. 8). In effect the process is an adaptation of farfield source location techniques to the duct of the engine to ascertain the effects of changes of blade numbers and configuration on tone and broadband noise generation. Recent findings have highlighted the beneficial effect of designing for interactive propagation patterns that rotate in the duct in a direction opposite to that of the fan[9], as an alternative to introducing large separations between rotating and stationary blades to allow wake decay.

In the quest for further reductions in noise and decreases in engine length and weight, such findings play an important part in freeing the fan designer from the constraints that basic noise rules place upon him. Equally, advances in predictive techniques that remove some of the inherent uncertainties from the design process are a valuable contribution. The application of ray acoustics to fan noise radiation theory[10] in the design of acoustic liners is one example of this process. Decisions made at the design stage can have an important impact on the development programme. Good decisions often go unnoticed (or unheard), but there are many examples of bad decisions resulting from a lack of detailed understanding of the issues that are still audible in the skies above the world's airports. Fan noise research will help to eliminate any future bad decisions.

(c) Turbine Noise

The turbine has been a noticeable source under approach-to-land conditions in the past, but the ability to incorporate the knowledge gained from fan experience, where the sources are very similar, and special turbine research findings have virtually removed the problem from modern engines. Turbine noise is almost uniquely tonal in nature, for there are many interactive effects in a multistage turbine, and the tones they produce all convect with the gasflow to radiate from the core nozzle. The principle control features include the choice of blade and vane numbers and spacing between stages, coupled with the lowest efficient gas velocities. Sound absorbent lining in the exhaust duct also assists in minimising the importance of turbine noise.

(d) Core Noise

Over the years, that portion of the exhaust noise signature that cannot be attributed to either the jet or the turbine has been variously referred to as excess, tailpipe, combustor or core noise. Broadband in nature, and usually peaking at a frequency close to that of the jet, its turbulent origins can be associated with many of the features of the core engine from the rear of the compressor, through the combustion system, to the final nozzle and even secondary effects on the jet mixing structure. Current belief is that its origin lies mainly in the combustion process, which is extremely turbulent by design, and in which a high level of energy is released. Predictive procedures have been developed[11] which consider heat release and turbine energy extraction, but detailed supportive research is limited. This situation reflects the experimental difficulties of separating combustor noise from the exit flow noise of the system, and the frequent insignificance of the source in any one series of engines. Although jet noise may be affected by combustion turbulence, the need for concerted research effort is questionable. Certainly little is active at present.

(e) Installation Effects

The presence of secondary engine and airframe structures close to an engine are extremely important, in that they both modify the observed radiation patterns of the engine sources and can create significant secondary sources. An example is shown in Fig. 9, an observation from a model test at RAE Pyestock that formed part of a series of examinations of conventional aircraft installations[12]. The presence of the wing above the pylon mounted engine was seen to induce a low frequency jet-surface interaction source, whilst the deployment of the flap structure created a higher frequency source. In all, the two effects increase the noise level by an amount equivalent to the addition of one or two complete extra engines. To date, airframe designers have paid little attention to the engine installation (from the noise point of view), although various posthumous claims for noise reduction by rear-fuselage or overwing installations are on record. If, as these tests imply, the installation can have as big an effect on the overall noise level of the aircraft as some of the more important engine sources, it behoves the aircraft manufacturers to embark upon research action to ensure that the effects are minimised in future designs. Apart from their effects on noise in the audible range, low frequencies are responsible for complaints about building structure vibration.

(f) Airframe Noise

As with installation effects, the aircraft structure is important in the overall noise at low engine powers on the approach in that it creates its own additional sources. In the "clean" configuration for climb and cruise, any structure-induced noise is only of real importance in the cabin noise context, but when flaps and landing gear are deployed they create considerable large scale turbulence, and hence low frequency noise. It has been demonstrated that airframe induced noise can be as great as any single engine source on many aircraft under approach conditions, and in consequence further lowering of engine sources will be less effective if airframe sources remain at their current levels. There is little evidence that the airframe manufacturing industry is taking the steps necessary to introduce noise control concepts in future designs.

Activity in the 1980's

The future requirements for continued and extensive noise research will be dictated by the degree of acceptability of current technological standards as they extend throughout the service fleet. This in turn will dictate whether or not the worldwide legal requirements need to be made more stringent, for were it not for the world recession of the recent past and the possibility that current technology has attained reasonable standards of acceptance, the noise levels demanded of the manufacturers might already have been lowered.

As it is there is now some recognition of the fact that there is little point in toughening standards for completely new designs of aircraft when the world fleet does not reflect the standards of 7 years ago. In fact only 30-35% of the world fleet incorporates high bypass technology, and some 20% is still incapable of meeting the original standards established 14-15 years ago.

If simplistic projections of the type illustrated in Fig. 3 are to be believed, the downward trend in noise exposure will be maintained for another 5-10 years as modern high bypass engines become the fleet-wide standard. At expanding airports exposure values will always tend to increase by virtue of the "number of movements" element in exposure rating indices. At these airports sensible structuring of the operational patterns and restrictions on urban developments will aid to contain the problem. At the more saturated airports it will be 5 years or so before it will become evident whether further noise reductions are necessary.

Until then a cautious approach should be adopted. Research should not be sacrificed on the altar of economic expedience, for it took almost two decades to build both the teams and facilities that have contributed to recent research findings. As pointed out earlier, the worldwide tendency is to do just this; moreover, the sacred cow of noise certification is consuming far more industrial effort than it merits, to the detriment of real research. A lessening of the legal strictures - firstly in the cost of compliance demonstration and subsequently in restructuring of the certification methodology to recognise operational reality - would aid to finance research in areas where there is hope of meaningful reward. These include:

(a) Full understanding of the generation and propagation of tonal and broadband components of fan, compressor and turbine noise. Whilst the basic design criteria for these engine components have remained substantially unchanged since the days of the early turbofan, detailed research has filled in some of the picture and produced additional techniques for controlling noise at source. The attractions of further improvements are great, for the need to specify tightly the numbers of blades on the rotating stages and the space in between each stage constrains the optimisation of both performance and weight which is otherwise possible where the designer is free to specify shorter compressor and turbine sections. It also offers the possibility of reducing intake length for a given noise standard, by shortening the length of acoustic linings necessary to suppress compressor and fan noise.

(b) Over a quarter of a century of jet noise studies have never produced a genuine exhaust suppressor. Modern engines are quiet because low specific thrust means low exhaust velocities, and research has managed to counteract any increase in turbomachinery noise brought about by the greater power handling. The incentive to produce a genuine suppressor lies in the potential for growth in engine development. Jet noise was the overriding issue 20 years ago, but even today it is still important in that modern engine growth is limited by the need to satisfy noise requirements at full power.

(c) Research in recent years has exposed the importance of the mating of the powerplant to the airframe, in that engine generated sources can be amplified (or reduced) and new sources created. The designers of the next new aircraft types should take existing findings fully into account before they mount their powerplants in one of the "conventional" manner.

(d) Propeller technology has advanced to the stage where some believe that the next major aircraft development will incorporate a swept, or even double-stage swept, open rotor. Fuel savings of up to 35% over the turbofan have been claimed. Noise seems to be the issue, in the cabin primarily, that might delay any early development. The issue should be addressed vigorously.

(e) Operational techniques for reducing noise should be positively encouraged. There is probably as much to gain in the near term from an enlightened approach to departure and approach techniques as there is to come from noise control technology. At present such techniques as those demonstrated by Concorde, and regularly in use at Frankfurt in the approach sector, are positively discouraged by administrators at all levels. They are claimed to present "a burden to the cockpit crew and air traffic controllers", but there is no evidence that this is true in the two cases quoted. Optimum take-off procedures such as those Gulfstream American have developed for their GII/GIII aircraft, and which are recognised at airports and by US Federal Authorities, cannot claim any benefit for their usefulness in the rigidly structured certification arena. These anomalies must be addressed.

Overall Conclusions

From the foregoing it may be concluded that:

1. Industry has responded well to demands for lower aircraft noise over the past two decades. Sound output per unit thrust has been reduced a hundredfold. We are now apparently close to a technology plateau, which will only be eroded by persistent research effort.

2. Further progress is frequently a function of the encouragement given by national governments. It would be unwise for governments to ignore the possibility of a decline in industrial research when faced with a possible increase in noise exposure in the 1990's.

3. There should be an objective review of the noise certification process to introduce incentive, greater relevance to actual operation and to minimise both the cost and labour intensive bureaucracy that it has created in government and industry.

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