

PROBLEMS OF AEROPLANE NOISE IN THE 1970S

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INTRODUCTION

During the past five years, noise has become a limiting factor in the design of practically every type of aircraft, other than those for initial training. Jet airliners are recognised as noisy by the people near airports, helicopters and VTOL types are far too noisy to land in very confined spaces, propellered airliners doing their best to compete speedwise with their jet driven counterparts, present problems of internal noise and vibration, while most first line military aircraft and missiles suffer from metal fatigue caused by vibrations arising from noise. In the future, the supersonic transport can only fly to the accompaniment of a sonic boom trailing the countryside behind it. It is clear that problems of aeroplane noise are likely to dominate the design situation completely in the future and that it is only by clear anticipation now of the problems of the 1970s that the requisite scientific knowledge can be obtained.

Those of us who cover the field of aircraft noise in our researches classify our problems under three headings:

1. Noise affecting people on the ground during takeoff, landing, ground running, and in cruising flight.
2. Noise affecting people within the aircraft during cruising flight.
3. Noise affecting the integrity of the structure and equipment.

Since each of these topics involves a study of essentially different factors, it is best to deal with them separately as three parts of a very broad problem:

PART I: THE EFFECTS OF NOISE ON PEOPLE ON THE GROUND THE ENVIRONMENT OF THE 1970S

In view of the overproduction of airliners in the past few years, and the economic difficulties of the smaller airlines, it is very difficult to predict the rate of development of civil aircraft in the future, particularly as the financial backing for development may depend very much on the way in which the airlines amalgamate into economic units. Thus, in Africa, for example, the move towards

fast jets generally must depend crucially on the rate at which the African countries build up a communal airline. In Europe, on the other hand, the establishment of a single Common Market airline and the amalgamation of large United States airlines has unquestionably provided the correct financial background for advanced designs to be ordered.

LONG-RANGE AIRCRAFT IN THE 1970S

The obvious new development in long-range aircraft lies in the supersonic transport. Floyd¹ (Fig. 1), has presented a clear indication of the increase of takeoff thrust which will go with this class of aircraft in the early 1970s. Thus, the thrust available must be expected to be double that of the latest jet airliners, and, other things being equal, the noise to go up with it. Fortunately, this increase of thrust will result in an increased initial rate of climb which is expected largely to offset the effect of increased thrust over the houses below the aircraft. Noise estimates vary depending on the details of the design. Figure 2 shows one such estimate for an $M = 2.2$ aircraft designed for a 3,000 nautical mile range, and with a slender delta configuration. It may be seen that although the noise of the supersonic airliner is some 5 db greater than that of the subsonic craft during the full power section of the initial climb, nevertheless the supersonic transport is marginally quieter when throttled back over an inhabited area to a low 500 ft a minute rate of climb. However, the reduction is very small and does not present a promising picture for night operations where noise limits of 102 PNdb are already being implied at such control points. It must

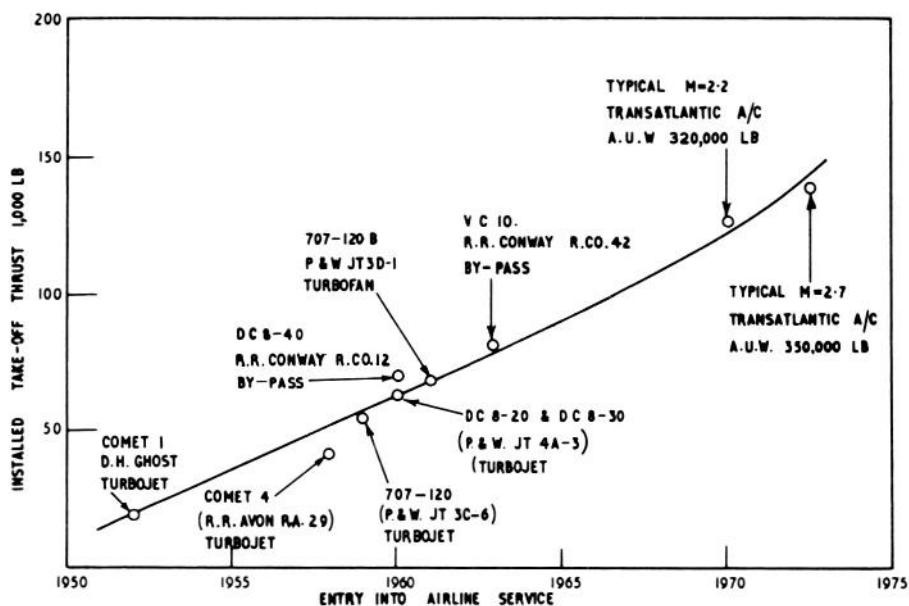


Fig. 1. The Increasing Take-Off Thrust of Civil Aircraft

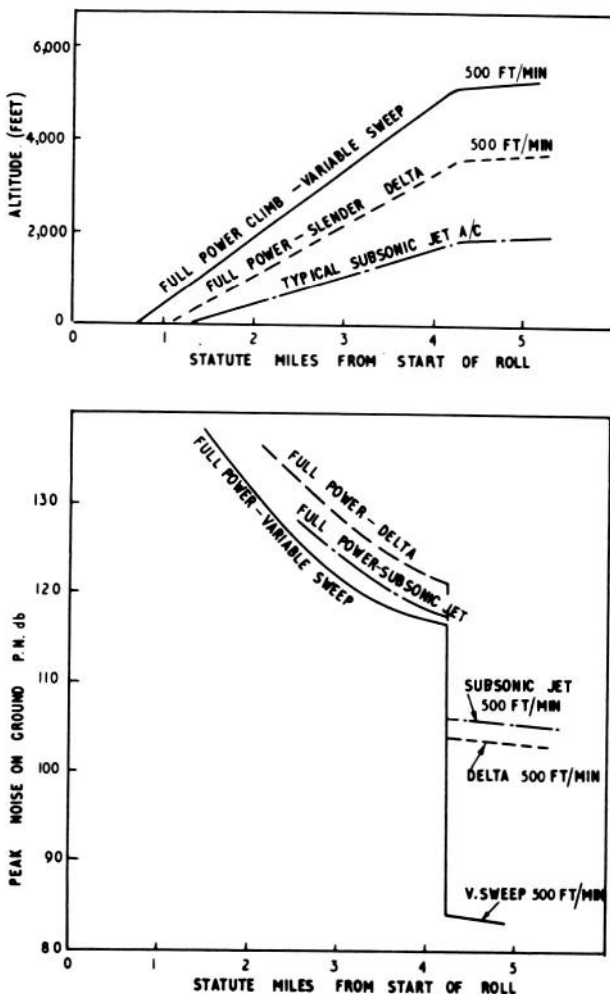


Fig. 2. Noise Levels Under Flight Path at Take-Off

also be remembered that thrust increases cannot be countered completely by an increase in aeroplane height, since to a great extent one is exchanging peak noise level for duration. Figure 3 illustrates this point. If one aircraft is at twice the height of the other and in this condition makes the same noise level immediately below, the lateral area over which a noise level, say, 6 PNdb less is made, is about double on the higher aircraft. This is really just another way of saying that no matter what the height reached is, half the noise energy must reach the ground. Even under the flight path, if an equal forward speed is postulated, the time over which the noise occurs will be lengthened in proportion to the thrust used. Thus a compromise is necessary in which a still greater throttling back is used, and possibly an earlier reduction of thrust at the expense of height.

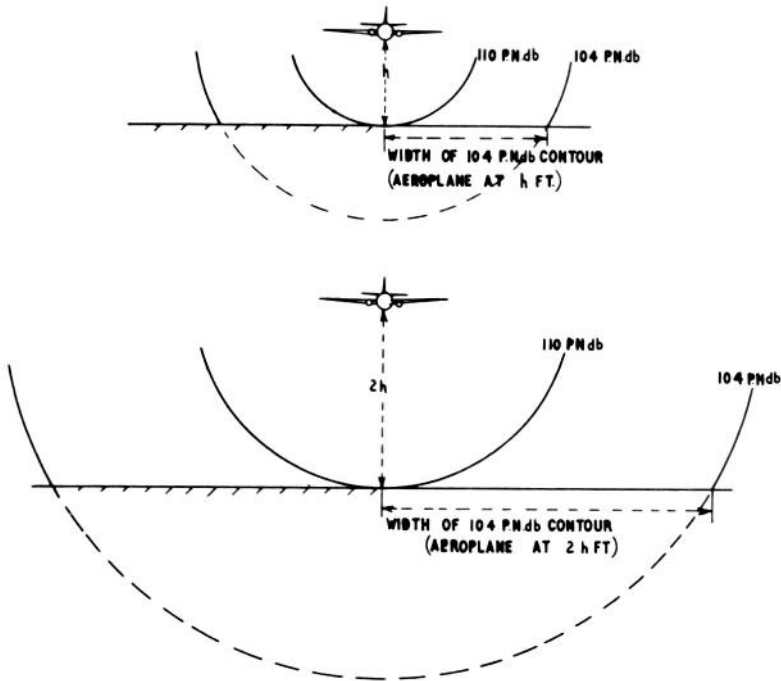


Fig. 3. Effect of Aeroplane Height on Lateral Spread of Noise

Even so the noise during the ground run and initial climb is considerably greater than that on subsonic jets. Figure 4 shows noise contours¹ for the present subsonic and future supersonic airliners. It may be seen that in fact the width of the noise contours are significantly greater and that an increase in the noise nuisance must occur unless some additional silencing devices are fitted to the engines, or lower velocity engines fitted.

During the past few years, noise during landing has gradually become a major cause for annoyance. This noise, emanating largely from the compressor rather than from the jet of the throttled engine, cannot be overcome by the use of height and must be tackled at source. The narrow-delta configuration is one in which the high induced drag during the final approach must be countered with engine thrust. It is therefore clear that landing noise is likely to increase significantly unless compressor noise is reduced at source. This problem will be aggravated by the growth of medium- and even short-range jet airliners all tending to use greater landing power and all landing via a very concentrated approach path, often over a crowded housing area. Indeed there is some indication² that with the increase in numbers of jet operations in ten years at London Airport the limits should be reduced by at least 8 PNdb to give the same annoyance levels.

Apart from the above, the acceptability of the supersonic airliner must depend on the acceptability of the sonic boom caused by the aircraft as it flies across the countryside. Although estimates change from time to time, Floyd's

picture¹ (Fig. 5) of the free-air pressure jump can be taken to illustrate the areas affected in a flight of a Mach 2.2 aircraft from London to New York. It is seen that there is a relatively small area suffering a pressure jump above 1½ lb/sq ft during the transonic acceleration and a region varying from 20 miles to 1 mile across along the whole route which suffers a free-air boom of from 1 to 1½ lb/sq ft. Theoretical calculations with optimum planforms suggest that it is possible to reduce this figure to 1 lb/sq ft but that it is highly improbable that any further significant reductions can be made.

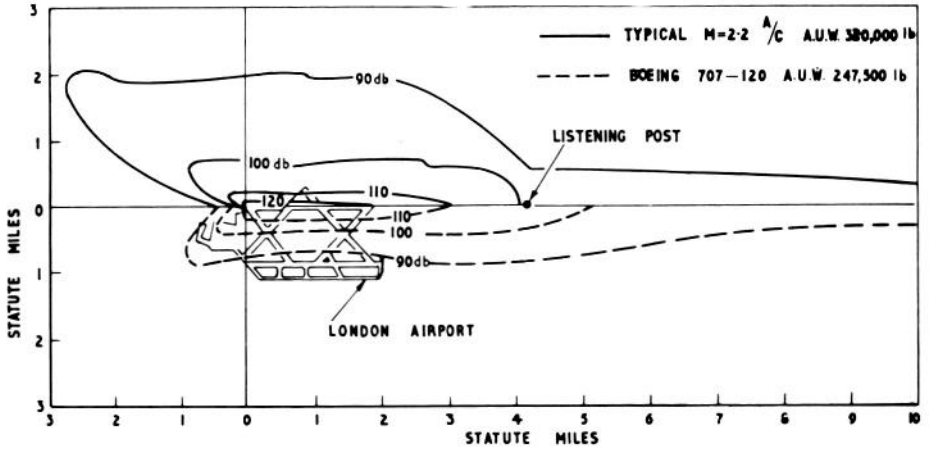


Fig. 4. Sound Pressure Level Contours at Take-Off for Subsonic and Supersonic Aircraft (Floyd)

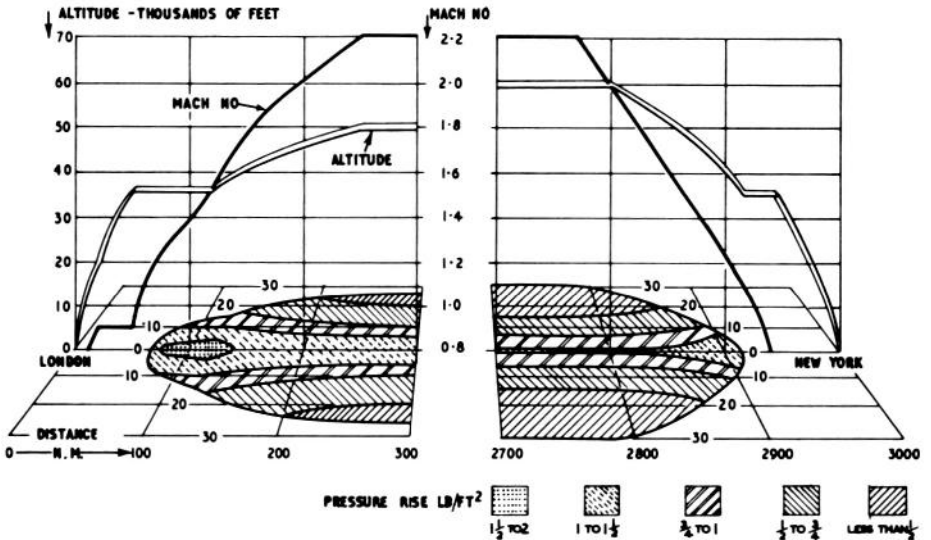


Fig. 5. Area Affected by Sonic Boom for Typical Flight of $M=2.2$ Transport (Floyd)

It is unfortunate in a way that restrictions on supersonic military flying have prevented us from obtaining extensive experience of the acceptability or otherwise of bangs of these amplitudes. It is still more unfortunate that the experience we do have points clearly to the marginal nature of things. There is some evidence, for example, that 0.75 lb/sq ft free-air jump is acceptable to the public. There is other evidence that 2.0 lb/sq ft is not. Since in acoustic terms this difference is small, it must in fact follow that no clear limit can be given to acceptability any more than it can be given in any social problem involving a community. There is also a basic social problem in that traffic noise affects only the noisy streets, takeoff noise only the vicinity of the airport, while sonic boom noise affects the whole country. Thus an objection by a hypersensitive fringe of, say, 3 percent, can amount to a major outcry. There is also evidence, for example, of a completely different reaction inside and outside a room, and that the strength of the boom is very much a function of the surrounding building structure, the atmospheric turbulence, wind conditions and so forth.

On the other hand, in respect of takeoff and landing noise, there is evidence that two of the greatest contributors to annoyance are the extensive interference with communication and a general feeling of insecurity arising respectively from the duration of the noise and the closeness overhead of the aircraft during landing. Once sonic booms are understood by the public neither of these objections need arise; the results of single tests with supersonic aircraft may therefore be misleading as a long-term indication of acceptability.

It seems obvious from the above that the establishment of sonic boom limits must be a gradual process and that any attempt to establish final limits on the basis of majority opinions of small flyover tests at this stage can only give a preliminary indication which practice may or may not confirm.

This lack of finality in assessing acceptability must react on the rate of development of supersonic transport aircraft and makes any prediction of trends in the 1970s very dependent on the shape which airlines have taken by that time. For example, if it is shown that sonic booms over populated areas are unacceptable, it may be necessary to establish a universal carrier service to operate special supersonic services across sea masses or unpopulated areas, the national airlines all booking space to suit their requirements. In this way, experience of supersonic travel on limited routes can be obtained economically and the way cleared for further developments, possibly with variable geometry aircraft evolved for part supersonic and part subsonic operation.

It is not the purpose of this lecture to argue the case for one or other type of aeroplane configuration. Nevertheless, the considerable advantages of a variable geometry arrangement from the noise point of view are worth emphasizing since the increased flexibility of operation must be attractive to an airline. As indicated in Fig. 2, for example, the takeoff and initial climb is improved by a high aspect ratio to an extent which reduces the noise in the immediate airport vicinity by 7 or 8 PNdb, while the much lower power required to climb at 500 ft per min over built up areas is sufficient to bring the climb noise some 20 PNdb below present-day jets. Thus the vital need for unlimited day and night operations is met by the variable geometry type.

Detailed calculations for various configurations of the sonic boom magnitudes during the transonic acceleration stages are of interest also. Figure 6 shows the magnitudes involved on two competitive configurations, one with variable geometry, the other a slender delta. This particular investigation, at least, does suggest that the improved height available with variable geometry may well bring the boom amplitude down to an acceptable figure. Since in many ways the variable geometry aeroplane is the easier one to develop, future supersonic transportation may well be accelerated by the acceptance of this principle.

It seems, therefore, that the 1970s will unquestionably see supersonic transport aircraft in operation, possibly limited in routes and very possibly using the variable geometry concept to give an optimum compromise between performance and noise: the growth of operations must depend on the long-term acceptability or otherwise of the sonic boom situation. In the meantime there is an urgent need to establish the wide bounds of acceptability by flyover experiments

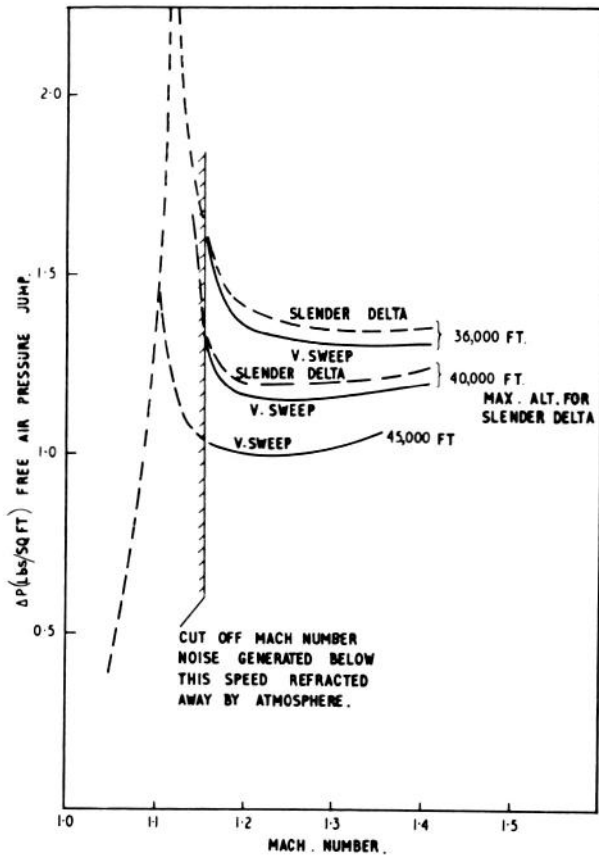


Fig. 6. Sonic Boom of Slender Delta and Variable Sweep Aircraft During Transonic Acceleration

and by simulated boom experiments in built up areas. There is also a good case for controlled relaxation of military embargoes on supersonic flying in order that some true long term experience can be gathered of the acceptability of mild booms of strengths which fall within the relatively wide limits of acceptable and unacceptable obtained from the flyover tests. Alongside these experiments, controlled laboratory work on the subject effects of the shape of the pressure jump, on frequency of occurrence, on changes of jump shape from reflections and from atmospheric scattering, must proceed before the true pattern of supersonic transport development can be predicted.

MEDIUM-RANGE AIRLINERS IN THE 1970S

The development of medium-range airliners, not having the same problems of national prestige as do their larger brothers, is easier to predict, though again the rate of development will depend on the airlines' financial background. Few who have flown extensively in large high-speed turboprop aircraft can be in any doubt about the advantages of pure jet transportation. The fight to maintain competitive blockspeeds on turboprop aircraft has led to higher and higher engine powers and higher and higher tip speeds, a combination which guarantees near-impossible problems of noise and vibration inside the cabin; a general replacement of propeller aircraft by jet-driven craft is likely therefore to extend gradually to shorter and shorter routes. This implies a manifold increase in jet takeoffs and landings at the main airports, and also a penetration of jet operations into many secondary airports now content with low powered propellered airliner movements.

At main airports, the noise increase following the growth in frequency of jet takeoffs will be countered to some extent by the shorter takeoffs of the medium range machines and the greater height achieved before leaving the precincts of the airport. However, there are many dangers involved in accepting this philosophy too blindly. There is some evidence that the public is offended by the *number* of noisy takeoffs rather than their exact noisiness, since it is the number of intrusions which counts rather than the degree of each intrusion.

Furthermore, it is the natural practice in designing aircraft to work *up* to the limits imposed, when some performance or economy gain can be achieved. Medium-range jet takeoff runs are therefore likely to be longer than those of equivalent present-day aircraft, involving more noise both in amplitude and duration to the sides of the runway very close to the airport.

Even away from the airport boundary the nuisance will be significantly greater since at schools, churches and offices, the number of interruptions per hour, whatever the detailed noise levels, is a significant factor in the formulation of people's reactions. The eightfold growth of jet operations expected at London Airport during the decade 1960-1970, for example, cannot be envisaged with too great a confidence, even though great strides have been made by the manufacturers and operators and every single operation is expected to fall well within the present-day limitations; the aggregate of aeroplane power and the general volume of noise, the number of interruptions, and the lateral spread, are all bound to be greater.

A second problem and one which is growing apace at the moment is that of noise on landing. Here, unless the approach path is altered, height is the same for all aircraft, so that unless landing noise is reduced drastically at source, the nuisance must increase. This is already happening at Idlewild and London, and complaint rates are growing. During the next ten years they must grow still further for a variety of reasons. The takeoff problem has in most cases been alleviated by a system of preferred runways based on the distribution of homes around the airport; at Idlewild, for example, takeoffs occur over the sea. Since, however there is usually a sharp population gradient from one side of an airport to another, the landing paths tend to be highly populated and extend almost to the perimeter itself. Thus, during landing, noise levels appreciably higher than takeoff limits often occur over built-up regions.

The introduction of the fan engine has also tended to aggravate the landing situation. In order to reduce takeoff noise these engines emit larger masses of air at lower velocities. This increased air has to be compressed, however, and the result is large compressors. Figure 7 illustrates the possible increase in noise during the landing between an orthodox jet and fan-type engine.³ It is seen that the area over which a given level of noise occurs can be more than doubled.

It is difficult to assess the noise reduction really needed to compensate for the increased frequency of landing. A direct adjustment based on a fixed total noise energy per hour, for example,² would involve a reduction of some 8 PNdb in the allowable peak noise over a built-up area and this is probably not too pessimistic an estimate.

To sum up therefore, the 1970s are likely to see the introduction of medium-range subsonic jet airliners into service in many of our major airports, and on

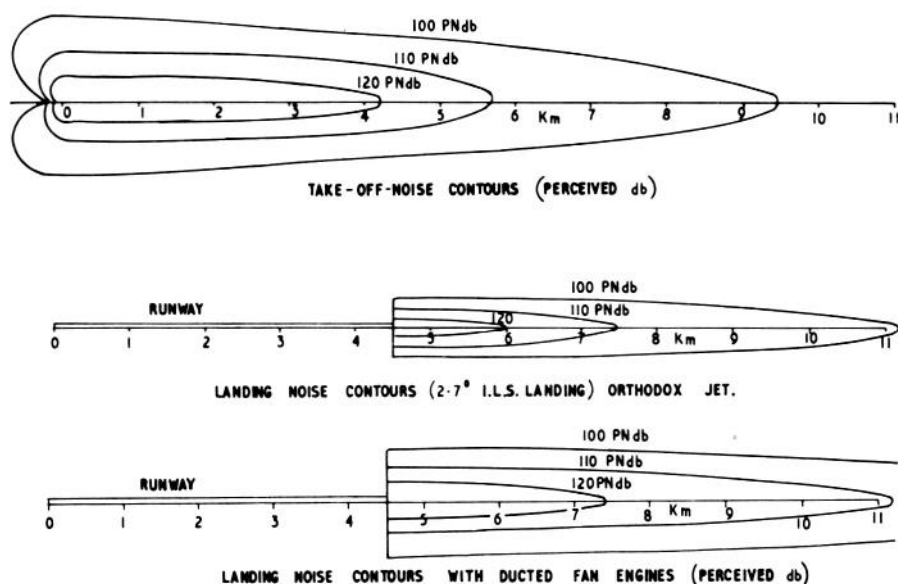


Fig. 7. Increase of Landing Noise with Fan Type Engines

such a scale as to require an appreciable reduction (8 db or more) in landing noise and possibly as much on takeoff. These reductions can only be obtained by the introduction of low-velocity engines and the successful suppression of the compressor noise.

VTOL AIRCRAFT

While it is unlikely that long range and medium range airliners in the 1970s will embody the vertical takeoff principle, by that time the awareness of time saving will have grown to the extent of accepting city center landing and takeoff as a necessary component of short range flights. Vertical takeoff and landing by jets has already been shown to be acceptable and relatively efficient, provided the landing time is kept to a minimum. Unfortunately, it has also demonstrated itself to be a particularly noisy process, partly because of the need for a high vertical thrust greater than the weight of the vehicle, partly because low velocity engines are too heavy, but also because city center landing implies the close proximity of offices, houses and schools.

Before VTOL can be accepted for city-center operation, jets must be replaced by much lower velocity fans, vertical propellers or helicopter-type configurations, or landing areas must be sited to keep vehicles away from the immediate vicinity of houses. Since fan aircraft have not yet flown it is unlikely that they will achieve operational status by the early 1970s and the problems of VTOL are really those of jet silencing and of suitable siting. In addition, the turbine-driven helicopter is a strong favorite and its problems must be looked at.

GROUND RUNNING

In this review of the noise environment of the 1970s, we cannot ignore the growing problems of ground-running noise in respect of the apron personnel, the public in the watching enclosures and the inhabitants during night testing. Engine testing at night has in fact tended to decrease with the years while ground mufflers have become available and are being used. In view of the increase in taxiing and flight noise at night, it is therefore safe to surmise that ground testing need present no great problems over and above those now existing, and that the greater worry arises from the much increased taxiing and takeoff noise of the supersonic airliner and its effect on apron personnel and observers in the terraces. Open-air terraces may, by then, be a thing of the past, and airport planners should accept this change in any new airport development. Figure 3 indicates quite clearly the vastly greater lateral spread of the noise. It is difficult to envisage the roof terraces at London Airport to be as popular as they are now with noise levels reaching 130 PNdb.

The greater worry involves the apron personnel. Figure 8 shows an indication of the number of minutes per day a person can be allowed to subject himself to noises of various levels without some degree of long term deafness. It is apparent that in the 1970s hearing conservation by using earplugs, earmuffs, and acoustic enclosures will have to be studied, and practiced with much greater rigidity, in respect to a much wider variety of apron personnel than at present.

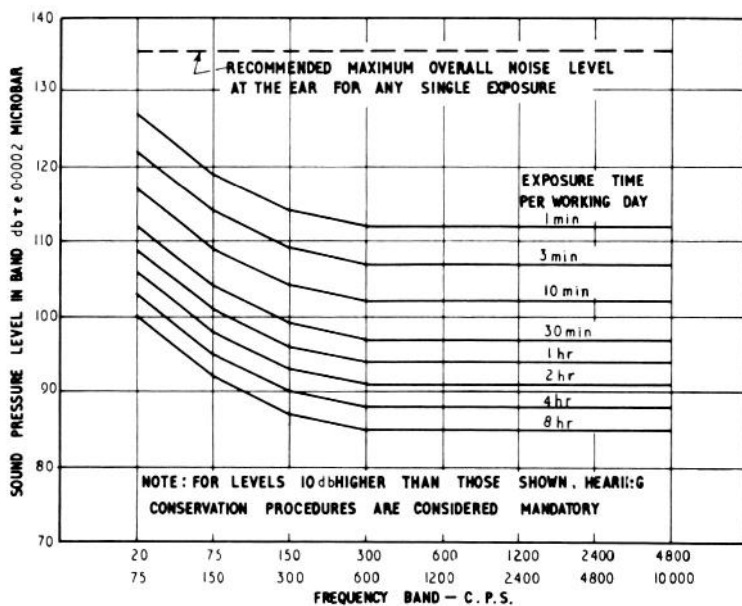


Fig. 8. Recommended Exposure Times for Different Noise Levels and Frequencies

NOISE PROBLEMS AND METHODS OF SUPPRESSION

If the survey of the previous sections is accepted as a true picture of the aircraft situation in the 1970s, it is immediately possible to list the outstanding noise problems as far as people on the ground are concerned. They are:

1. With the increase of takeoffs and landings new and lower limits of allowable noise will be necessary. Their form and amplitude should be agreed upon now internationally, in order that each aircraft and engine designer can abide by them without fear of a unilateral performance penalty.
2. Landing noise must increase in significance and annoyance unless steps are taken to counteract the increase in operational frequency by a reduction at source. Work aimed at studying compressor noise reduction is vital.
3. Supersonic transport aircraft will increase noise significantly near the airport and may require noise suppressors to cope with this section of its flight. New work on noise suppressors is urgent.
4. Sonic booms are sure to cause extensive objections under some circumstances, even though flight planning is aimed at keeping the objections within bounds. Experience over a period of time with military aircraft operating to give mild booms of the kind likely in the future is needed now in addition to single flights and simulated boom experiments. The effect of an indoor or outdoor environment turbulence in the atmosphere, sharpness and reflections of the boom, surprise element, etc., are all factors which will modify the limits.

5. VTOL operation of civil airliners is limited by noise, even on helicopters. There is a need for studies of the noise of fan systems, multiple jets and low-velocity interacting jets to indicate the possibilities of VTOL jet operations.
6. Increased power and number of jet aircraft is likely to imply changes in observers' enclosures and in hearing conservation measures on the apron.

It is impossible to make a full coverage of possible methods of overcoming the above problems in a paper like this. The remarks of the next sections are therefore intended as an introduction to a discussion, raising possibilities, rather than claiming conclusive answers.

SUBJECTIVE LIMITS

When jet airliners were first introduced, it was agreed by the New York Authority that they should not be subjectively noisier over the nearest community than the worst quarter of the then existing movements. This led to the concept of perceived noise units (PNdb) and to the limiting value of 112 PNdb at Idlewild and a somewhat lower figure at London, Dusseldorf, and elsewhere. Such limitations are not extensive, and rigorous noise limitations are in fact the exception rather than the rule, if one takes all the world's major airports into account. Since, in general, limitations follow complaints, it follows that we cannot accept that a universal nuisance is being committed, and that all airlines and airports will accept the economic consequences of arbitrary limits.

Against this, is the fact that jet airliner operations are growing on a world basis, houses are being erected closer to airports, and that engine and airframe designers must anticipate a different noise nuisance situation in the 1970s when the aircraft now being planned become operational. Engine and airframe designers should therefore be given a target in keeping with the future rather than be allowed to design up to the present limits. We must therefore ask ourselves three questions:

1. In what form should limitations be imposed?
2. What should be the values of these limits?
3. How can such limits be agreed upon?

In a way it is easier to answer these questions in the reverse order, since no technical limits are worth anything if they cannot be agreed upon by all concerned to be fair, workable and economically reasonable. Three alternatives are possible. Each airport can indicate its own limits and the reductions required in the future in the light of traffic increases, an international agreement can be achieved which will relate future noise limits to local conditions and traffic densities, or thirdly, the engine manufacturers can get together and agree on a code of practice in terms of total acoustic output of their engines in future years.

This last proposal, while appearing to interfere with commercial competition, may in fact be more satisfactory than the others. Pearson has pointed out,⁴ for example, that there are only five prime producers of aircraft engines in the Western world, two in the United Kingdom, three in the U.S. Agreement on progressive reductions in noise output in such a way that technical progress in each firm is shared fairly between improved performance and noise reduction

should not, therefore, be dismissed without a thorough investigation of its possibility.

Failing the above, there is certainly an urgent need for some international agreement between airports in the manufacturing countries (i.e., U.S. and the United Kingdom), on a future code of practice in airline operations. Manufacturers must be given this at least six years before they put aircraft into service for it to be of value in assessing engines.

Coming now to the form of these limits, it has become apparent that annoyance is strongly related to the degree of intrusion into life caused by the noise, and that this intrusion, once it occurs, need not be related directly to the level nor to the duration of the noise. Thus the fear element in regard to landings, the interference with a television picture, the disturbance from sleep and the interference with communication, all contribute to annoyance. Indeed, in view of comments on the annoyance arising from television picture distortion, one wonders whether or not there should be limits on the electronic as well as acoustic noise made by an aircraft. Certainly some at least of the present annoyance could be dispelled by more satisfactory electrical screening methods on future aircraft. Apart from this, limits should be established to minimize intrusiveness in every sense, and more attention should be given to the reasons put forward by the public for their adverse reactions.

Landing noise is an example, since at the moment it involves the relatively small number of people below the approach path. Here there is a definite element of fear arising to some degree from the suddenness of the noise which in turn arises from the low aeroplane altitude over the houses. This fear can be minimized by better explanations of landing techniques to these people, by steepening the approach path even by half a degree, by using more than one runway and possibly by adjusting the landing path for, say, the smaller aircraft to provide landings well up the runway. An additional 50 ft height over houses above the usual 100 ft, say, makes several decibels difference to the noise overhead itself, but more importantly, decreases the rate of build-up of landing noise by virtue of the increased slant distance and the beaming of compressor noise in the forward direction.

This suggestion of a separate landing arrangement for the smaller aircraft not needing the full runway length leads to the broader issue of differential limits depending on the range of the aircraft. The present limits have already been paid for dearly by the longest range aircraft whose payload has to be eaten into to reduce takeoff weight and power. At the other extreme, it is absurd to allow short-range airplanes to make the same noise. There is a good case therefore for subjective limits both during takeoff and landing to be graduated according to the range of the aircraft and according to the true economic gain obtained from being allowed to make such a noise. It is more than possible that the public will accept a relatively small and decreasing number of noisy aircraft, if as the numbers of operations increase the rest do not intrude into their houses to anything like those at the moment.

The alternative is a definite reduction of the present limits systematically with the number of operations. Thus as London jet traffic grows there will

need to be a reduction of daytime noise limits at the control points from 110 PNdb now to some 100 PNdb in the 1970s. Such a reduction should occur in any case and should be stated as an aim fairly soon. However, much can be done by spreading intrusiveness by fanning out at takeoff, by greater height at landing, by insisting that aircraft types which do not need to be noisy meet lower limits, and by giving greater attention to television interference and fear complexes.

This last aspect of public relations is most important and should deal with the public at large and not only with people who complain. In a recent survey in London, one of the noticeable differences in reactions between the general public and those who had already made complaints was the impression of "mind made up" among the latter. An earlier explanation, before opinions harden, of the national significance of aviation, the safety arrangements on landing and the steps being taken to reduce noise progressively would be most valuable.

Some mention must be made of the present reliance on control points some four miles away under the airplane's flight path. There are in general plenty of houses nearer than this, particularly alongside the runway and it has been common form in the past to class these as exceptional areas. The supersonic transport does (as shown in Fig. 4) throw out sideways excessive noise during the ground run to such a degree that some attempt should be made to control it. The pilot cannot do so, since he has nothing to control, and the only available variable is the runway to be used. Since the distance the noise carries is in fact very much a function of the upward gradient of horizontal wind, a lateral control point would allow an indication to be made to the airport controller of the lateral spread of noise occurring and would allow a more satisfactory choice of runway at airports where such a choice existed. This lateral spread is undoubtedly one of the major problems on the supersonic transport and needs tackling both at source and operationally.

COMPRESSOR NOISE

Figure 9 portrays typical spectra of the noise of an early fan engine, obtained in the forward direction when the engine is nearly at full power and at landing power. It is seen that the noise radiated, when computed as an overall perceived noise level, is very little less during the approach than it is at full throttle. This particular engine is an early version and has since been improved; it does, nevertheless, illustrate the significance of the relatively high-frequency compressor noise and its influence on people under the approach path.

This noise has two components, discrete tones at frequencies related to the blade passage rate, and random noise covering all frequencies. Both must be reduced if an acceptable level is to be achieved, either by reducing the source strength, stopping it getting out, or by a combination of both. The process of stopping the noise emerging by using a sonic throat is now well known, and the results are promising. By causing the intake air to flow supersonically, high frequency noise reductions⁸ of over 20 db in the forward direction, and 6 db at right angles to the engine intake have been obtained, this poor sideways

suppression presumably being due to noise radiated through the intake casing. Apart from arguments of engine efficiency losses, there are many details of design which may minimize the advantages of such a system. For example, unless very carefully designed, the flow may separate after the choke, thereby causing a highly turbulent inflow and a significant increase in white-noise generation, in blade vibration, and in fluctuating pressures on the intake structure. On some test rigs, the intake noise increased violently as the velocity at the choke increased from subsonic to transonic and was only reduced significantly when the velocity in the choked entry was well and truly supersonic. The need for a quickly adjustable choke, and careful internal design is therefore paramount, if metal fatigue is to be prevented.

Another interesting mechanism of preventing noise from emerging has been put forward by Tyler and Sofrin.⁵ They argue that the dominant discrete frequency sound arises from the interactions between rotor blades and stators, and that although the frequency at which these interactions occur will be the product of the number of blades times number of stators times the rotation rate (i.e., very high indeed), nevertheless, their phase difference is such as to give rise to helical wavefronts spiraling out of the intake at the blade-passage frequency and its harmonics. It is argued that if these fronts have a supersonic speed of rotation they will be propagated out of the duct with very little attenuation, but that if they have a subsonic rotation speed they will be quickly dissipated. Thus for each harmonic there is a combination number of blades, stators, for any diameter and rotational speed which can "cut off" the noise output. Figure 10 illustrates this, the hatched region presenting a combination of conditions where noise is not emitted. Since it has not been established that the above mechanism is the predominant one in discrete frequency noise creation, we at Southampton have carried out experiments to show whether or not the

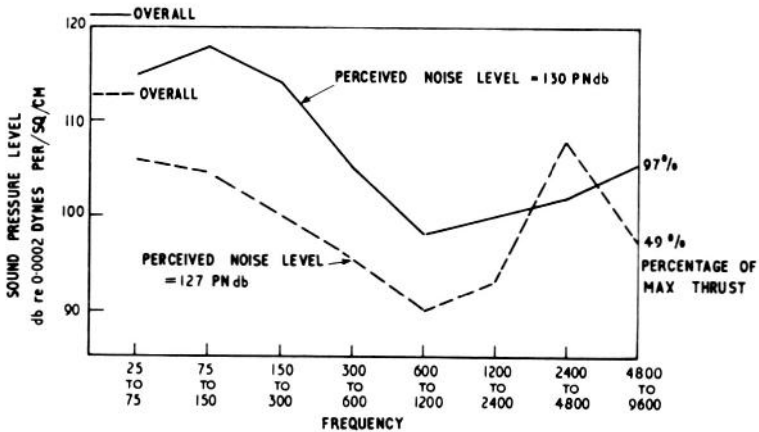


Fig. 9. Comparison of Noise on G.E. X-220 Engine at Full and Half Thrust (In Direction 47° off Thrust Line Distance 200FT)

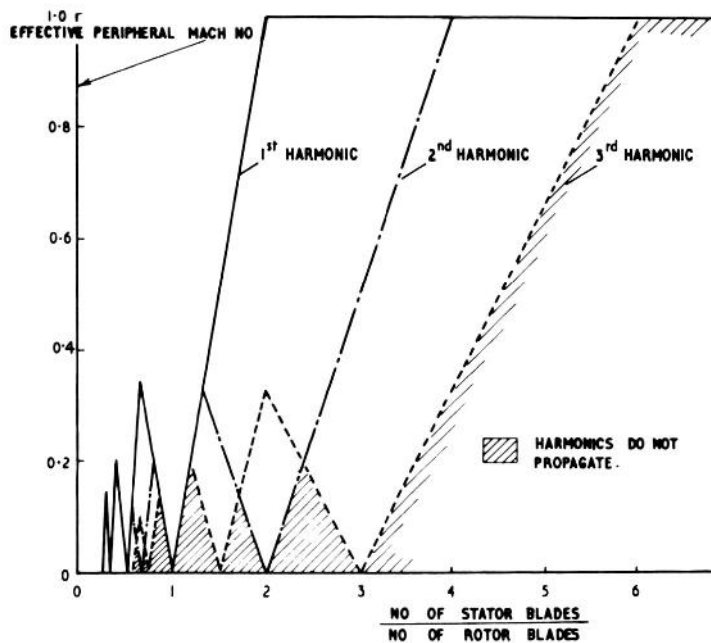


Fig. 10. Rotor—Stator Interaction: Conditions for Propagation

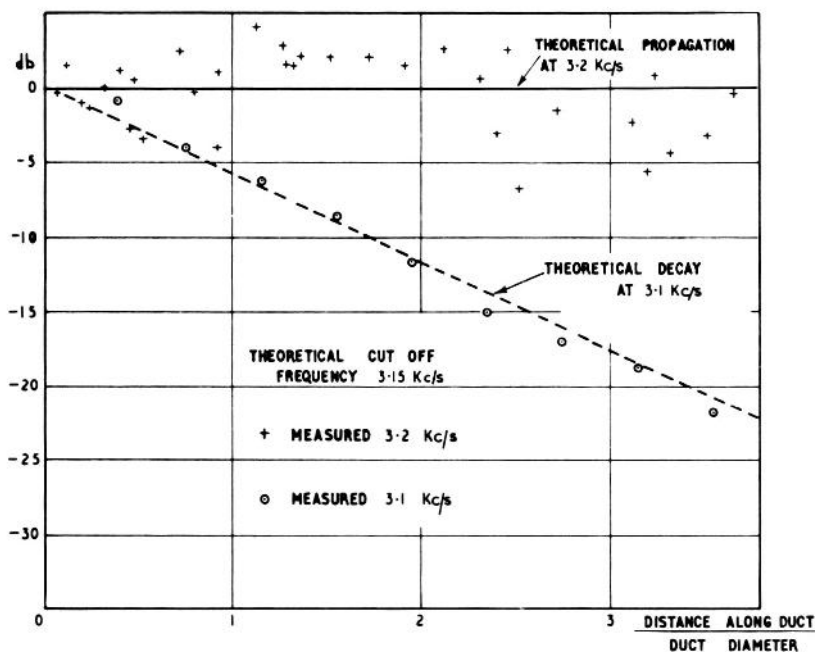


Fig. 11. Propagation Along A Duct Transverse Pressure Waves from a Rotating Source.

above propagation mechanism exists if the source is a rotating one. Figure 11 shows the variation of noise level along an infinite duct when the source rotates around the periphery of the duct.⁶ It is seen that for a fixed rotational speed, there is a cutoff in propagation at a frequency which agrees quite closely with the Tyler and Sofrin theory. There can be no doubt, therefore, that the propagation cutoff argument is correct, and that on engines in which the rotor-stator blade interaction noise predominates, the noise can be suppressed by a suitable choice of stator blades and the other quantities involved. Unfortunately, there is some evidence, both full- and model-scale, that on many compressors this is not the predominating initiating mechanism and that consequently the Tyler and Sofrin method of suppression does not help. For example, on compressor experiments at Southampton,⁷ the noise output variation with rpm did not show an appreciable change of shape (Fig. 12) with a series of rotor blades alone and the same series of rotor blades followed by stators, even though the theoretical cutoff frequency of the first and second harmonics with the stators in situ fell in the range of rpm tested. Thus, while the nature of the source is still being investigated, it is clear that on some compressors, at least, the above form of intake noise suppression is limited and that a better understanding of the effects on discrete frequency noise of initial turbulence, wakes, intake boundary layers, blade and stator spacing, is vital if landing problems of the 1970s are to be overcome.

The above parameters influence white noise also. Figure 13 shows the variation of radiated noise from a single stationary blade placed in a low-speed jet stream with varying turbulence. It is seen that the noise is far greater if the

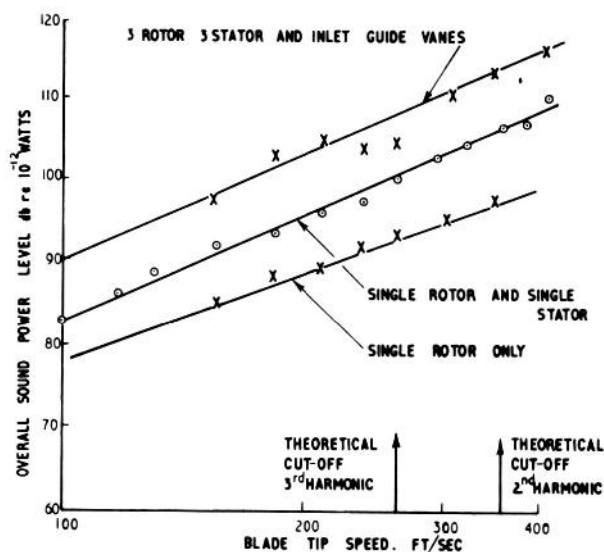


Fig. 12. Effect of Stator Blades on Noise from Axial Flow Compressor

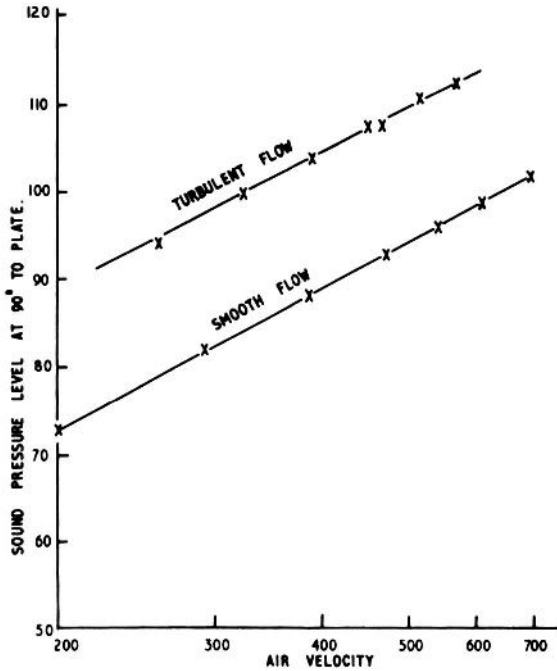


Fig. 13. Noise Radiated from a Flat Plate Aerofoil.

initial turbulence is great, the increase of noise with incidence, incidentally, being very little until the stall is reached. It may be presumed therefore that random noise from the compressor will depend greatly on the thickness of the boundary layer of the duct, on any turbulence in the wake of supporting spiders, and on the interaction of the wakes of one stage of blades on the next. Thus an effort must be made to eliminate bad inflow in all its aspects, particularly large scale separations arising from bad duct design.

SUPERSONIC TRANSPORT TAKEOFF NOISE

Although in general the noise of the supersonic transport at takeoff is alleviated by the quick climb to height, the laterally spread noise is far greater than occurs nowadays, while the time over which the noise persists as the aircraft flies overhead is much greater. There is a grave need therefore to develop additional methods of lateral noise suppression, particularly as the limits of the 1970s may be lower than those now in existence.

In order to cast out some of the more fanciful suggestions it is worthwhile explaining at once that noise arises from the mixing of the gas with the surrounding air, the noise source extending many jet diameters downstream. As the engine pressure ratio increases and the efflux velocity is raised, this sheet increases from some 5 to 25 diameters. Figure 14 shows⁹ the distribution of sources from a low-velocity air jet on the one hand and on a rocket engine on the other

(pressure ratio 30). This change follows from the poor mixing in the supersonic region, the noise emanating from the near-subsonic region of the jet where the turbulence is far greater. Since the economic penalty of a low-pressure ratio engine is quite large on a supersonic transport, we must expect high velocity engines to be used. Any scheme, such as a stream curtain, magnetohydrodynamic gas controller and the like, which is only likely to modify the initial conditions of the noise sheet is unlikely to be profitable.

It has been found that in short ejectors there is insufficient mixing between the primary and induced streams to lower the efflux velocity greatly and hence little noise reduction ensues. Figure 15 shows the contours of overall noise measured around the primary jet and around an ejector sufficiently long to give significant attenuation. The reduction of overall noise obtained with the various ejectors tested is shown in Figure 16, the attenuation being virtually independent of pressure ratio, provided it is subcritical. However, once choking occurs, the effect of the ejector on the broad band noise characteristic of jets is much more difficult to determine.

Some years ago at Southampton¹⁰ we examined a phenomenon of "back reaction" or resonance in which, when the flow was choked, any fluctuation

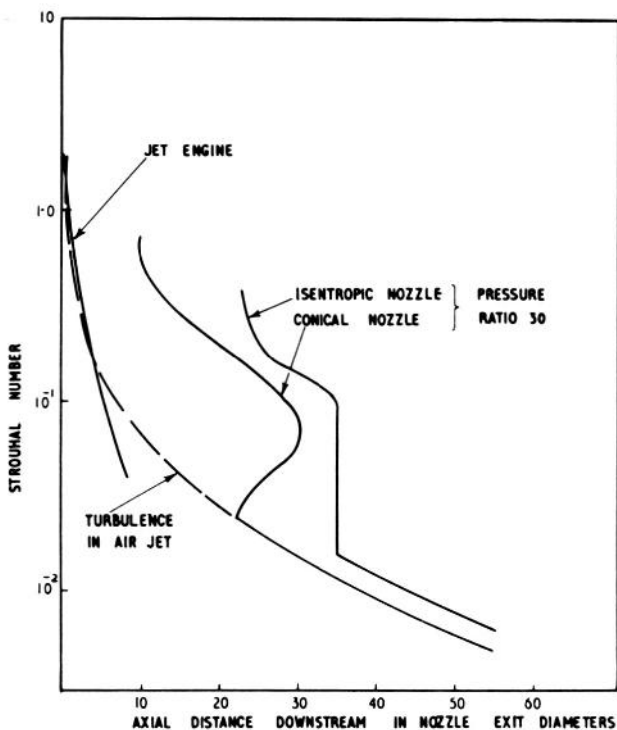


Fig. 14. Location of Maximum Sound Pressure Downstream of Jet Exit

convected from the lip of the nozzle caused a radial shock wave to occur as it passed one of the standing shocks in the supersonic flow. On passing the lip of the jet, this radiated shock modified the pressure ratio in the jet, thereby incurring a further unsteadiness which in turn gave rise to a further radiated spherical shock. At certain resonant frequencies, the system became a self-perpetuating one and extremely high intensity discrete frequency noises were recorded. Exactly the same kind of but strengthened phenomena arise in ejectors. Figure

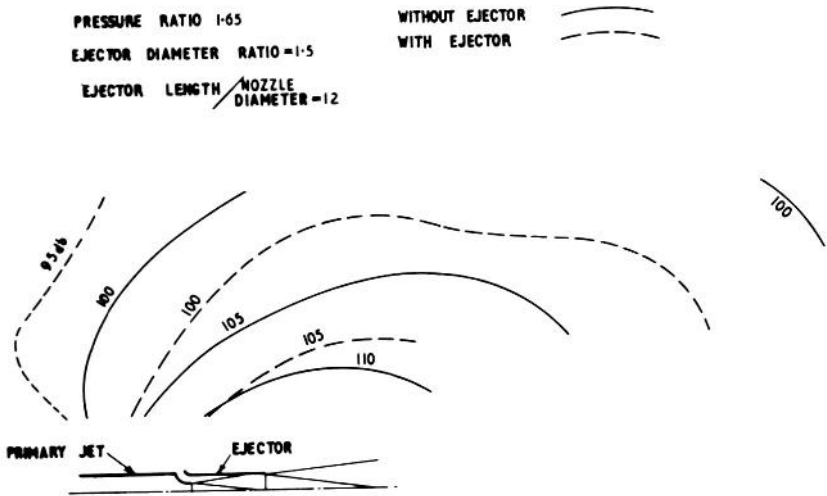


Fig. 15. Typical Contours of Noise With and Without Ejector

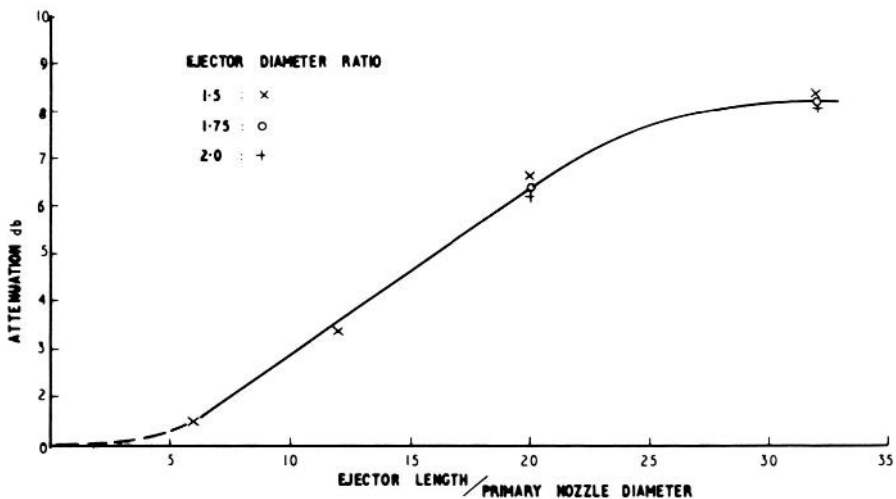


Fig. 16. Reduction in Overall Noise; Ejectors of Various Lengths, Diameters

17 shows a typical spectrum of noise radiated from a supersonic jet with ejector fitted, the discrete frequency sound being many decibels above the normal white noise spectrum. Indeed, the existence of the ejector pipe channels the radiated shock towards the lip of the jet and accentuates this "back reaction" tendency. Quite severe roughening of the jet exit has to be resorted to to reduce the resonance and on our model scale it has never been completely eliminated. Although in practice no "back reaction" has been noticed on normal choked jet engines, nevertheless, the presence of the ejector pipe has strengthened the mechanism to such an extent that it may well occur in full scale installations. If so, much of the noise reduction arising from the lower efflux velocity will be nullified, while also adding severe pressure fluctuations in the ejector which may give rise to metal fatigue in the structure of the ejector.

Promising methods of suppression of the static noise of supersonic transports therefore include any satisfactory method of reducing efflux velocities at takeoff, multinozzle arrangements, and long shielded jets. The reduction of efflux velocity by the use of fan or bypass engines is not attractive for supersonic travel owing to the greater engine volume and its consequential increase in drag and weight. We are, therefore, left to consider ejectors which must be very long, multi-nozzle jets, and aircraft layouts which screen the jets from the ground. Positioning of the jet on the upper surface of the aircraft is unlikely to be satisfactory in reducing noise laterally during the ground run, since true shielding occurs only when the aircraft is in the air. Also a long length of shield is implied, since noise emanates some ten or more jet diameters downstream, i.e., 20 or 30 ft downstream of the nozzle. There is a possibility of a satisfactory layout with a series of much smaller nozzles spaced laterally to shield one another, particularly if twin fins are placed to either side of the jet-pipe array and well downstream

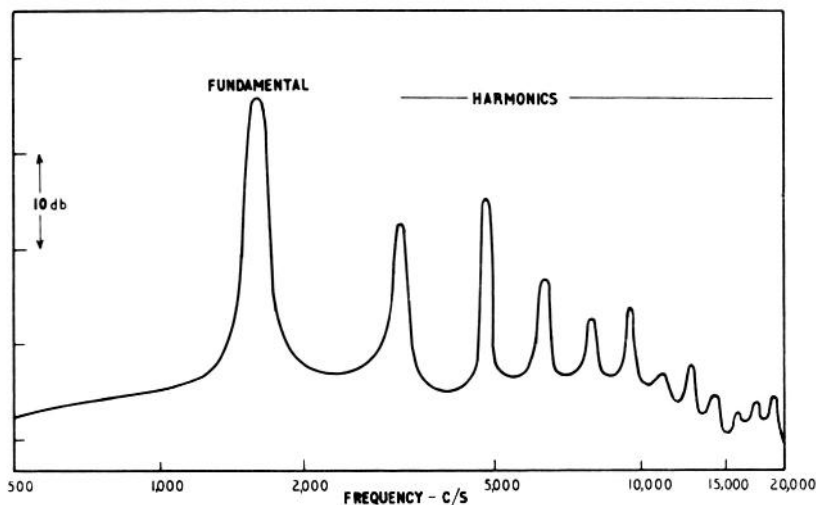


Fig. 17. Typical 1 Spectrum of Shock Noise for Choked Jet with Ejector

of them. It is known that the noise radiated laterally from an array of jets in the direction in which one shields the other is very little greater than that of the outer jet on its own. Rolls Royce,⁸ for example (Fig. 18), showed that in this direction the noise was at least as low as that of a single unit, whereas that at right angles was that expected from a pure summation of the power.

This type of installation, involving as many small jets as possible, is particularly suited to the long chord slender delta planform. Thus it may well be that this configuration can be used to minimize the noise spread laterally while even the downward-directed noise will be suitably shielded if the jets are placed well forward on the wing (fifteen individual diameters). There is certainly sufficient promise in this arrangement to hope for moderate noise reductions of some 5 or 8 db, though it is imperative to prove this experimentally at an early stage. In this context, the fact that the frequency will be raised inversely as the individual jet diameter implies that the noise will, for a given amplitude, appear subjectively more annoying. This was true for the Boeing 707 multinozzle and the Rolls Royce corrugated-nozzle arrangement. The need for experimental verification of the merits of such a system must therefore be emphasised still further.

The slender delta configuration also lends itself to the use of long ejector nozzles, with noise suppression properties of the kind shown in Fig. 15. Thus if the engines are placed well forward, and a similar multinozzle arrangement is used, a low velocity efflux is attainable with an appreciable noise reduction. The exact reduction cannot be predicted from cold gas model experiments, the details of the mixing process being a function of jet temperature and nozzle design. However, noise reduction devices of this kind involving clearly reduced efflux velocities are very much to be preferred to devices of the kind mentioned

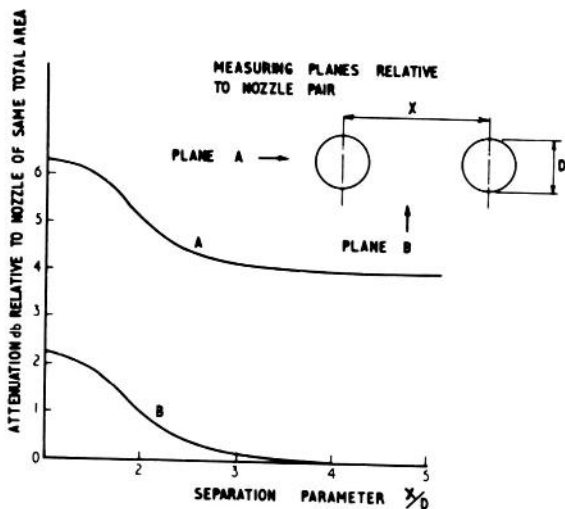


Fig. 18. The Noise Pattern of Two Jets in Proximity

above which depend on shielding or scattering for their efficiency, since shielded or scattered noise has the annoying habit of appearing elsewhere where it is least expected. Devices which involve weaker initiating sources are therefore more certain to work. Care must be taken, however, not to introduce extraneous noises by virtue of the ejector mixing process.

SONIC BOOM PROBLEMS

The problem of sonic booms is fundamental, and no absolute cure is possible. Even with the most favorable distribution of volume and lift over the aircraft (even though this presents an impossible layout and balance problem), the free-air pressure jump is still likely to be above 0.8 lb/ft² and that at the ear greater than 1.5 lb/ft². All that can be done therefore is to establish the limits and keep to them. Some idea of the difficulty of establishing such limits is indicated by the results (Fig. 19) of a few exploratory tests carried out recently in the United Kingdom. No great importance should be given to the detailed figures, the tests having been carried out to indicate the form of the problem rather than the solution to it. Three points are worth emphasizing however. One is the similarity of reactions of people to both sonic and simulated booms. This leads us to hope that useful and realistic experiments can be carried out simulating sonic booms under controlled conditions.

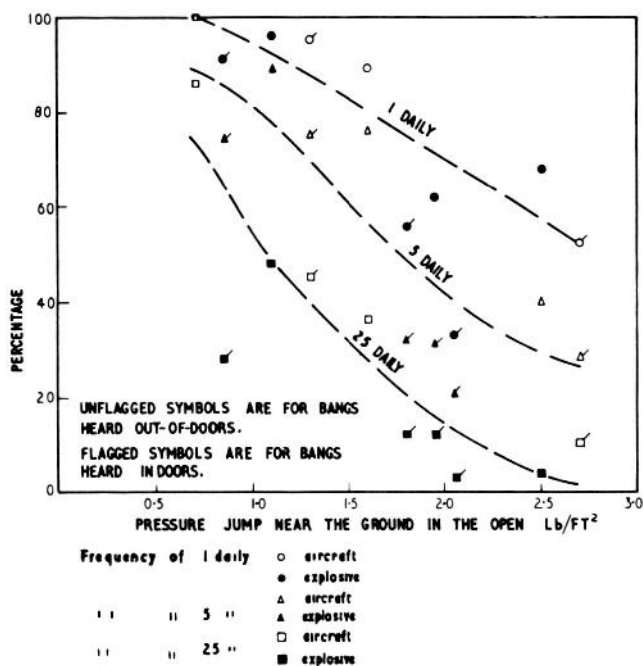


Fig. 19. Percentages of Those Who Would Tolerate Bangs of Various Pressure Jumps at Different Frequencies.

The second point requiring comment is the relatively slow fall away in acceptability with increasing pressure jump. This can be looked on with satisfaction or otherwise depending on one's point of view. Thus, while the results can be interpreted to mean that the average person will tolerate quite large booms in the future and that once people have become used to them, the proportion of people who are likely to find them objectionable will be small, it also means that the establishment of satisfactory limits from a small series of experiments is questionable, since we cannot hope to cover the hypersensitive fringe of the population who are sincerely inconvenienced by such booms and who may only amount to, say, 2 percent of the population, i.e., say 4,000 in Stockholm. The need for a social survey type of approach by easing but carefully controlling the military limitations on supersonic flying over inhabited areas, and recording reactions after a period of months is, in my opinion, the only way of establishing limits in an essentially sociological situation.

The third point on which some comment is necessary is the apparent agreement between outdoor and indoor reactions, when plotted against the outdoor pressure jump, in spite of the fact that, as shown in Fig. 20, the shape of the pressure excitation is completely different. There is clearly an exchange rate between amplitude of the pressure jump, the room reverberation time and number of booms per day, while visual cues such as the windows rattling and crockery shaking will contribute significantly. It is obvious that amplitude in itself is only one of the parameters on which limits should be based and that an amplitude limit based on the worst of all these factors will be necessary.

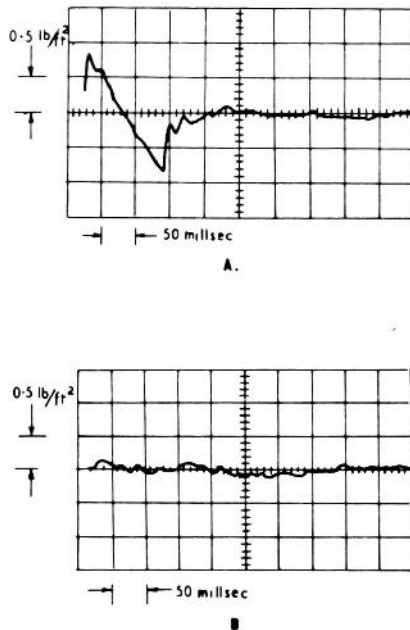


Fig. 20. Sonic Bang From an Aircraft as Heard in the Open Air and Inside a Room

Wilby and Clarke¹¹ have made some attempt at explaining the above, by assessing the increase in apparent loudness due to reverberation and comparing it with the transmission loss through the closed windows. For a large living room it is estimated that the reverberation effect is to increase the apparent loudness by 5 db, as opposed to a transmission drop of 15 db through the windows. This 10-db advantage does not appear in practice, thereby suggesting that other subjective effects such as surprise, visual cues and interruption all may have significance in assessing human reaction.

Experiments carried out in the United States suggest that atmospheric conditions also have a large effect on the uniformity of the *N* wave. It is therefore likely that the indoor characteristics may well be a function of the outdoor atmospheric conditions, and that booms will be worst at certain times of day and weather conditions. All these factors may have a bearing on the scheduling of supersonic aircraft and require urgent attention in more than one country.

PART II: THE EFFECT OF NOISE ON PASSENGERS

INTERNAL NOISE ENVIRONMENT

While the most severe noise problems on aircraft of the 1970s are undoubtedly those concerning people on the ground, those involving passengers and crew in the air are also of great interest and in many ways are different from those in existing aeroplanes.

Cabin noise on propellered aircraft arises largely from the propellers, the noise from which impinges on the cabin wall, some proportion of it being transmitted to the interior. As engine powers have increased, propeller-tip speeds have increased and the noise environment and that of vibration have both increased seriously. Empirical rules regarding noise in the cabin have been formulated, which bring into account the transmission loss through the walls and the absorption of the soundproofing material. Even so the situation is hardly satisfactory and predictions if made at all have on occasions been woefully in error.

On jet airliners, the noise during takeoff and climb has emanated largely from the jet engine, but in the cruise the velocity of the jets relative to the surrounding air has fallen to such an extent that the noise has been reduced and has an amplitude less than that from the turbulent boundary layer along the fuselage. This mechanism of internal noise production is very different from that from the engine, the rough boundary layer air causing pressure fluctuations along the side of the fuselage as the air is convected along its side. Our knowledge of the response of the structure to these fluctuations and of the sound radiated into the cabin as a result of this response is very rudimentary at the moment, and needs urgent attention if we are to be able to predict the noise levels inside the cabin of a supersonic transport.

THE NOISE INSIDE SUPERSONIC AIRLINERS

Some idea of the difficulty of translating empirical laws developed for propellered or jet aircraft (in which the sound impinges more or less uniformly on the surface of the fuselage) to deal with boundary-layer excitation may be obtained from Fig. 21. Here we have plotted spectra of strain fluctuations and of the pressure excitations adjacent to the wall on a small panel set into the wings of the Fairey Delta aircraft¹² when excited respectively by the turbulent boundary layer in supersonic flow at $M = 1.5$ and by jet noise on the ground. While the overall rms levels of the pressure fluctuations are the same, nevertheless the strain spectra are quite different, and, it may be inferred, so will the internal noise spectra. In particular the turbulent boundary layer excites the low-frequency oscillations in the panels to a level 15 db lower than does the jet; similarly the internal noise levels will be different, depending on the type of excitation.

Fortunately, although we are lacking in prediction methods, we do have some experience of the magnitudes of boundary-layer noise in the cabins of the existing jet airliners, and can at least indicate comparatively the magnitude of the prob-

lem on the assumption that the construction and soundproofing of the supersonic transport will be similar. While research on the overall amplitude of turbulent boundary-layer pressure fluctuations on the wall has been extensive for subsonic flow both in my own laboratory¹³ and elsewhere, the data available at supersonic Mach numbers is scanty, though indicating a fall off above $M = 2.0$. Our own results¹⁴ at $M = 1.5$ and full scale experiments both in the U.K. and the U.S. indicate that this fall is not significant at $M = 2.0$. In Fig. 22 the ratio of the root mean square pressure p' to the local skin friction is plotted. Bearing in mind that at $M = 2.0$ the skin friction coefficient falls only by some twenty percent from the subsonic value, it is reasonable to assume the pressure fluctuations to be a function of equivalent air speed only, this assumption implying a conservation of say, twenty percent at $M = 2.0$ (i.e., 1 or 2 db over-estimation).

The Boeing 707 and others of the same class cruise typically at a speed of 525 mph at 36,000 ft, i.e., at 249 knots equivalent air speed. The $M = 2.7$ supersonic transport put forward by Floyd¹ would climb for some forty minutes at an equivalent air speed of 490 knots and cruise at an equivalent air speed of 440 knots. Both the slender delta and variable geometry $M = 2.2$ aircraft referred to earlier would cruise at an equivalent air speed of about 400 knots. An examination of Fig. 23, which shows the variation of surface-pressure fluctuation level with equivalent air speed, indicates that the supersonic designs

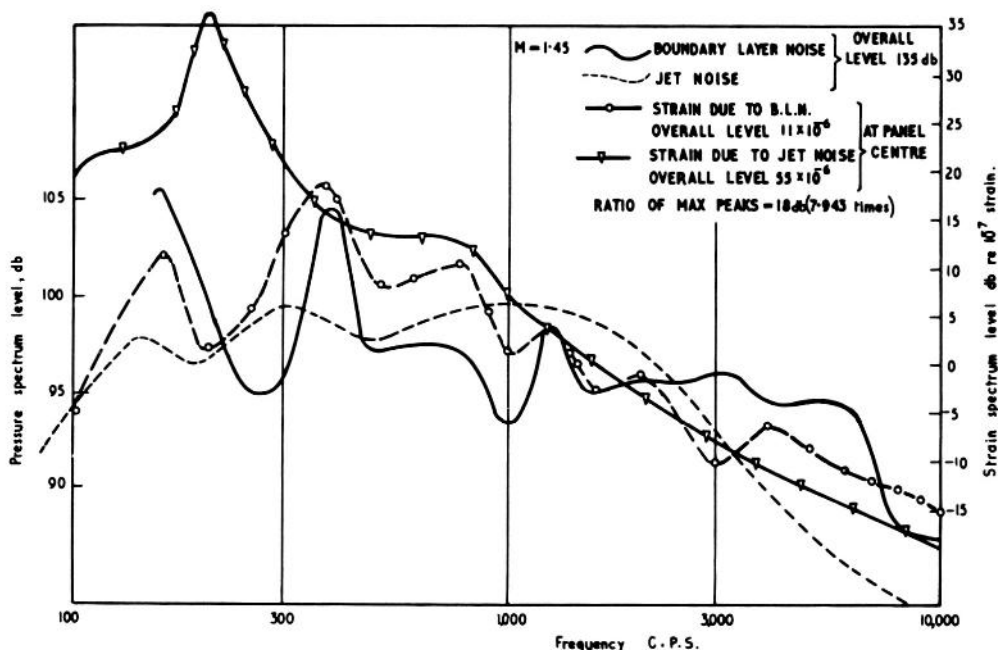


Fig. 21. Spectra of Jet Noise and Boundary Layer Noise and Strain Produced by Them in Test Panel of Fairey F.D.2. (Reference 7)

will be some 12 or more decibels noisier than that of the present jets unless additional structure and soundproofing are added.

While the standards of quietness in jet airliners is highly satisfactory, this increase cannot be tolerated. In the field of supersonic airliners we therefore go forward to the 1970s with a significant problem in cabin noise and with, at the moment, an inadequate state of knowledge to deal with it with any degree of precision.

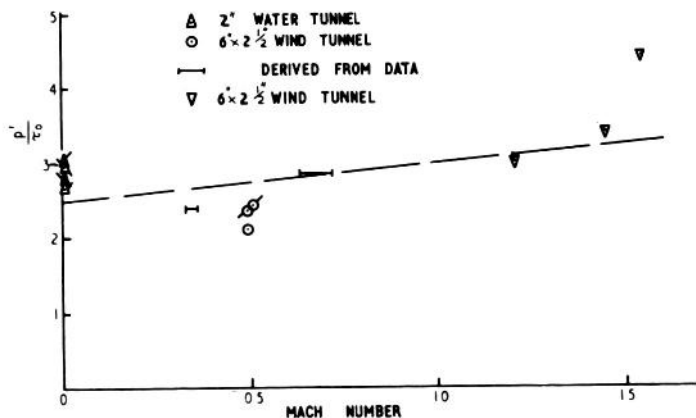


Fig. 22. Variation of ρ^1/τ_0 with Mach Number Corrected to Zero Transducer Size.

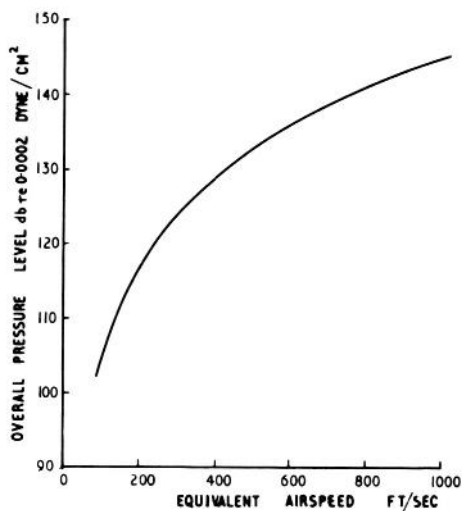


Fig. 23. Overall Level of Boundary Layer Pressure Fluctuations on Surface

THE NOISE INSIDE MEDIUM- AND SHORT-RANGE AIRCRAFT

As mentioned in a previous section, the advent of the jet engine has fortunately postponed the growth of vibrational problems inside the aircraft cabin, and has presented a standard of comfort never achieved in propeller aeroplanes. Nevertheless, for any one type of engine, the vibration energy must be expected to grow with the power developed, and this energy must be absorbed in the structure if a low vibration level is to be achieved and a comfortable cabin maintained. Since noise and vibration are invariable team mates this is a requirement for acceptable cabin noise also.

The prototype Viscount aircraft, the first of the turboprop airliners, presented a clear step forward in vibration-free travel. However, the power passing through the propellers was relatively small, and when this power was increased in order to present competitive speeds on the various versions of the aircraft, and later on the Vanguard, Electra and Britannia, the vibration and noise returned. This vibration was caused in a variety of ways, partly by the increased tip speeds and the increased noise and shocks hitting the fuselage, but also from the increased slipstream energy passing close to the rear structure. This tendency has continued, and there are now few, if any, large, high-powered propeller aircraft free of noise and vibration problems.

The same is true of helicopters which have a particularly acute problem of vibration isolation. On twin and single rotor craft, the engine, gearboxes, bearing housings and rotor heads are all near the cabin, and are of necessity attached

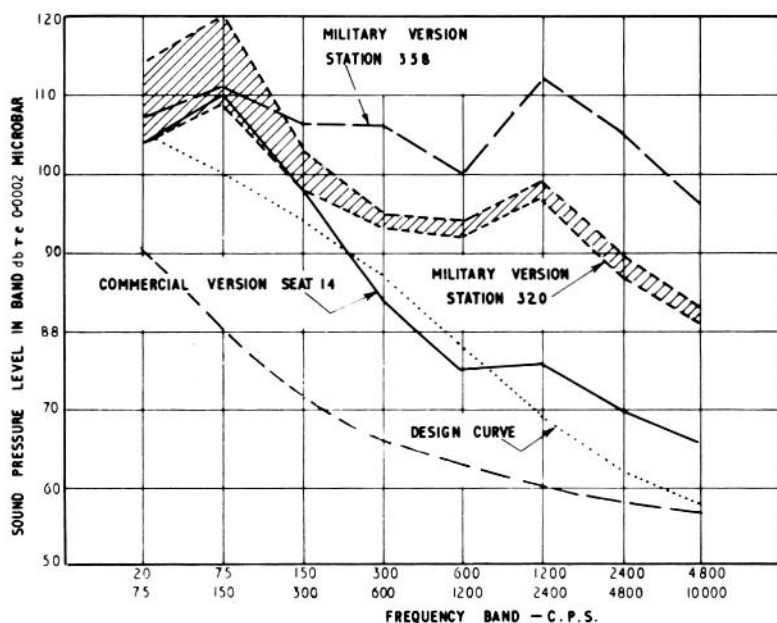


Fig. 24. Noise Inside the Vertol Helicopter Compared with Criterion for Conventional Airliner

in some way to a relatively flimsy cabin structure. As a result, even with the relatively low powers involved so far, the internal noise levels are high, by orthodox aircraft standards. Figure 24 shows the internal noise levels occurring within the Vertol helicopters,¹⁵ recognized as being unusually quiet in its class. It is seen that even with a liberal treatment of soundproofing material, the internal noise level is well above that which is now accepted as a reasonable standard for civil operation.

Although such standards are arbitrary, and have been based on the need to eliminate interference with speech in the cabin, it cannot be raised to any great extent without it entering the deafness regime for the crew. The levels needed to prevent all deafness has been illustrated in Fig. 8; the high frequency attainment shown in Fig. 24 is sufficient to prevent deafness, but the low frequency component appears to be a little excessive, and should be reduced. Unfortunately, it is this noise which is so difficult to reduce.

To meet the increases in size and power of VTOL aircraft and helicopters to be expected in the 1970s, it will therefore be necessary to improve noise control methods to a considerable degree to get down to modern orthodox aeroplane standards and even in extreme cases to maintain noise levels below the hearing-damage levels for extended exposure.

REDUCTION OF INTERNAL NOISE INSIDE SUPERSONIC AIRLINERS

Present-day methods of estimating noise attenuation through cabin walls are based effectively on experimental and theoretical findings for sound waves either normal to, or at random incidences to typical structural specimens. With normal waves the whole specimen is under compression at the same time, while with random incidences there are phase-amplitude relationships across the structure. Boundary-layer turbulence has a flowing characteristic, which can, in a way, be likened to rain falling on an inclined roof, the droplets having an impact as they fall and a limited life before breaking up into still smaller droplets. No adequate theory has yet been propounded, on the one hand a modification of the old empirical method being used and an attenuation similar to the mass law obtained; at the other extreme, a coincidence wave approach has been used on an infinite skin, no allowance being made for the details of the structure. No doubt, the truth is somewhere in between.

Structurally, the first mechanism implies forced vibrations with no resonances. Thus, on this hypothesis, the addition of damping to the structure, and the use of viscoelastic interlayers between double skins are unlikely to be effective. The running-wave mechanism implies resonant waves, in which case structural damping will be of great advantage as a method of reduction. The establishment of the mechanism of internal noise production is therefore a vital precursor to establishing satisfactory methods of reducing noise inside the cabin.

Recently we have analyzed the internal spectra of noise on the Boeing 707 and Comet in order to compare with the external excitation spectra of the fuselage surface pressures. It may be seen from Fig. 25 that if allowance is made

for the absorption properties of the cabin furnishings and soundproofing, the internal noise spectra reflects the external excitation spectrum fairly well and that a mass law method may be satisfactory. On the other hand, Clarkson¹⁶ has shown on the Caravelle that, at least for jet-noise excitation, resonant modes of oscillation account for most of the energy of vibration of the structure. Extensive researches on noise attenuation through structures of various kinds subjected both to jet noise and boundary-layer pressure fluctuations are needed before we can hope to establish satisfactory methods of noise control.

There is one favorable aspect of the problem which has not yet been mentioned. Fig. 26 shows a nondimensional spectrum of the surface-pressure fluctuations as obtained by Bull¹³ after analysis of a series of experiments covering a range of subsonic conditions. It is seen that the spectral density function is constant with increasing Strouhal number until approximately unity is reached, the energy falling off sharply after this. If this spectrum is retained at supersonic speeds, it follows that the energy is shared over a much greater frequency range and that for a given overall figure of root-mean-square pressure fluctuation (and experiment indicates this to be so) the excitation in any one octave will be less. In other words, at a point on the fuselage of a given boundary-layer displacement thickness, the $M = 2.0$ airplane will have a spectrum extending to higher frequencies than the Boeing 707, say, but that the amplitude at each frequency will be significantly less. Thus in the low frequency range the energy may be halved, and the sound pressure level inside the cabin reduced by 3 db. The doubling of the frequency range implies a greater need for more high-frequency soundproofing material to be added, but the weight of such a treatment need be far less than that added to improve the low frequency transmission loss.

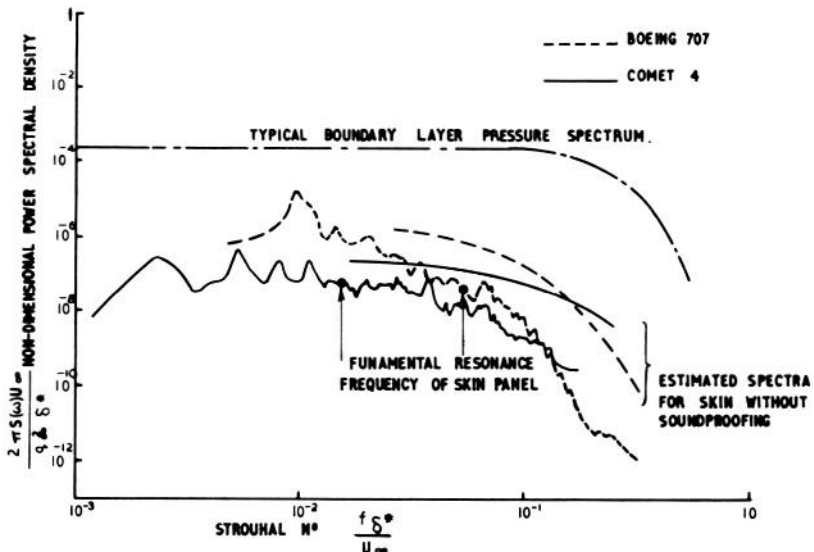


Fig. 25. Spectra of Boundary Layer Noise in Jet Aircraft

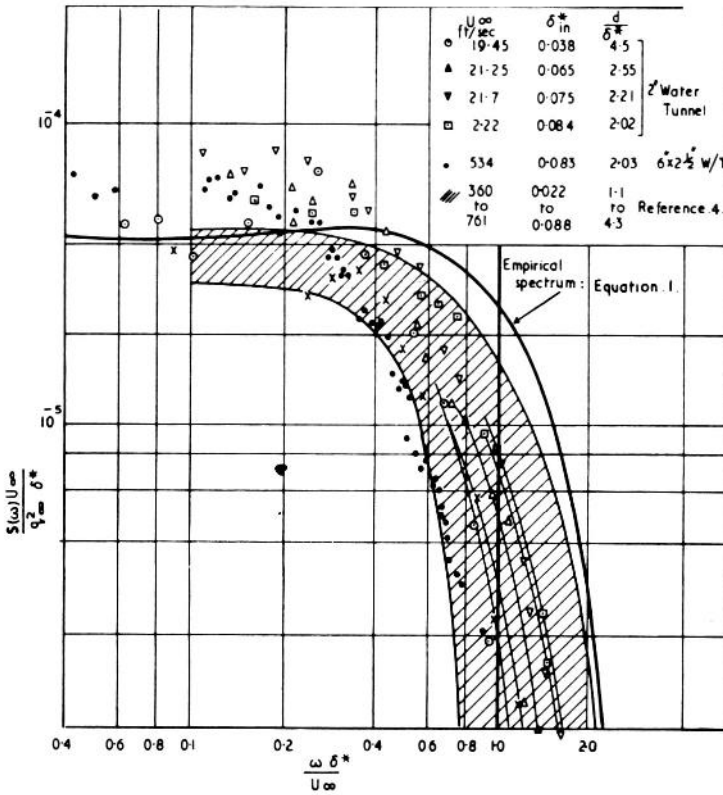


Fig. 26. Power Spectrum of the Wall Pressure Due to a Turbulent Boundary Layer

Since the above alleviation still leaves us with some 7-9 db increase over present-day jet aircraft in the difficult low frequency range, experimental data on low-frequency excitation and transmission losses through supersonic aircraft walls is vital. The differences in structural excitation between boundary layer and jet noise was mentioned above and illustrated in Fig. 21. Some of this difference arises from the relatively smaller spatial correlation area of the eddies of a given frequency compared with that from the jet. It is interesting therefore to know whether correlation areas differ similarly for boundary-layer pressure fluctuations at different Mach numbers. Bull has indicated recently¹³ that spatial correlations of filtered boundary-layer pressure fluctuations can be plotted universally against the spatial separation ξ divided by the boundary-layer displacement thickness, δ^* , rather than against $f\xi/U$ as previously supposed. It follows that correlation areas will be similar for all frequencies and that they will only vary with speed insofar as the boundary-layer displacement thickness varies. Thus, while the fear that the correlation length would be directly proportional to U for eddies giving any mid-frequency value f is no

longer worrying, nevertheless, there is no indication that the structural excitation in supersonic flight will be significantly less than that for, say, the Boeing 707 at the same equivalent air speed and boundary-layer thickness. We are left therefore to create our noise reductions by the use of heavier structures and a more careful choice of materials.

There is at the moment a great interest in double skins with viscoelastic interlayers. While there is no obvious reason why such arrangements should be advantageous (and indeed damping additives in the form of tape and "aquaplas" have not shown any great gains at low frequencies), there is a great need to establish the properties of such structures and their use not only for fuselage skins but also for frames and stringers. Depending upon the mechanism of sound radiation into the cabin, there is also a need to obtain optimum distributions of soundproofing materials over the cabin walls. High-frequency waves running along the skin will radiate only where they come to an end at a frame junction. There is something to be said, therefore, for added protection in this region rather than elsewhere. It is also possible to design the frames away from the skin, thereby allowing running waves to progress along the fuselage without interruption. Needless to say, diagonally running waves will still radiate, but presumably at a lower level of acoustic efficiency.

To conclude, therefore, it must be emphasised that the present grave deficiencies in knowledge and in methods of calculation, in respect to aerodynamic excitation, structural response and acoustic radiation, are all likely to produce serious errors in noise prediction on the supersonic airliners of the 1970s. Industry must take steps to overcome this by the establishment of aerodynamic and acoustical facilities in which optimum structures and furnishings can be developed under as realistic conditions as possible.

NOISE REDUCTION IN PROPELLER AIRCRAFT

Propeller noise increases basically with engine power and with tip speed. There are various improvements arising from rounding the tips, and using a larger number of lower chord blades, but it is generally true to say that as power increases the noise must increase unless tip speed is reduced. Unfortunately, the increase of power often occurs after the aircraft layout and propeller diameter have been decided upon, and the increased power is almost invariably accompanied by an increase in tip speeds, sometimes sufficient to involve supersonic helical tip speeds in flight. The only real cure lies in careful design in the first place; from then on only minor improvements can be hoped for.

A few points of design are worth mentioning. Apart from when supersonic tip speeds are used (in which case the aeroplane is subjected to a supersonic boom along much of its length), the peak amplitude of the noise along the fuselage occurs over only a small region of the aeroplane near the propeller disk. If therefore this area is increased in mass, less noise will penetrate the skin. This peak amplitude can be reduced by increasing the blade-fuselage clearance. However, if this is done it must be remembered that the new peak is much flatter and the increase of skin thickness must extend over a much greater area

of the fuselage. Thus internal noise reduction by increasing tip clearance can only be really successful when accompanied by significant structural modifications.

Another palliative which is now used regularly is that of amplitude reduction by phase synchronization. Figure 27 gives a typical picture of the near field pressures and relative phase angles in the plane of the propellers around the fuselage of the two inboard engines. It may be seen that the optimum phasing of the various propellers to give least noise internally depends crucially on where the noise penetrates. Thus if, for example, the noise penetrates the floor, a suitable antiphasing of the two opposing inner propellers is advisable. If, on the other hand, the noise enters the cabin side, there may be a case, though a limited one, for suitable phasing of the inner and outer propellers.

It is suspected that when very high helical tip speed and near-shock conditions are involved a further source of noise and vibration arises from the variation of loading due to local differences of flow across the propeller disk. This gives rise to propeller vibrations which transmit through the structure. As speeds increase, greater care should be taken to insure that local shocks do not occur, and that the propellers are in as uniform a flow as possible.

NOISE REDUCTION IN HELICOPTERS AND VTOL AIRCRAFT

Nonuniform flow conditions are more than ever prevalent through helicopter rotor disks and through vertical fan or propellered aircraft. In forward flight, the variation of blade loading on a helicopter blade is severe, in spite of the

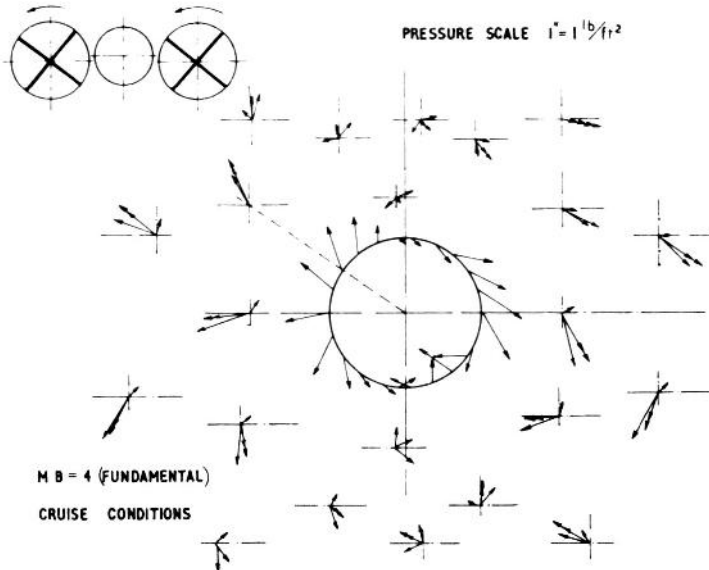


Fig. 27. Diagram to Illustrate the Summation of Pressures Due to the Above Configuration at the Fuselage Surface

adjustment made by the cyclic pitch change, and much of the noise, particularly in the higher frequency ranges, can be traced to this source.

If fan lift VTOL aircraft are introduced, one of the reasons for such development lies in the excessive noise made by VTOL jet aircraft. Thus, it can be assumed that they will approximate to the turbofan in that tip speeds will be as high as can be tolerated from a noise point of view. Care must be taken, therefore, to establish that the highly nonuniform flow through the fan disk will not present a serious addition to the calculated noise output. Little is known about such variation. As indicated earlier, if white noise predominates, it is likely that the noise will not be increased excessively, provided the blades do not stall. There is a great need, however, to verify this assumption. If, on the other hand, fans give rise to a predominance of discrete frequency sound we can expect great increases in the higher harmonics of the blade passage frequency—increases which can be assessed only after experimental studies under conditions approaching those of the full-scale design.

PART III: THE EFFECTS OF NOISE AND PRESSURE FLUCTUATIONS ON STRUCTURAL FATIGUE

THE PROBLEMS OF THE 1970S

For many years now it has been known that noise and other types of pressure fluctuations give rise to fluctuating stresses which eventually cause metal fatigue of various parts of the structure. On subsonic airliners, such cracks and failures have arisen almost exclusively from the noise of the jet during ground running or takeoff, the decrease in relative jet velocity once the aircraft is in flight reducing the stresses to a safe level. It is not anticipated that any basically new problems will arise with future subsonic airliners, particularly as much of the problem has been averted by the use of rear engine installations. However, the advent of VTOL configurations in which large jet thrusts are used close to aircraft surfaces must be expected to aggravate the difficulties both in respect to structural fatigue and internal noise.

On the supersonic airliner several entirely new problems arise, and it is these which are commented upon in this paper. They may be listed as follows:

1. Close to the engines, the noise intensity will increase roughly as the power output. We can therefore expect an increase in noise level during ground running and takeoff of at least four decibels for the same representative position. Since in several supersonic configurations the engines are in the rear, this increase may be more than nullified by the improved layout; the degree of alleviation must be established, however, especially as we have so little experience of such layouts.
2. Early fatigue of skin-frame attachments have occurred on poorly designed structures at pressure fluctuation levels as low as 140 db. Boundary-layer fluctuating pressures of 130–140 db magnitude will occur on the fuselage and wings of the supersonic airliner throughout its cruising flight. While it is not difficult to design structures to withstand this magnitude of fluctuating pressure for a long life in terms of takeoffs, the establishment of a crack-free flying lifetime of as much as 20,000 hr is well beyond our ability at the moment. At 1,000 cps, such a lifetime implies almost 10^{11} reversals; it is associated with a random-type loading, and is difficult to simulate without recourse to a tangential flow type of excitation. The validation of a satisfactory life is certain to be one of the main problems of the 1970s.
3. If cracks do occur it is argued that fail-safe procedures guarantee that such cracks will not exceed a certain length before the next inspection. Our experiments indicate that the environment of noise superimposed upon the static pressurization load can alter these criteria significantly, once the crack has spread a little.
4. On the narrow-delta type of configuration, conical vortices emanate from the leading edge of the wings (as in the form shown in Fig. 28) at incidences above a certain value depending upon the configuration. These vortices will certainly occur during subsonic flight and may well do so in supersonic cruising flight. These vortices are not completely steady and set up

random-pressure fluctuations on the wing structure which are not only two or three times greater than the turbulent boundary-layer pressure fluctuations, but are also closely correlated over large areas of the wing. The fluctuating stress levels in the wing structure may therefore present a still greater fatigue problem than that mentioned in item two above.

5. Some distance downstream, depending on the Reynolds number, the leading edge sweep angle, and the wing incidence, the vortex bursts, giving rise to a very much higher level of pressure fluctuation or noise in the vicinity of the burst.

If full-scale conditions are such as to bring this bursting point above the surface of the wing or tailplane, then pressure fluctuation levels of as much as ten times that in the boundary layer may occur.

6. Supersonic flight involves shock waves and some of these may fall on some other part of the structure. Experience on missiles suggests that these shocks oscillate and cause random fluctuating pressures at their point of origin and at any point of impact with the structure. This then provides an additional source of fluctuating stress which can cause vibration and metal fatigue.

TAKEOFF

The increased thrust required on the supersonic transport implies an increase of some 2 or 3 db in the near-field noise level over that of, say, the Boeing 707.

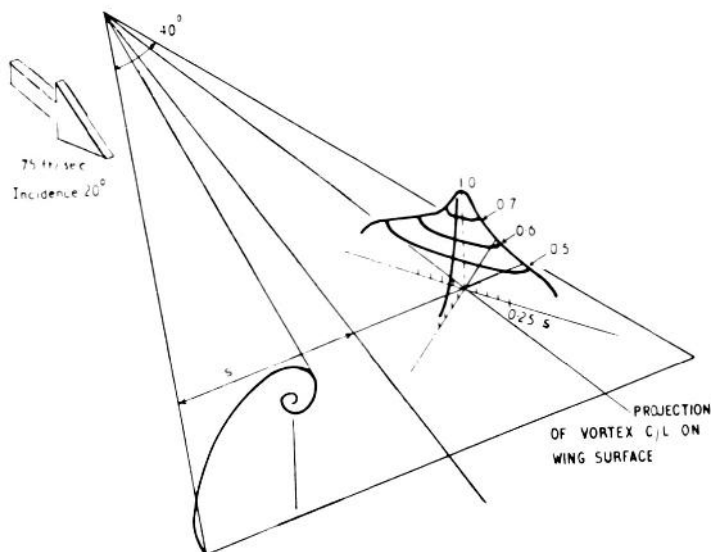


Fig. 28. Typical Surface Distribution of Space Correlation Coefficient Under the Separation Vertex of a Sharp Edged Flat Plate Delta Wing (0.8 Root Chord Aft of Apex)

On the other hand, the equal noise contours on the 707 (Fig. 29) indicate a very significant reduction of noise in the forward direction. On an aircraft with a rear engine installation we can therefore expect no worsening of the problem, and if anything a real alleviation. However, if for some reason, a forward jet installation is favored, care must be taken to establish that excessive structural stress levels are not obtained.

Some mention of the use of ejectors must be made since it was concluded in Part I that some such devices would be necessary. Referring to Fig. 15, it is seen that in the forward area, where a wing or fuselage structure would certainly be situated, the noise is reduced by using an ejector. Measurements in the neighborhood have been difficult to make in the laboratory, but results show that the noise which is radiated forward comes almost entirely from the ejector discharge, with little contribution from the intake or through the sides of the ejector.

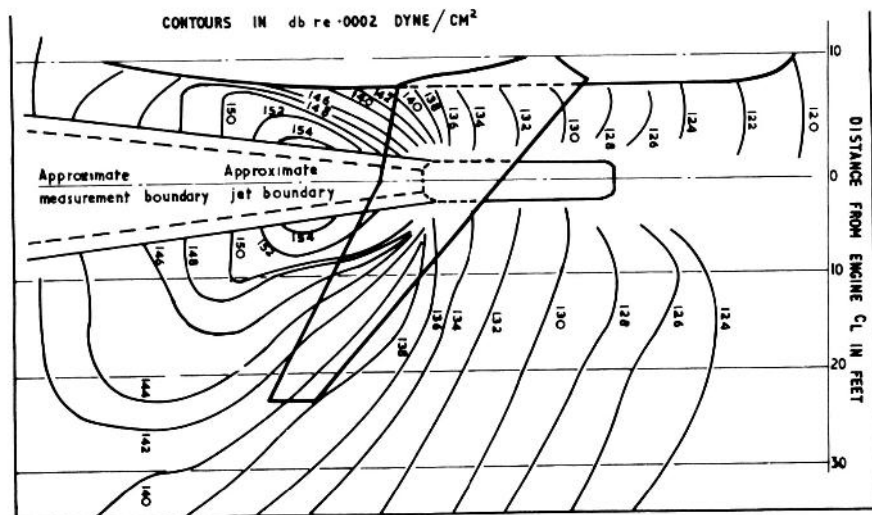


Fig. 29. Plain View of B-66 Fuselage with J-71 Overall Sound Pressure Level Contours on db re .0002 Dyne/CM²

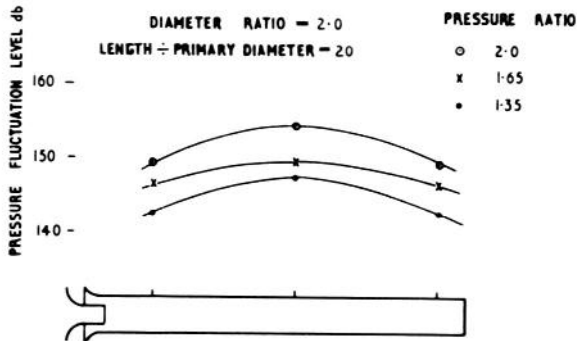


Fig. 30. Ejector Wall Internal Noise Levels

Mention has been made in Part II of the existence of discrete frequency tones as a result of "back reaction" resonances inside the ejector. This implies a high noise level inside the ejector which in itself can cause fatigue within the casing. Figure 30 shows the variation of wall-pressure fluctuation levels in decibels as a function of distance along the ejector and for three pressure ratios. While these figures were obtained on a long model ejector using a cold air jet, and extrapolation is difficult, the design problem in respect to fatigue life may be seen to be severe, particularly as the high noise level will be maintained in cruising flight.

FATIGUE DUE TO BOUNDARY-LAYER PRESSURE FLUCTUATIONS

The problem of fatigue of a structure due to boundary-layer pressure fluctuations is beset by a deficiency of knowledge throughout all the steps involved in such an investigation. There is no conclusive information regarding the rms amplitude of the pressure fluctuations in supersonic boundary layers, its frequency spectrum is not completely defined, the spatial correlation areas are undetermined, the distribution curve of alternating stresses has not been measured for boundary layers, the extrapolation of the normal cumulative damage law to as many as 10^{11} reversals is highly suspect, and methods of proof testing to this number of reversals, without excessively accelerated methods involving changes in metallurgical properties, cannot be carried out in less than a year.

We are in dire need of more knowledge in respect to every single one of the above parameters and long term researches are essential. Since, however, we are not likely to obtain them in the near future, we must once again fall back on a comparison between present and future. It was explained in Part II that it is to be expected that, depending on design, root mean square pressure fluctuations of between 130 and 140 db are to be expected on the surface, and that owing to the difference in spectral density and correlation patterns, the low-frequency response of the structure need not occur to the same degree as when

excited by a jet. At frequencies of 1,000 cps, however, the response was not dissimilar and since Clarkson has often found peak responses of the Caravelle to jet noise around this frequency, it is probably not an untypical response frequency.

Figure 31 gives some S-N diagram for aluminum alloy notched specimens, together with Clarkson's suggested extrapolation curve to 10^9 reversals.¹⁷ If, for the sake of argument, we extrapolate the lower limit to 10^{11} reversals, it is seen that an acceptable rms stress level of, say, 1,500 psi can be tolerated by the structure as compared with 15,000 psi for 10^5 effective reversals. Thus, in order to establish a safe life of the order of 20,000 flying hours on the supersonic transport, it is necessary to bargain on a stress level of less than one-tenth of that in structures which show early failure (minutes) when subject to jet noise. Another way of saying the same thing is that supersonic transport type structures must not fail prematurely (in minutes) when excited by a jet noise of some 20 db higher than the boundary layer rms pressure amplitude.

Until more satisfactory information is available, we are therefore confronted with the need to design wings and fuselages to be capable of withstanding for a reasonable number of minutes, noise levels of between 150 and 160 db. Figure 32 shows the results of some of Hubbard's tests¹⁵ on skin-rib attachments subject to discrete frequency siren testing. It is seen that orthodox riveting of stringers or frames to a fuselage has a limited life at the higher of these limits

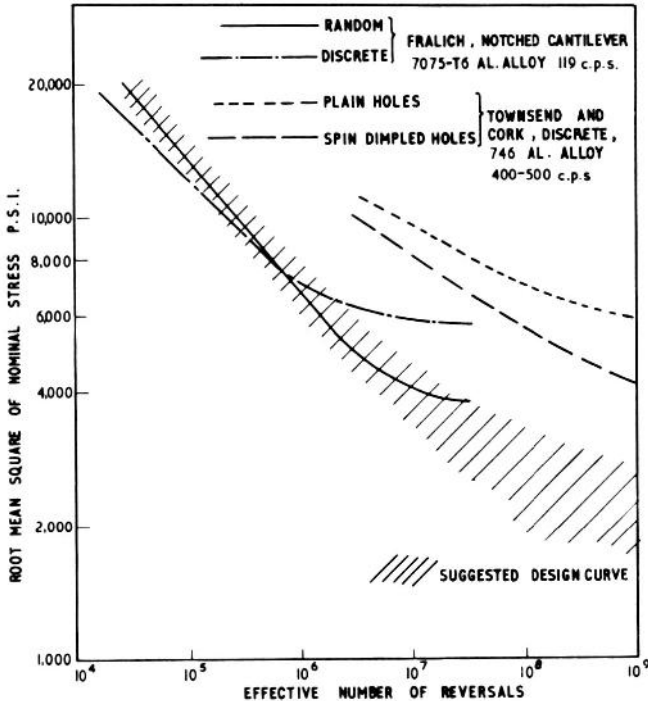


Fig. 31. Random S-N Curve for Aluminium Alloy Notched Specimens

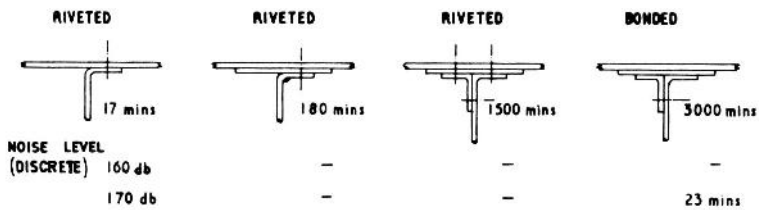


Fig. 32. Life of Various Skin Rib Attachments Subjected to Discrete Frequency Siren Testing

and that, to be safe, considerable care must be taken to minimize stress concentrations around rivets and joints. Other tests carried out have indicated even poorer rivet properties, and indicate clearly the need for every care to be taken in the structural design of the supersonic aircraft of the future.

In the above extrapolation, what may be a pessimistic view of the available information has been taken deliberately in order to illustrate the problem, and in order to emphasize the need for a careful study of the various aspects of the problem. Among the more reasonable assumptions are those involving the root mean square amplitude of the boundary-layer pressure fluctuations in supersonic flow, and the allowable stress reduction with number of reversals. It is probably quite wrong, on the other hand, to assume that equal root mean square stress levels will result in a structure when excited to the same root mean square pressure level by the boundary layer and jet noise respectively. As mentioned earlier full scale experiments on panels of the Fairey Delta airplane¹² when excited by equal overall levels of jet noise and boundary-layer pressure fluctuations are of significance even though the deficiencies of instrumentation tend to throw some suspicion on the comparisons. Figure 21 shows spectra of both excitation pressures and strains when the panels are excited respectively by jet noise and by a turbulent boundary layer at $M = 1.45$. It may be seen that although the overall excitation levels are equal and the spectra not vastly different, the peak strains resulting from the two excitations are vastly different (18 db) owing to the apparent lack of low-frequency response of the structure to the boundary-layer pressure fluctuations. If fatigue results basically from the low-frequency response of the structure, it is clear that tests carried out with jet noise will be grossly misleading and pessimistic in predicting boundary-layer fatigue. If, on the other hand, the greatest cumulative damage arises from much higher frequency response, the jet results may not be in serious error.

Some explanation of the above discrepancy is to be obtained from a study of the correlation areas of the excitation in the two cases. As mentioned in Part II, Bull has suggested¹³ that the amplitude of filtered longitudinal correlations can be plotted uniquely against the spatial separation of the points as a fraction of the boundary-layer displacement thickness, whatever the frequency being examined. This implies that the "size of the eddies" will be, say, 30 displacement thicknesses or four boundary-layer thicknesses for all frequencies of excita-

tion. Since in the Fairey Delta tests, the boundary-layer thickness was of the order of one inch, the correlation length of 3–4 in. was very much less than the 18 in. or more measured by Clarkson¹⁶ for jet noise on typical tailplanes in the lowest frequency range centered about 160 cps. Thus in such a case as this the low frequency loading would be proportional to the correlation areas, i.e., the rms amplitude of the low-frequency jet-excited load would be about 20 times that arising from the boundary-layer excitation of the same rms pressure.

At the rear of the large fuselage of a supersonic transport the same argument cannot be used since panels are likely to be smaller and the boundary-layer thicknesses much greater. Here the boundary-layer pressures will be closely correlated over the whole panel and the excitation loads on the panel will not be significantly different from those arising from jet excitation. Over the rear fuselage, therefore, the extrapolation described earlier may not be far from the truth and we must conclude that boundary-layer pressure fluctuations may well present problems of structural failure on supersonic airliners of the future.

Experimental methods of validation of structural fatigue life for relatively low-pressure variations, occurring at high frequency for a large number of hours, must be established before satisfactory structural lifetimes can be guaranteed. We must also establish the validity of cumulative damage laws with random excitation, and must learn more about the rms amplitude, amplitude distribution, convection speed and longitudinal and lateral spatial correlations of the pressure fluctuations along aircraft structures operating at supersonic speeds. Only then will we be able to predict actual structural fatigue life in terms of the life measured on relatively simple specimens excited, say, by a siren operating at a discrete frequency under accelerated conditions. On a longer term basis, theoretical or semitheoretical methods of prediction of the structural response of real structures to random loading of the boundary layer kind need pursuing, while mode shape calculations, and work aimed at an understanding of structural and acoustic damping, must go on with greater urgency.

FAIL-SAFE STRUCTURES AND CRACK-PROPAGATION RATES

In sheet materials subjected to a given tensile loading, there is found to be an associated "critical" crack length normal to the applied loading, and damage or cracking in excess of this results in catastrophic self propagating fracture. This stress is clearly a function of the crack length divided by the width of the panel, a typical curve being of the kind B in Fig. 33. Different materials have different cracking properties and while some fracture at an ultimate stress for the remaining material (curve A), others fracture (curve B) at a stress much below the expected strength of the residual material.

On aircraft materials, lower stresses are used, and in order to propagate a crack the stress has to be raised to a certain level (curve C) at which a small increase in crack length will occur. The crack will not propagate any further until the stress is increased once again, and catastrophic failure does not occur until a crack length on curve B is achieved. A typical static crack propagation curve is included in Fig. 33.

If, for some reason, a crack already exists in the structure, for example, as a result of ground running jet noise, but does not propagate under the static pressurization stress in the skin, it is possible under certain conditions of noise intensity, static stress, and crack-width-panel-width ratio, for the crack to propagate and eventually reach the catastrophic failure condition.

A comparison of the "noise present" and "no noise" critical crack length curves (curve C) indicates (Fig. 34) that there can be significant crack propagation in the presence of noise when cracks reach two thirds of the static safe crack length. (See Fig. 34—not over the whole range of stresses.) This need not be a severe restriction but one which should be allowed for in establishing inspection techniques and safe stress levels in the skins.

The mechanism of this change in propagation properties is of interest and has been studied extensively by Pietruszewicz at Southampton. It is found that the

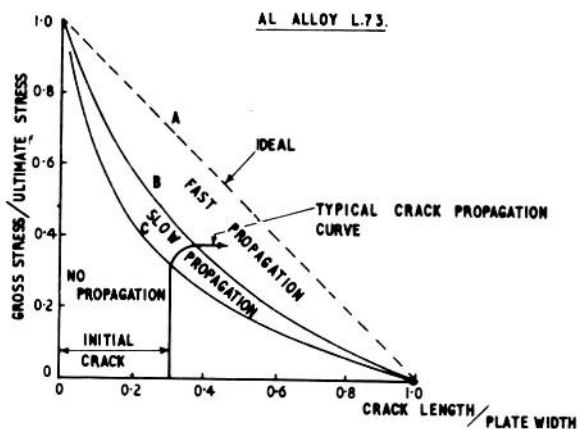


Fig. 33. Static Crack Propagation Thresholds

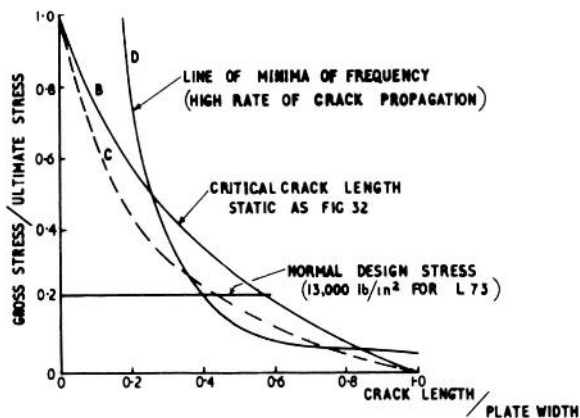


Fig. 34. Dynamic Crack Propagation Thresholds

behavior of the system is closely related to the behavior of the two semielliptic areas of the plate which have the crack as their minor axis. The predominant form of vibration is one in which each of these areas vibrate in its lowest mode. For short crack lengths the compressive stress in these semielliptic areas is below the buckling stress but as the crack length increases buckling occurs. In this condition the semielliptic areas are unstable and move from one extreme position to the other. This gives rise to a tearing action and a premature severe crack propagation rate.

This critical length seems to be independent of the amplitude of the noise. However, the rate of propagation once this length is exceeded depends very much on the intensity. In one test on an 18 Imperial standard wire gage L.73 alloy panel operating at a mean tensile stress of 13,000 psi and with a crack-width-panel-width ratio of 0.343, the following rates of propagation were obtained:

<i>Noise level, db</i>	<i>Rate, in. per hr</i>
140	infinitesimal
145	0.035
150	0.189

While such a crack length is not typical, nevertheless it is clear that stress levels particularly in areas difficult to inspect, should be kept to safe stress limits determined from "noise present" investigations and that care should be taken to use materials in which the two critical length curves are well spaced.

VORTEX-INDUCED PRESSURE FLUCTUATIONS

If the leading edge of an aircraft is swept back through a very large angle, as happens, for example, on the narrow delta type of configuration, the airflow over the wings alters as the incidence increases. For small incidences, the flow is unseparated and the only vortices occurring are those emanating from the wing tip. As the incidence increases, however, an incidence is reached (depending on the camber and sweep angle) above which the streamline flow is maintained at the expense of a wrapped up vortex sheet of the kind shown in Fig. 28, and emanating from near the nose. These vortices fluctuate slightly in position, presumably due to small fluctuations in the flow at the nose of the aircraft, thereby inducing pressure fluctuations on the wing surface below them. As has been shown (Fig. 28) in experiments on elementary models at Southampton, these pressure fluctuations are well correlated over very significant areas of the wing surface, certainly much greater than panel areas and can add up to give large random fluctuating loads on the wing structure.

In the above experiments, the overall root mean square amplitude of the pressure fluctuations (Fig. 35) coincides with that to be expected from a normal turbulent boundary layer until an incidence of 5° or so, depending on the design, the vortices form, and the root mean square pressure level increases threefold, remaining at this level with increasing incidence until the vortex bursting point moves upstream to locate itself above the measurement point on the wing. At this stage the fluctuating pressure level increases to about ten times that

of the normal turbulent boundary layer. The spectrum of the excitation is shown in Fig. 36. It may be seen that the whole of the energy is contained below 300 cps. The excitation level in the low frequency range is therefore much greater than that in the boundary layer where the energy is spread far more widely.

This phenomenon which has not been studied fully, certainly not on truly representative supersonic aircraft shapes, presents a possible source of trouble particularly if separated flows occur in cruising flight. Since the energy is contained in the low frequencies, and the pressures are well correlated over areas several orders greater than that of boundary-layer noise, it follows that buffeting of panels and control surfaces can occur, especially when the aircraft is at high incidence during landing and takeoff. There is in fact no confirmation of such a trouble in flight and it is to be hoped that, in practice on full-scale craft, the fluctuations of pressure are acceptable. The existence of this effect does however suggest the need for further studies of the mechanism of vortex oscillations and the variation of amplitude and correlation area on ogee, gothic and delta plan-forms in flight.

This type of aircraft is not likely to spend sufficient time in subsonic flight at high incidence to introduce serious fatigue failures due to these pressure fluctuations. The question must be asked, however, whether or not similar vortex flows occur in supersonic cruising flight. If so, then acoustic fatigue must

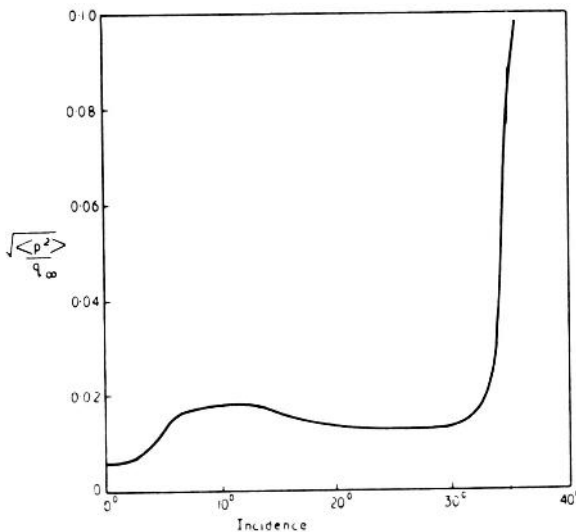


Fig. 35. Typical Variation with Incidence of R.M.S. Surface Pressure Fluctuations on a Sharp Edged Flat Plate Delta Wing.

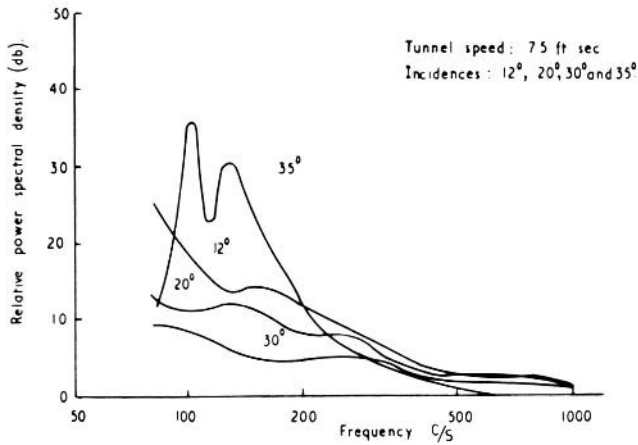


Fig. 36. Frequency Spectra of Pressure Fluctuations on Model Flat Plate Delta Wing

be considered, particularly as high-frequency boundary-layer pressure fluctuations themselves may be of sufficient amplitude to cause long-term cracking. Unfortunately, though work is proceeding to establish the magnitude of the problem, it is not possible at the moment to do more than draw attention to it. It is now generally accepted that some small degree of vortex flow will exist, the vortices nevertheless being relatively weak. They will remain rather near the surface, however, and may well consist of a whole series of diagonal vortices rather than a single one on each side of the aeroplane. The nearness of the vortices to the surface will tend to accentuate the amplitudes of the pressure fluctuations, while at the same time reduce the correlation areas. Single panels may therefore vibrate as much as in subsonic flight at the same equivalent air speed, but for the whole flight.

A further difficulty arises from the possibility of early bursting of the vortices over the wing surface of gothic and ogee planforms, as a result of the reduced leading-edge sweep at some spanwise stations. The severity or otherwise of the problem must therefore await detailed measurements of amplitudes and areas of correlation of the pressure fluctuations on wing and body configurations with the correct planform, camber shape and Reynolds number.

SHOCK-WAVE OSCILLATIONS

Shock-wave oscillations are no new thing in the 1970s and need only be mentioned here for completeness. Thus, we must expect rapid variations of pressure when a strong shock emanating from some other part of the aircraft impinges on the fin or elsewhere, and oscillates in position of impingement. The theoretical value of the amplitude is, of course, equal to the pressure rise across the shock and is, for example, as much as decibels for a Mach 2.2 aircraft

at 50,000 ft altitude. Naturally, therefore, it is wise to ascertain in the early stages of design that there are no shocks emanating from regions of fluctuation flows and striking some other section of the aeroplane.

Two examples can be given, the first being the oscillating shock from a poorly designed pilot's cabin striking the fin in its rear. The second and probably of far greater significance involves the shock emanating from the lip of the engine intake striking the other side of the intake with some periodic or random variation. Very high fluctuating pressure levels of over 160 db have been recorded in some cases, though it is true to say these have arisen from gross intake shock instabilities and not small movements of the above kind.

Significant pressure fluctuations occur also if intakes are designed for cruising conditions without sufficient reference to the ground running conditions. Thus if as a result of overemphasis of good intake efficiency in supersonic flight, separations occur within the intake during ground running, acoustic fatigue of the intake can occur. Figure 37 illustrates this on a series of intake arrangements on engines being tested in the U.S. The flight pressure fluctuations are not significantly different from those to be expected in a turbulent boundary layer.

On the other hand, the ground-pressure fluctuations for similar duct dynamic pressures are raised by a factor of ten, the sound pressure levels of 155 db being sufficient to insure early fatigue of the intake unless some form of carefully designed structure is used. While this is not a new problem, the increased range of velocity conditions for which intakes have to be made acceptable on supersonic transport will undoubtedly tend to add to the difficulty of satisfactory entry flow design for good ground running.

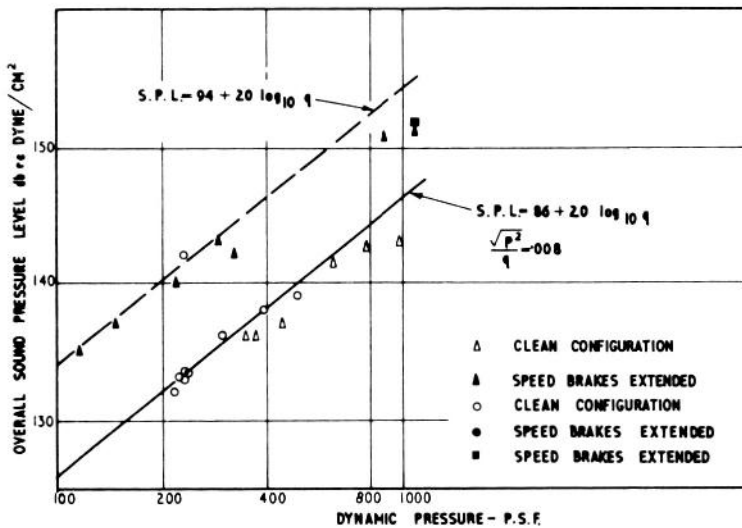


Fig. 37. Pressure Fluctuations on T-38 Downstream of Speed Brake Position

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DISCUSSION

Author: E. J. Richards

Discussor: Bo Lundberg, The Aeronautical Research Institute of Sweden

Professor Richards has indeed presented an excellent paper. The points I wish to make all concern the sonic boom.

I am very glad that Professor Richards has touched upon the question of scatter in sonic-boom intensity by referring to the influence of atmospheric turbulence and wind conditions. I should, however, appreciate knowing more precisely how Professor Richards looks upon this problem, which in my opinion is of utmost importance. Briefly, present knowledge seems to indicate that if the theoretical or mean value of the boom intensity—which are in fairly good agreement—is, for instance, 1 or 1.5 lb/sq ft, boom intensities of

the order of 2 or 3 lb/sq ft will be very common and also that "super bangs" with intensities of the order of 5 to 10 lb/sq ft might be fairly frequent, once we have a great amount of supersonic aviation. It might be possible to reduce the scatter to a certain extent by very careful flying, but focussing effects due to normal maneuvers including normal phugoid movement of the SST and, above all, due to atmospheric conditions, will probably not be avoidable.

Thus, the big scatter in boom intensities makes the problem enormously more serious than if we only had to deal with the mean value. It therefore seems almost incredible that in most previous discussions of the acceptability of sonic booms the implications of the scatter have been almost completely neglected.

I also very much appreciate Professor Richards' basic view that we must consider not only the average public reaction but, in particular, what Professor Richards calls the "hypersensitive fringe of, say, 3 percent" of the population. However, I cannot follow Professor Richards' statement that:

"Once the sonic booms are understood by the public neither of these objections (one being 'a general feeling of insecurity') need arise; the results of single tests with supersonic aircraft may therefore be misleading as a long term indication of acceptability."

There has been much talk that "education" of the public should reduce the public opposition to the sonic booms. I very much doubt that education can ever play a very important role when it comes to this unexpected and sharp type of noise claps. It is possible that education might have a certain positive effect on some people who by nature are not very much disturbed by any type of noise. However, when it comes to disturbances that affect the whole countries, the important part of the population is those people who are sensitive to noise, due to illness, nervousness, old age or any other reason, and I do not think that they can be relieved at all by any kind of education.

I think that the whole sonic-boom problem was stated very clearly by a spokesman of ICAO during the IATA Symposium on Supersonics in April, 1961. He asked why people in countries which have no interest in supersonic aviation should tolerate any boom disturbance at all. On the basis of this question, I think the proponents of supersonic aviation would be wise if they saw to it that complete information about possible sonic-boom disturbances, including the effect of scatter, be given to the people of all countries which might be overflowed by SST's in the future. If such information, part of which must be subjecting such people to real or artificial sonic booms, is not given, there is a risk that countries which have no interest in supersonic aviation, will prohibit or severely restrict such flying.

I wish to emphasize, and I am sure that Professor Richards agrees, that the "number of complaints" is not an adequate criterion for the acceptability of sonic-boom disturbances. It is the extent to which people are disturbed, not the extent to which they care to complain, that is most important. The extent to which people are disturbed must be assessed on the basis of scientific medical investigations, comprising, in particular, noise-sensitive people living in a quiet countryside.

Professor Richards mentions the idea of operating "special supersonic services across sea masses or unpopulated areas," if it is shown "that sonic booms over populated areas are unacceptable." I am glad that Professor Richards does not subscribe to the opinion expressed by others that the density of the population is significant, in other words that boom intensities unacceptable for densely populated areas should or could be tolerated by people living in sparsely populated areas.

Discussor: L. F. Nicholson, Ministry of Aviation, U.K.

I should like to ask Professor Richards for his comments on three points relevant to the problem of noise near airports. First, I should like to emphasize the importance, in cases where takeoff or initial climb can be made at less than full thrust (as in the typical supersonic transport) of reducing thrust by increase of jet exit area at full rpm, rather than by closing the throttle in the normal way. Does Professor Richards agree?

Second, with respect to compressor noise during landing it has often been suggested, and I believe checked experimentally, that noise can be reduced markedly by arranging to choke the air intake, possibly by partially closing the inlet guide vanes. Is this technique now discounted and, if not, might it not be lighter and more convenient than tackling the problem by respacing successive rows of blades in the compressor?

Finally, on supersonic aircraft where the noise to the sides of the takeoff path is liable to be troublesome, would Professor Richards agree that the idea of reducing noise by accelerating the aircraft on the runway, where noise can at least be partially screened, to a speed well above the minimum flying speed, so that the initial climb can be made at lower power with some deceleration has long term possibilities?

(Author did not reply.)