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'Crackle': an annoying component of jet noise

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The paper describes an investigation of a subjectively distinguishable element of high speed jet noise known as 'crackle'. 'Crackle' cannot be characterized by the normal spectral description of noise. It is shown to be due to intense spasmodic short-duration compressive elements of the wave form. These elements have low energy spread over a wide frequency range. The crackling of a large jet engine is caused by groups of sharp compressions in association with gradual expansions. The groups occur at random and persist for some 10^{-1} s, each group containing about 10 compressions, typically of strength 5×10^{-3} atmos at a distance of 50 m. The skewness of the amplitude probability distribution of the recorded sound quantifies crackle, though the recording process probably changes the skewness level. Skewness values in excess of unity have been measured; noises with skewness less than 0·3 seem to be crackle free. Crackle is uninfluenced by the jet scale, but varies strongly with jet velocity and angular position. The jet temperature does not affect crackle, neither does combustion. Supersonic jets crackle strongly whether or not they are ideally expanded through convergent–divergent nozzles. Crackle is formed (we think) because of local shock formation due to nonlinear wave steepening at the source and not from long-term nonlinear propagation. Such long-term effects are important in flight, where they are additive. Some jet noise suppressors inhibit crackle.

1. Introduction

Anyone who has listened at close range to the take-off of aircraft powered by jet engines of high specific thrust will be familiar with the phenomenon of 'crackle'. The large jet transports of the first generation and high performance military aircraft are, at full power, particularly prone to producing sudden spasmodic bursts of a rasping fricative sound not dissimilar to that made by the irregular tearing of paper. Some observers liken it to the sound of an electric arc welder or of a badly connected loud speaker; others liken it to the spitting of water added to extremely hot fat. It is a startling staccato of cracks and bangs and its onomatope, 'crackle', conveys a subjectively accurate impression.

Crackle is an especially annoying and subjectively distinct aspect of jet noise, yet we are not aware of any previous investigation into its cause and structure. Technicians involved in the testing of jet engines often have decided views on the cause of crackle. There is an acknowledged tendency for the effect to be more pronounced at the highest power settings, where the jet is often supercritical and sometimes boosted by an afterburner, where the combustion process is relatively rough. Noting this, some attribute crackle to rough burning, others think it to be a characteristic of the reheated jet and equally many seem convinced that it originates in shock waves that form in the jet whenever it exhausts at supercritical conditions from an imperfectly expanded nozzle flow. There seems to be no systematic basis for these views, which are an impression formed as a result of practical experience. The phenomenon has yet to be examined in any systematic way.

Our interest in crackle originates from work to control the noise of the Rolls-Royce/SNECMA Olympus 593, an engine of particularly high specific thrust that powers the Concorde supersonic transport. In its unsuppressed form this engine crackles in a striking manner. In fact when listening at close quarters it is the intermittent crackle that makes the dominant subjective impression, and one feels considerable relief in the crackle-free intervals that occur from time to time. We think that crackle contributes significantly to the annoyance caused by jet aircraft at high thrust, and that therefore its control and eventual elimination could lead to a significant improvement of the current aircraft noise problem as well as helping towards the social acceptance of Concorde. It was to this end that the investigation described here was directed.

Crackle is not easily quantified on any of the common scales of sound. In fact we cannot distinguish through the usual measures any indication of whether a jet is crackling or not. We have conducted a thorough examination of the various spectral representations of noise in an attempt to correlate spectral idiosyncrasies with crackle and our failure to do so convinced us that there is none. We believe that it is only because the qualities of crackle are not displayed through conventional measures that this obviously annoying component of jet noise has escaped previous study and quantification on the various scales on which aircraft noise levels are measured, the PNdB and EPNdB for example. A quantitative measure of the effect is an essential prerequisite for its systematic study.

Though the spectral representation is insensitive to crackle, the wave form of the pressure, i.e. the pressure time history, has distinct characteristics with which the effect can be quantified. The wave form of a crackling jet, measured and recorded with standard high fidelity amplitude-modulation equipment, is easily distinguished from that of a non-crackling jet by the random occurrence of distinct bursts of strong narrow positive pressure transients; figure 1 illustrates such a burst. In a recorded reproduction of the noise signal measured around the Olympus they last for between 10^{-1} and 1 s, occurring chaotically but at about 1 or 2 s intervals. Within the bursts the compressions also occur

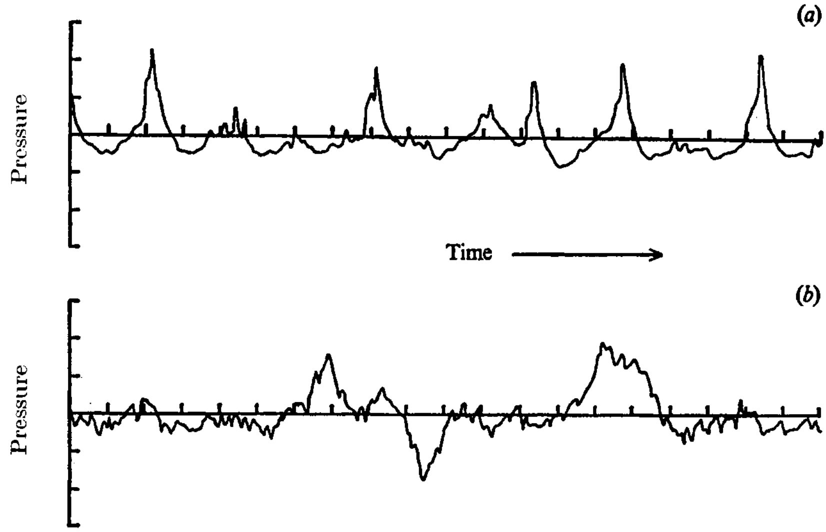

FIGURE 1. Two 20 ms segments of the jet noise wave form measured on the Olympus 593 engine. The sound of (*a*) crackles distinctly, that of (*b*) does not.

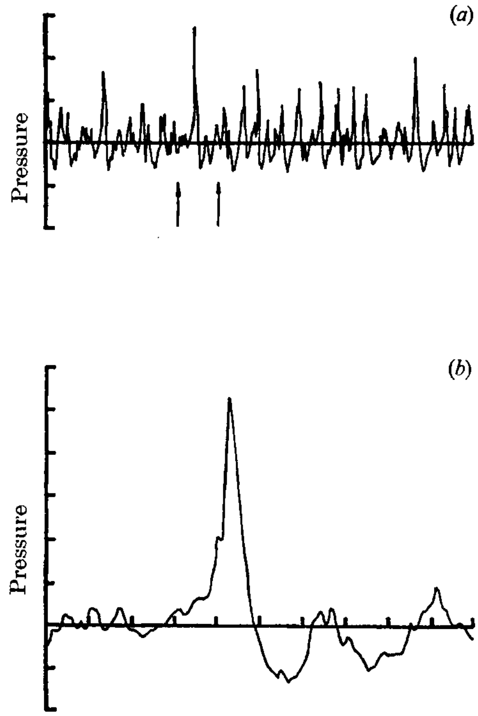

FIGURE 2. An illustration of the characteristic 'shape' of crackle. (*a*) 100 ms sample. (*b*) 10 ms sample, an enlargement of the part of (*a*) between the arrows. The signal was measured on the Olympus 593 engine at high power.

chaotically but with a typical frequency of occurrence of about 10^{-2} s. The compressive parts of the recorded signal have a distinctive shape (figure 2), being composed of a strong sharp rise followed by a gradual relaxation and weak expansion that may, or may not, mimic accurately those details of the actual pressure signal. The compressions are typically up to 5×10^{-3} atmos 50 m away from the engine exhaust and the relaxation covers a period of 2 or 3 ms to an expansion of less than a quarter (usually less than a tenth) of the initial compression. This tendency of the recorded signal to have strong compressive levels with no accompanying expansive counterparts suggests that the skewness of the recorded signal amplitude probability density function might be an appropriate statistical measure for quantifying crackle. We find this measure to be extremely convincing and from many aural tests have concluded that noise signals with a normalized skewness† less than 0·3 do not crackle while those with a skewness in excess of 0·4 crackle distinctly. We have measured skewness factors in excess of unity in the noise field of the Olympus jet at high power; this factor is typically of order 10^{-1} in non-crackling jet noise. This high degree of crackle is found at about 60° to the jet axis, which happens to be close to the eddy Mach wave angle and the position of peak noise.

It is our view that the subjective impression of crackle is faithfully reproduced throughout the process of recording and replay with conventional high fidelity equipment. The components of such equipment, the measurement microphone, attenuators, filters, amplifiers, amplitude-modulated tape recorders and loud speakers, are all high-pass filters of various types, incapable of dealing with parts of the signal that change sufficiently slowly. But the ear too is a high-pass filter, and this lack of low frequency response is immaterial to the accurate reproduction of subjective features of the sound wave. But the skewness of a signal can be totally distorted because of this lack of low frequency response, and the 'shape' of the recorded signal need not be even remotely similar to that of the actual sound wave. Lack of low frequency response makes the signal undetermined on the long time scale corresponding to Fourier elements below the cut-off frequency. If rapid rises tend to occur at the ends of slow decays, then only the rapid rises are reproduced, and then from a common datum level. Even a symmetric N-wave will be recorded and reproduced as a highly skewed signal whenever the expansion between the jumps is too slow for the 'a.m.' equipment to handle faithfully. The crackle spikes in the engine case are unfortunately exactly in this indeterminate time range, a point apparent from the description of the experimental equipment we give in an appendix. The skewness of the signal may therefore be an artifact of the recording process. But on the positive side, that artifact provides the means by which the subjective impression can be quantified, the skewness being easily identifiable and the equipment being of an internationally accepted standard type in general use. The drawbacks are on the other hand all too apparent, for we wish to study in depth the form and cause of the crackle wave form, and we can be sure only that high positive skewness tells us that there are more rapid compressive

† The third central moment of the probability distribution normalized by the standard deviation.

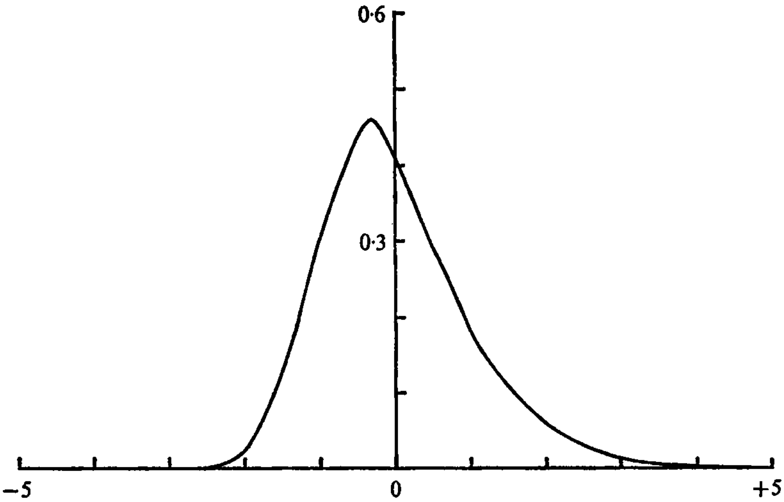

FIGURE 3. The probability distribution of the pressure in crackling jet noise.

phases than expansions. The strength of the gradual expansions cannot be determined from the available experimental evidence.†

There is very little energy contained in the spikes responsible for crackle. This is clear from figure 3, where the probability distribution of a 'high crackle' noise is shown. The 'tail' of the curve shows that the high crackle signals have an extremely low probability of occurrence and the area under that part of the curve is a negligible fraction of the whole. This is a direct measure of the relative energy content of the crackle spikes. Spectral measures centre on energy, and since the spectrum of a sharp-edged spike is extremely flat and evenly distributed over a wide frequency range, it is little wonder that the noise spectrum fails to contain the information from which crackle can be identified. The annoyance of crackling sound must evade quantification by any measure based on the spectrum of that sound. We are convinced from our many listening tests that the skewness factor of the recorded signal is an effective direct measure of crackle and from now on shall regard the two as equivalent.

Crackle can be scaled. We have tested a $\frac{1}{10}$ scale model jet under Olympus 593 temperature, velocity and pressure conditions. Though when listening to the noise of the model, where the time scale is one-tenth of that in the engine, crackle is difficult to distinguish, it is perfectly clear when the signal is recorded and played back at $\frac{1}{10}$ speed. This slowed model signal is to us indistinguishable from real engine noise. It is also virtually indistinguishable on a spectral and probability density basis (figure 4). The measured engine noise had of course travelled much further than that of the model: in fact over twenty times

† *Note added in proof.* Many of these experiments have now been repeated using frequency-modulated recording equipment with a flat low frequency response. These tests completely verify the earlier experiments and lead us to conclude that the reproduced signals are faithful copies of the originals.

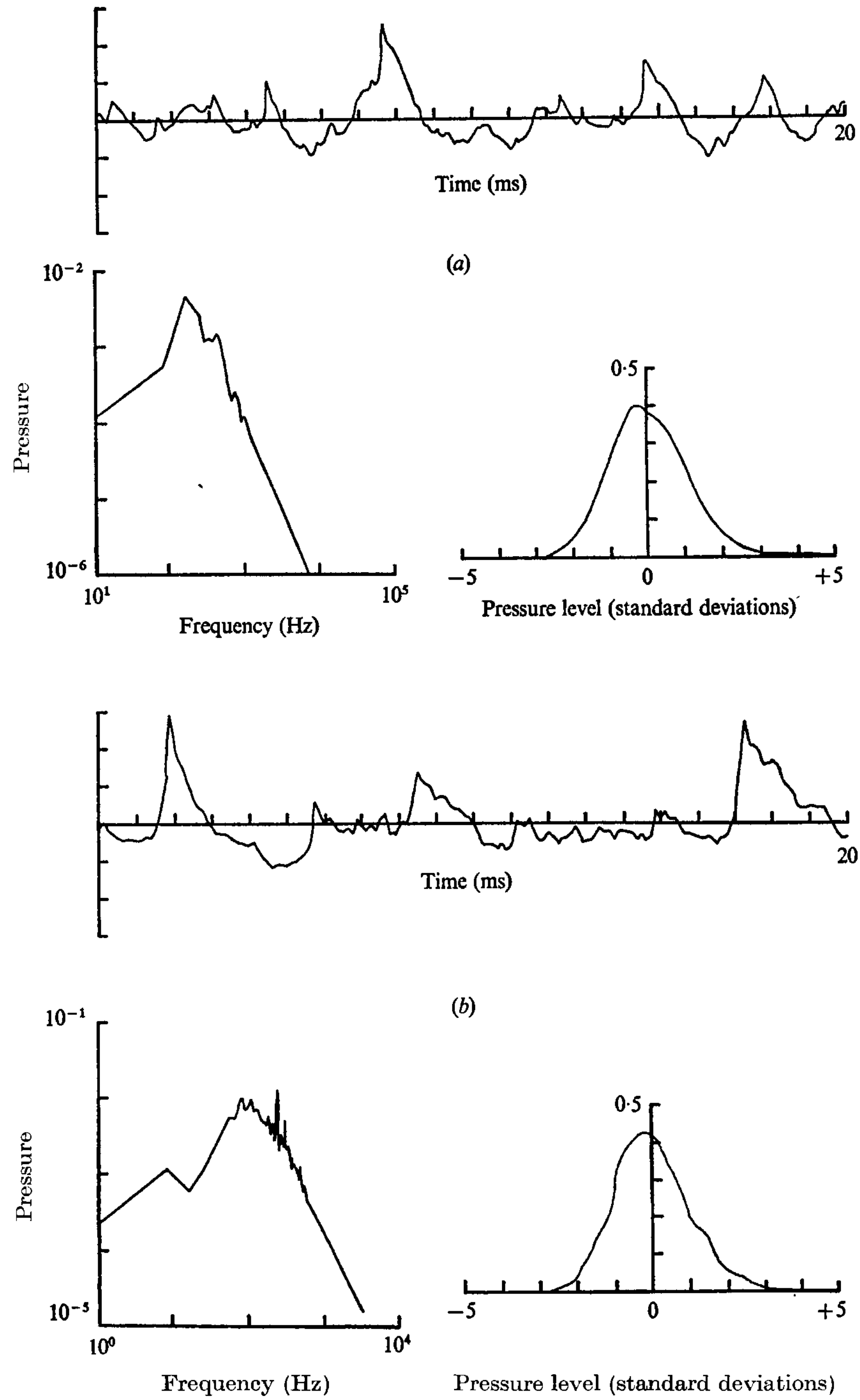

FIGURE 4. Typical examples of high crackle level noise together with their spectra and amplitude probability distributions. (*a*) Olympus 593 engine. (*b*) $\frac{1}{10}$ scale model jet (time scaled to engine conditions).

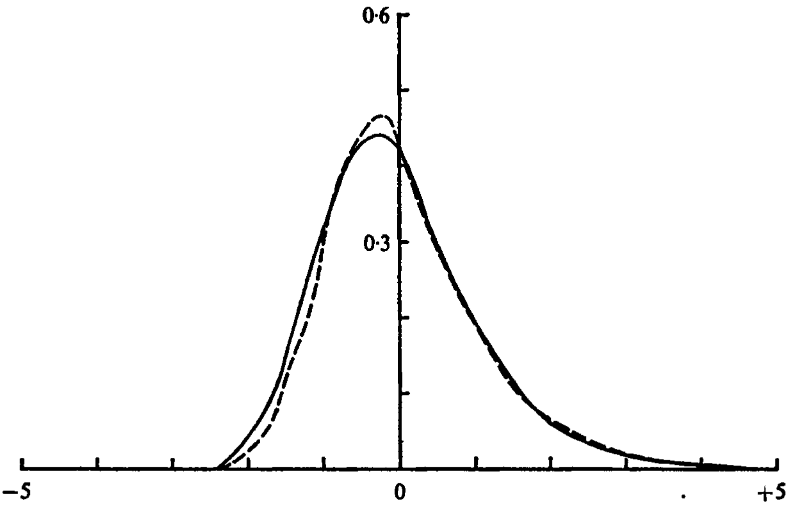

FIGURE 5. A comparison of the probability distributions for a high crackle noise from the Olympus 593 and a shock-free $\frac{1}{10}$ scale model jet at the same velocity. ——, ol. 593 conical nozzle, pressure ratio = 2·46, jet velocity = 622 m/s, skewness = 0·72; – – –, convergent–divergent nozzle model, pressure ratio = 3·18, jet velocity = 642 m/s, skewness = 0·67.

further, to a position usually regarded as typical of the far acoustic field. Measurements were also made at half that distance from the engine but we could distinguish no difference in the crackle level. It seems therefore that observed crackle is independent of the distance travelled by the sound provided that observations are confined to positions outside the immediate near field yet close enough to the source that long-term propagation effects are negligible. We shall return to this point later.

Our investigations rule out any jet shock structure as the source of crackle. We found that shock-free jets ideally expanded through convergent–divergent nozzles crackle in precisely the same way as do imperfectly expanded jets from conical nozzles (figure 5). Neither do we think that crackle has anything to do with rough combustion. Our full-scale engine gives similar results to those produced in our laboratory, though admittedly both jets are heated by the combustion of kerosene. Similar signals have been measured by Professor Laufer and his colleagues at the University of Southern California. Their jet is electrically heated to the same conditions as our jets, and emerges from an extremely smooth plenum chamber flow with an initial turbulence level inevitably lower than ours.

The afterburner is similarly excluded as the cause of crackle. We found no significant difference between the skewness of the reheated jet and that of the bare engine at a similar exhaust velocity. Neither do we have any evidence that the jet temperature is a prime parameter but admit that we have not been able to vary this over a significant range at constant jet velocity, so that we cannot make a definite statement at this stage.

The individual spikes, at first sight, suggest shock wavelets, which might

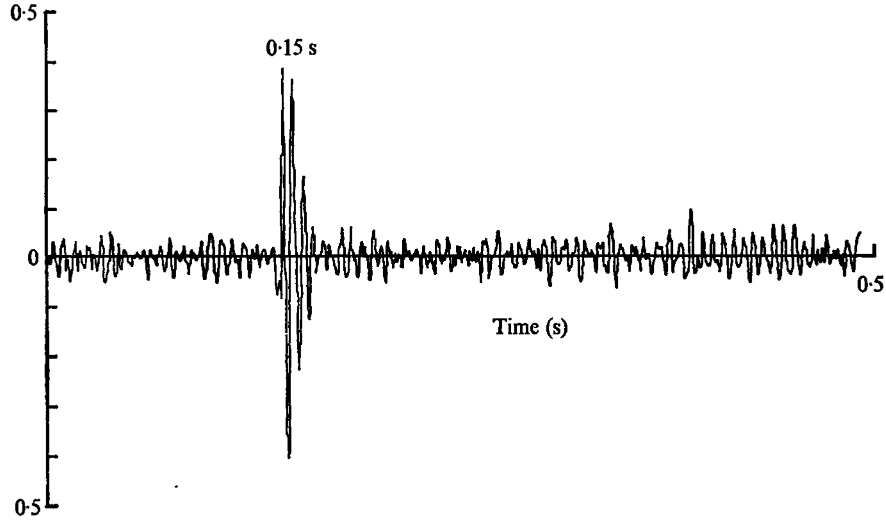

FIGURE 6. Cross-correlation coefficient of the sound radiated by the Olympus 593 engine at high power. The field is measured at two positions, one 5 diameters from the axis and 15 diameters downstream of the nozzle and the other more than 50 diameters from the jet.

well be formed by nonlinear propagation effects. But on reflexion we do not believe that there is any substantial wave-form evolution during propagation under the particular conditions we have tested. Though the waves originate in nonlinear fluid motion, as does all aerodynamic sound (Lighthill 1952), subsequent nonlinear propagation is not important. We conclude this for three reasons. First, nonlinear distortion occurs because compressive sections of the wave travel faster than their expansive counterparts. This distorts the signal in an essentially symmetric manner (Lighthill 1956). Skewness, the measure of crackle, is not changed by nonlinear propagation though, of course, nonlinear effects eventually cause the wave form to evolve into long N-waves, which are distorted by a.m. equipment into skewed signals. We cannot tell with certainty whether or not this occurs in our equipment, but incline to the view that it does not, since the skewness measures are reproducible in scaled experiments, where finite amplitude effects are at a different level and signal distortion due to the limited bandwidth is also different. Second, any major distortion of the wave form will lead to a loss of coherence in the wave and will tend to destroy the correlation between the near- and far-field sound. In fact we measured a remarkably high wave correlation coefficient during crackle (figure 6), showing that the retarded-time correlation between signals 5 diameters and 50 diameters from the jet is as high as 40 %, an unusually high value for jet noise fields; see for example Meecham & Hurdle (1974). Correlations are of course an energy measure and we have already pointed out that such measures fail to describe significant features of the improbable (but significant) crackle, so that this second point is not a strong one. Our third argument is more definite, but again not conclusive. Professor D. T. Blackstock has, at the University of Texas, an effective computational procedure for calculating the nonlinear development of

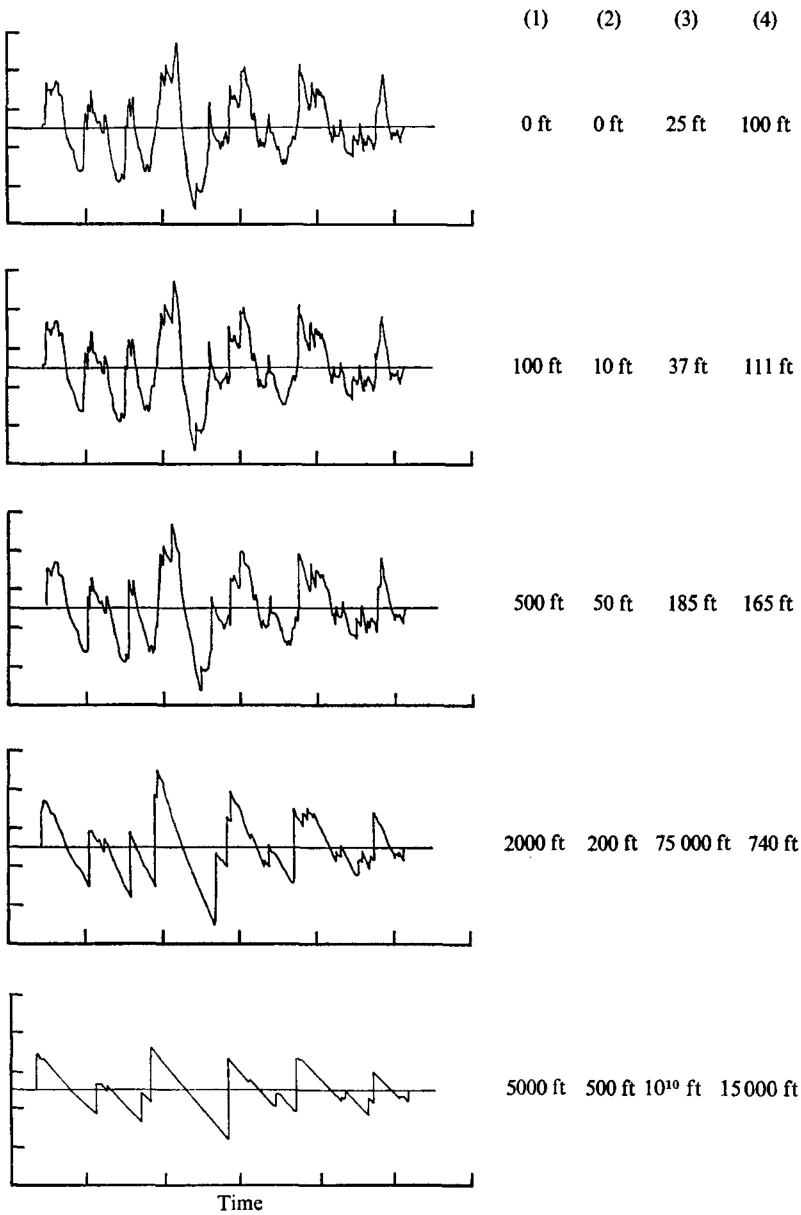

FIGURE 7. The nonlinear evolution of sound measured near the exhaust of the Olympus 593 engine. The first column shows the distance at which the indicated wave forms would be observed if the wave were plane and the overall sound pressure level 125 db. Column 2 shows the distances at which the same wave forms would be observed if the overall sound pressure level were 20 db higher (or if the sound pressure level were the same but the peak frequency 2000 Hz instead of the actual 200 Hz). Columns 3 and 4 show the distances for a spherically spreading wave if the source wave was 145 db at a radius of 25 and 100 ft, respectively. The first signal is that measured 25 ft from the engine; its level is less than 145 db. (Diffusive effects are neglected.)

noise signals (Pestorius & Blackstock 1974). That program has been applied to samples of the data measured and recorded in the near noise field of the Olympus 593 and the nonlinear evolution of that signal determined. From these calculations Blackstock has concluded that our measured sound levels are simply too low for *any significant* nonlinear amplitude distortion to occur. Eventually of course they become important, and we reproduce Blackstock's prediction of how the wave evolves in figure 7, but in doing so emphasize that, even if this effect could induce skewness, the distances needed for nonlinear evolution are altogether too large for finite amplitude propagation to be the prime cause of crackle in our experiments with static jets.

But even this observation has to be qualified somewhat because of the lack of low frequency response in the acoustic equipment. Since the recorded signal is different from the real signal by a slowly varying indeterminate amount, it is not possible to guarantee the absolute sound pressure levels on which the nonlinear propagation calculations are based. It can only be said that we feel it improbable that the pressure amplitudes can be significantly different from those given in figure 7, and, on that basis, nonlinear propagation effects seem to be unimportant.

Obermeier (comment on introductory lecture of AGARD Conference on Noise Mechanisms, *AGARD Conf. Proc.* no. 131 (1974)) has made the interesting observation that turbulent focusing of an N-wave leads inevitably to the formation near a caustic of spiked positive pressure fluctuations and rounded negative ones. The details of the mechanism are described by Obermeier (1974) as due to phase scrambling of the individual Fourier components. This process, in association with the random nonlinear N-wave formation quantified by Pestorius & Blackstock (1974), will eventually lead to crackle formation when high amplitude noise propagates over long distances through atmospheric turbulence. As we have already reported, we do not believe that there are any significant propagation effects in our experiments with static engines and models. We believe that the crackle spikes observed there are formed within, or in the very near vicinity of, the turbulent jet flow. But we have also measured the noise of jet aircraft in flight and observed there a quite different variation of crackle with changes in the parameters that characterize noise. For example, figure 8 depicts the crackle levels we have measured in jets some of whose eddy convection speeds (taken as 0·6 of the fully expanded jet velocity) exceeded the ambient speed of sound. The noise of these jets always peaks near the eddy Mach angle, and the highest crackle is observed there also. We have emphasized this point by plotting the measured skewness factors as a function of the observation angle measured from the Mach angle and have set the Mach angle to zero for those jets with subsonic eddy convection speeds. The jet axis lies in the range $-50°$ to zero on this scale, depending on the particular jet. The extensive scatter of the data points shows how much the levels depend on other parameters, but one point is clear. The crackle levels of static high speed jets, whether model or engine, tend to peak near the eddy Mach angle in the quadrant downstream of the jet exhaust. Crackle levels increase with jet velocity, and this display of high velocity data was chosen because the noise it characterizes

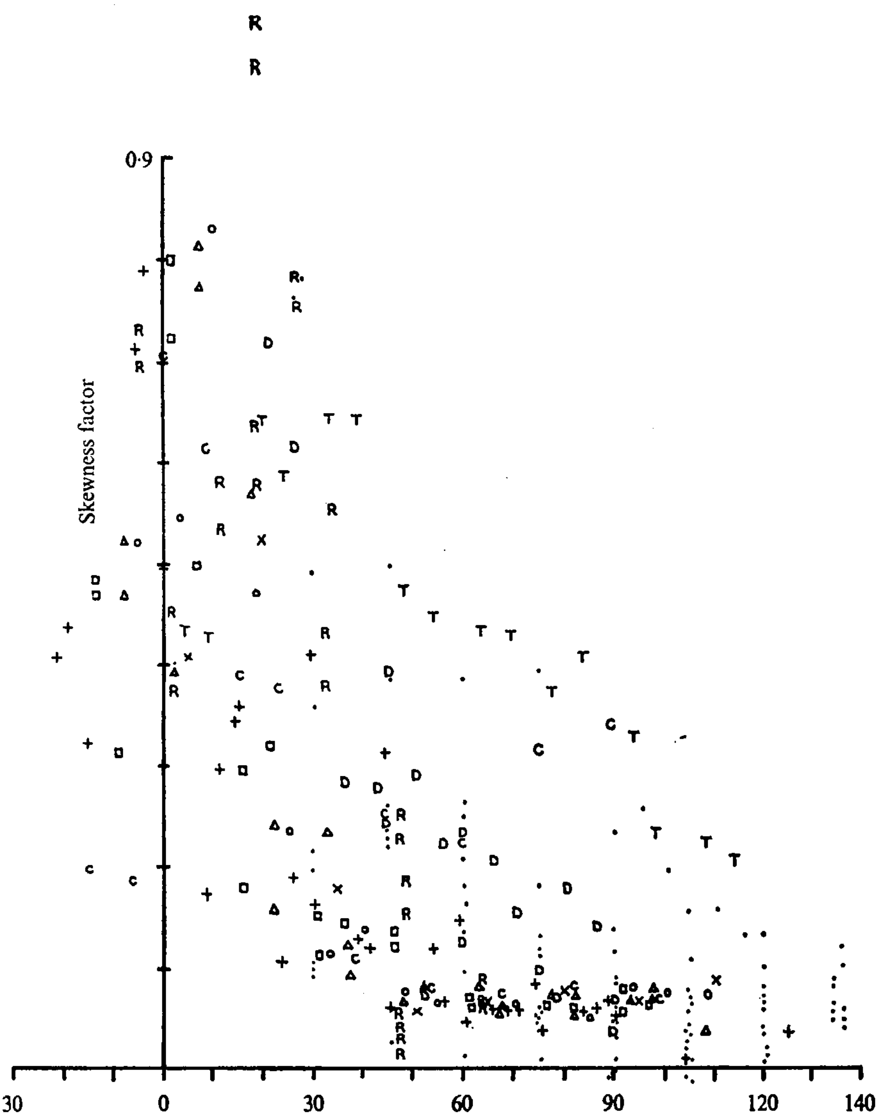

FIGURE 8. The directional distribution of high skewness factors in the noise field of high speed jets. The jet axis lies in the range $-50°$ to zero, depending on the jet conditions. $+$, $\square$, $\triangle$, $\bigcirc$, convergent–divergent nozzle model jets; *C*, conical nozzle model jets; *T*, Olympus 593 with experimental nozzle; *D*, Olympus 593 with conical nozzle; *R*, Olympus 593 with reheat; ●, jets with subsonic eddy speeds.

crackles distinctly, and yet relatively low crackle levels are found in the noise radiating forward (in what would be the direction of flight) of the static engine.

We have found a quite different variation in flight. High crackle levels occurred ahead of the aircraft even though the eddy convection speed in our particular flight tests was much lower (in fact subsonic) and the same engine when static under the same relative jet conditions displays low crackle levels.

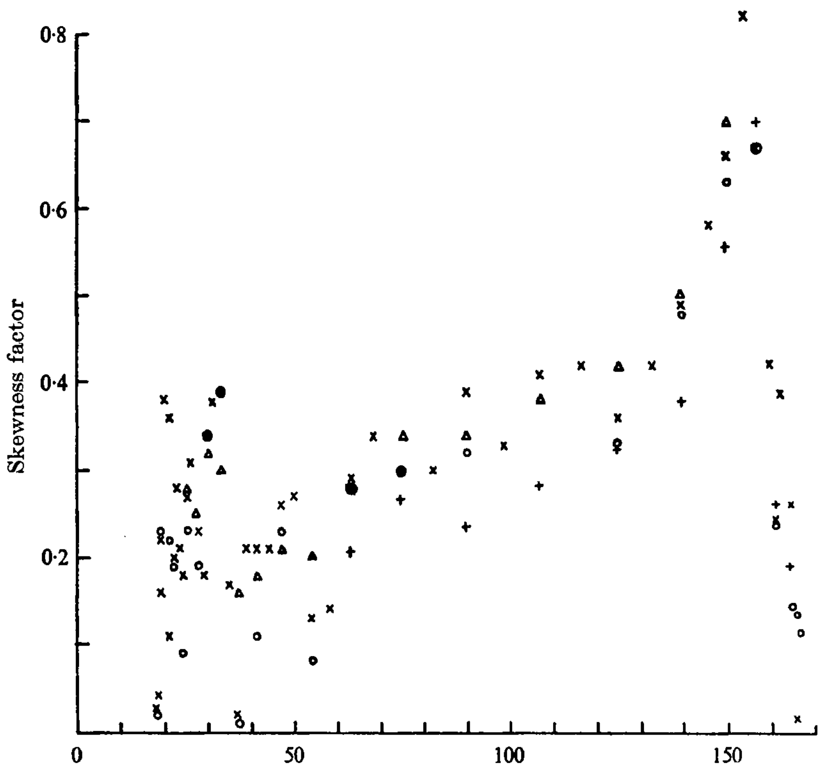

FIGURE 9. Skewness factors measured for the ground-level noise from an Olympus 593 engine in a Vulcan aircraft flying at an altitude of 300 m and speed of 200 m/s. The various symbols indicate the magnitude of the scatter in the data; each symbol represents results from one of several nominally identical experiments.

Some flight data (which we think are typical) are shown in figure 9. This depicts the skewness factors measured in the noise made by an Olympus 593 engine mounted under a Vulcan aircraft flying at a height of 300 m at a speed of 200 m/s. The noise was measured on the ground, and was different from the static case in that the most intense crackle was observed ahead of the aircraft. We think that this is not simply a flight effect because we have observed no distinct difference between simulated flight on the 'spinning rig'† and the static case. But in that experiment there are no long-distance propagation effects, the observations being made some 10 m from the jet 'flight path'. It is probably significant that in the aircraft situation the high skewness tends to be found in the louder sound that has travelled further from its point of generation to the observer. It is in our view highly probable that this is because the noise levels and distances involved are such that nonlinear steepening generates N-waves and these are then distorted by atmospheric turbulence into crackle as caustics form. But the origin of this crackle is then different from the origin of that

† A rig where a $\frac{1}{10}$ scale engine nozzle moves at the tip of a 10 m rotating arm at flight velocities. The jet noise and crackle measured for this hot jet scale on the relative jet velocity.

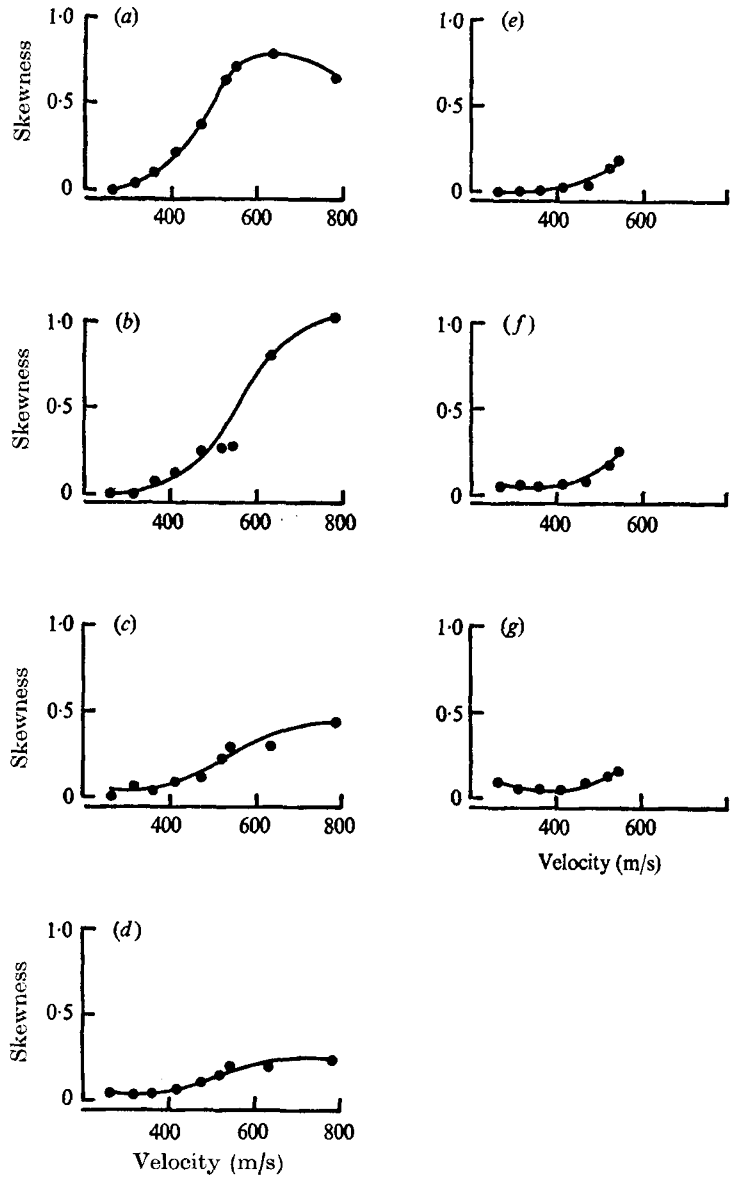

FIGURE 10. Curves showing the variation of skewness in the noise of an Olympus 593 engine as a function of the fully expanded jet velocity. Angles from jet axis: (a) 45°; (b) 60°; (c) 75°; (d) 90°; (e) 105°; (f) 120°; (g) 135°.

which we have studied more systematically under static conditions. There the important parameters are much more easily controlled and this is reflected in our data, which are far more self-consistent. From now on we shall refer only to the static case.

Crackle is already present but to a lesser degree in the close proximity of the jet flow and Dr H. V. Fuchs (comment on introductory lecture of AGARD

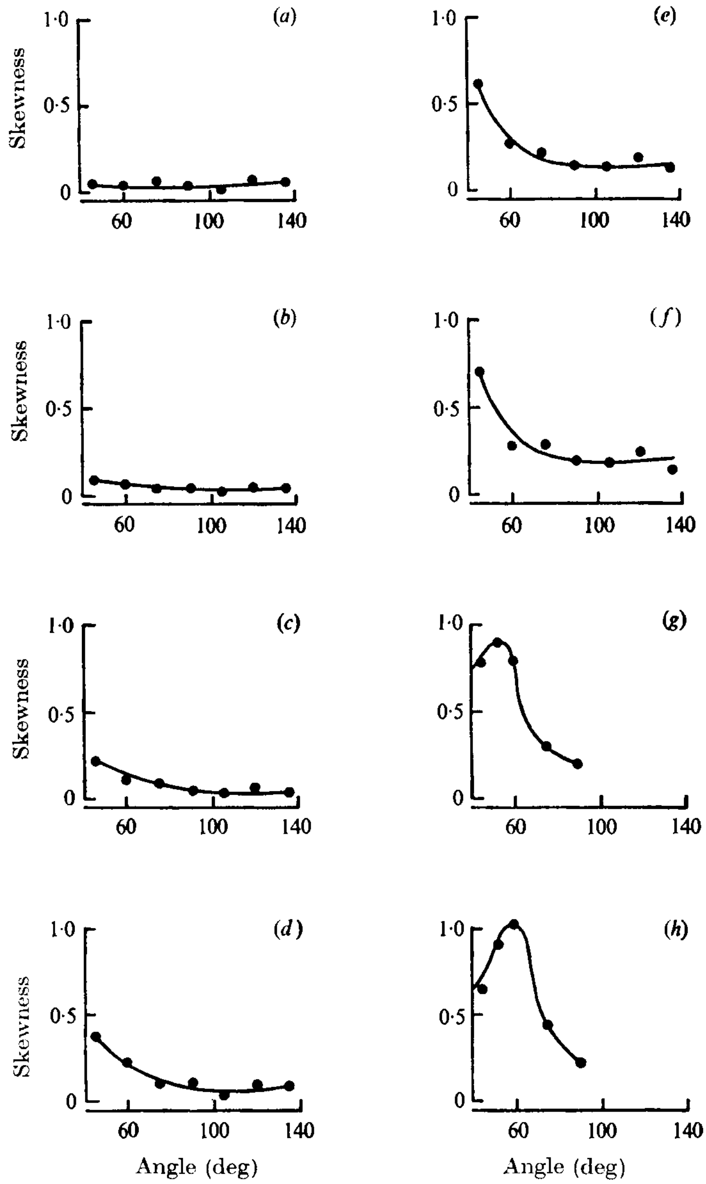

FIGURE 11. Curves showing the skewness in the noise field of the Olympus 593 engine as a function of the angle from the jet axis. Fully expanded jet velocity (m/s): (a) 317; (b) 360; (c) 412; (d) 473; (e) 524; (f) 543; (g) 635; (h) 785.

Conference on Noise Mechanisms, *AGARD Conf. Proc.* no. 131 (1974)) has made the interesting observation that the crackle pressure–time signature is similar to that of the unsteady pressure in the jet *interior*. The skewness increases with distance from the source flow not, we think, because propagation causes skewness but because much of the near-field signal, forming the bulk of the motion with a symmetric probability distribution, fails to propagate. The crackle

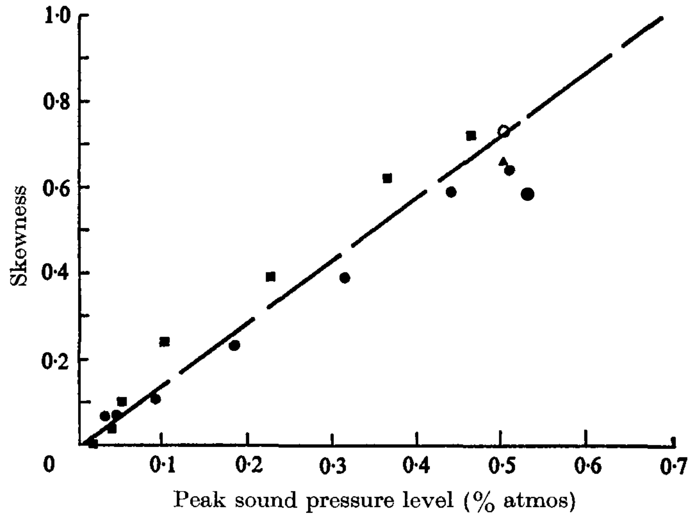

FIGURE 12. An illustration of the dependence of the skewness factor on the peak sound level. The measurements were made at 45° to the axis of the Olympus 593 engine operating with a series of nozzles over a range of conditions. The peak sound level is arbitrarily set at that level with a 10^{-2} probability of occurrence, a level which was determined to be 4·8 times the standard deviation of the signal. ■, conical nozzle; ○, ●, experimental nozzles; ▲, with reheat.

spikes propagate very effectively. They are already ordered into a wave field. Impulsive, or non-compact, sources of sound are known to have no conventional non-propagating near field and these spikes are likely to be sharp enough to belong to that category. (See Ffowcs Williams 1974*a*.) The sound is the product of nonlinear turbulent motion in the jet. The spikes are probably formed because of local convective steepening within the eddying motion, and as such must be level dependent. All the results we have show a strong dependence of skewness on both jet velocity and angular position; in fact it varies in much the same qualitative way as the sound itself. Like the sound, the skewness is high aft of the engine, peaking at 30° or 40° to the jet axis at a level increasing rapidly with jet velocity. Figures 10 and 11 show this variation for the noise of the Olympus 593 engine, and figure 12 shows more specifically how the skewness scales with the peak sound level, the data points being taken from measurements made at 45° to the jet axis for the Olympus 593 fitted with various nozzles and operating over a range of conditions. The peak noise level is determined as 4·8 times the standard deviation of the signal, a level that is exceeded on the positive side with a probability close to 10^{-2}.

The skewness only reaches really high values when the eddy Mach number exceeds unity, and then only near the Mach wave direction. Away from this angle the skewness drops rapidly, eventually reaching a 'floor' value that may well be sound-level dependent. In this process the leading edges of the crackle spikes become much less steep. Also, once attained, the peak skewness is relatively insensitive to jet velocity variation. Figure 13 illustrates the characteristic difference in wave form, figure 13(*a*) being a sample of that generated

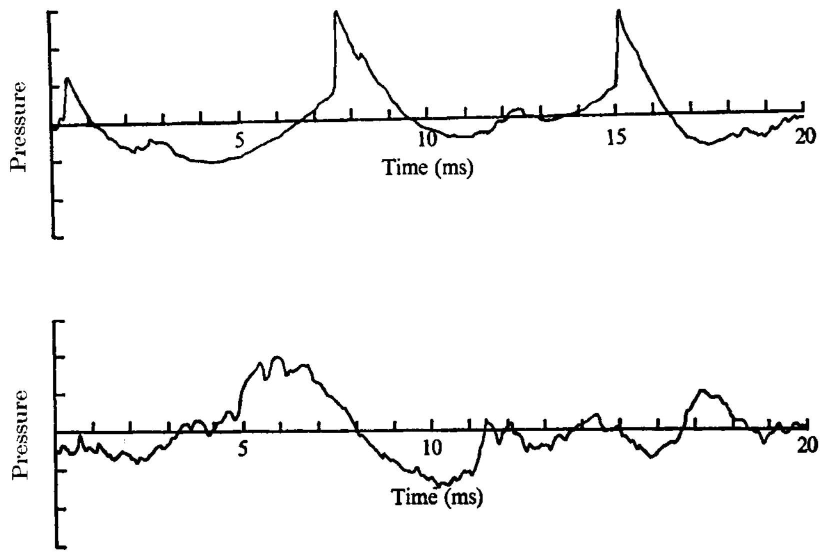

FIGURE 13. Two typical pressure-time signatures observed in the noise field of the Olympus 593 engine at 45° to the jet axis. The upper curve was measured during maximum thrust (reheat) operation, the lower at a much reduced power setting.

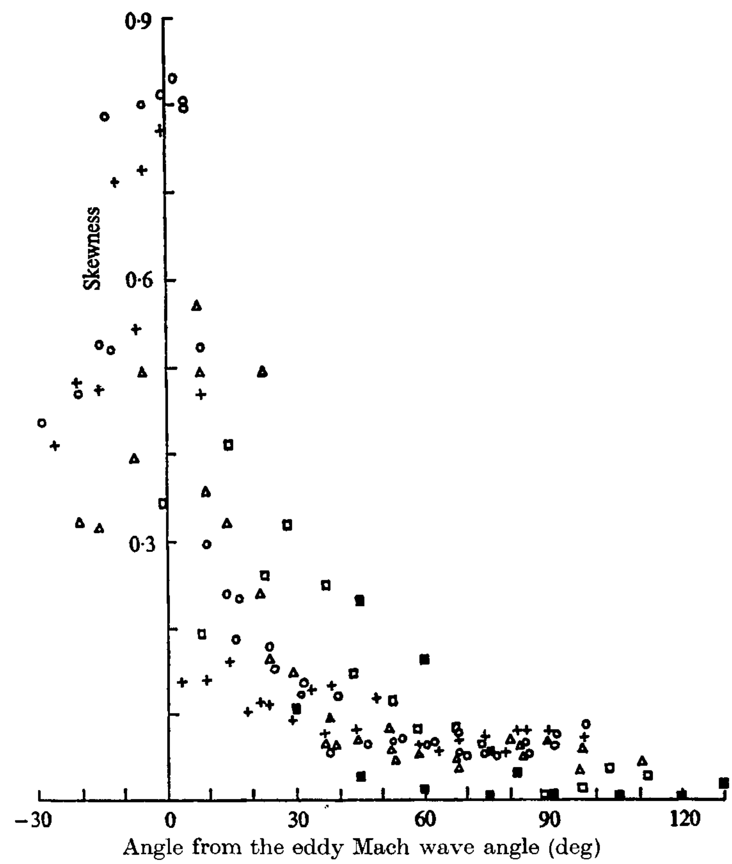

FIGURE 14. Skewness values measured in the sound field of supersonic jets ideally expanded through convergent-divergent nozzles as a function of the angle measured from the eddy Mach angle. Nozzle pressure ratios: +, 4·95; ○, 4·25; △, 3·18; □, 1·80.

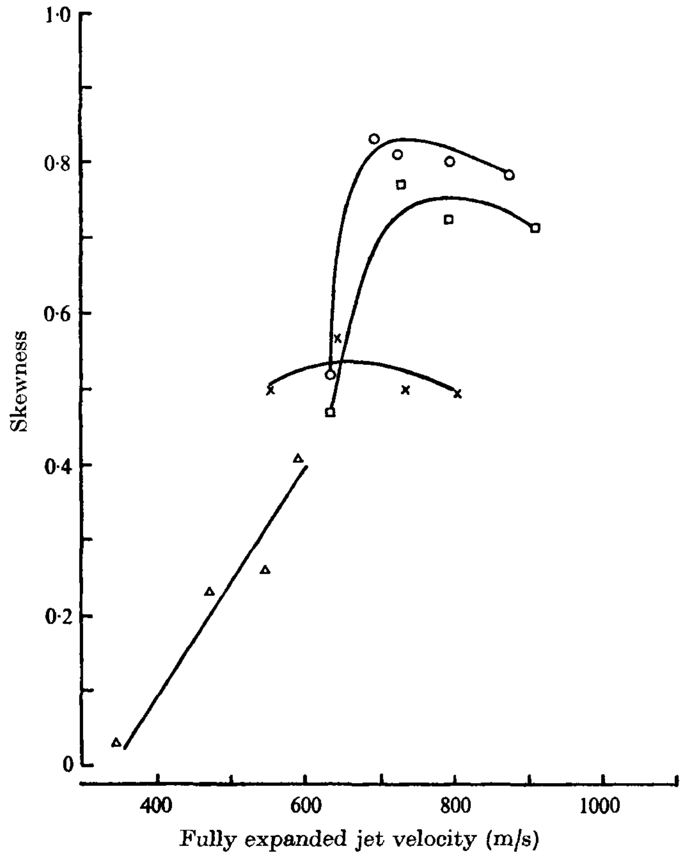

FIGURE 15. Variation of the maximum skewness levels measured in the noise field of heated supersonic jets ideally expanded through a set of convergent–divergent nozzles. Jet pressure ratio: □, 4·95; ○, 4·25; ×, 3·18; △, 1·80.

at 45° by the Olympus 593 at maximum reheat thrust and figure 13 (*b*) a sample observed at the same position but at a much reduced power setting. The concentration of the high skewness noise at the Mach angle is illustrated in figure 14, which shows values measured at various angles (from the Mach wave direction) with supersonic model jets ideally expanded through a series of convergent–divergent nozzles. These contoured nozzles were tested at their design pressure ratio over a range of operating temperatures, so that the jet speed was thereby altered. The results of this test are shown in figure 15, where the skewness is plotted as a function of the fully expanded jet velocity at the indicated pressure ratios. In these curves it is the peak value of the skewness, which always occurred near the eddy Mach angle, that is plotted.

Crackle, quantified by the skewness of the noise signal, tends to add to the annoyance of sound. We therefore regard our final observation as being significant. This is that there are several jet noise suppression schemes under study which significantly reduce its level. When the jet is passed through a 'twin notched' nozzle of the type described by Hoch & Hawkins (1974), the crackle

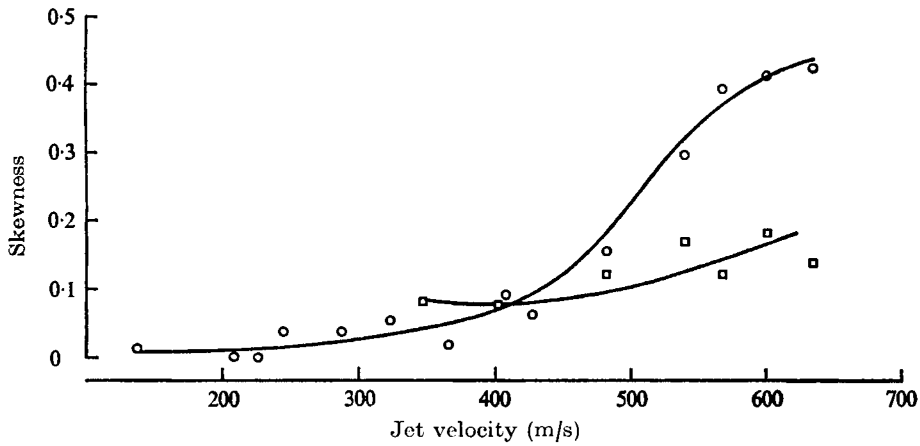

FIGURE 16. The influence of jet noise suppressors on crackle. The curves indicate the maximum skewness in the sound generated by the Rolls-Royce Viper engine at various jet speeds. One curve is for the unsuppressed engine, the other for the engine fitted with a convoluted silencer nozzle. ○, conical nozzle; □, convoluted nozzle.

in the notch plane disappears completely. An efficient convoluted silencer also controls crackle. In figure 16 we give the peak skewness in the sound field of the Rolls-Royce Viper engine, with and without its convolted nozzle suppressor, as a function of the fully expanded jet speed. Again it is seen that the skewness is controlled below a level of 0·3, and, as we have remarked earlier, signals of that type do not convey the subjective impression of crackle.

2. Conclusions

The physical feature of a sound wave that gives rise to the readily identifiable subjective impression of 'crackle' is shown to be the sharp shock-like compressive waves that sometimes occur in the wave form. The accompanying expansions are always more gradual and less intense. This feature can be quantified by the skewness factor (normalized with respect to the standard deviation) of the amplitude probability distribution of the recorded signal. It is our clear impression from extensive aural tests that crackle is easily distinguished when the individual peaks last for a millisecond or so and the skewness factor exceeds 0·4. We could not distinguish any crackle in sounds of skewness lower than 0·3.

Skewness does not seem to depend on the scale of the generating jet flow nor on the distance of the observer from that flow, provided only that the sound is observed out of the immediate source region yet near enough that long-term convective steepening remains unimportant. We have reported some distant measurements for aircraft in flight, in which high skewness (and crackle) is observed under conditions that we think are relatively crackle free nearer the jet. The cause of that crackle is, we think, the inevitable N-wave formation caused by long-term finite amplitude propagation coupled with an atmospheric scattering process that brings such waves to occasional focal points. N-waves are deformed near such caustics into spiked positive pressure pulses followed by weak and gradual expansions. This process can be quantified through the analytic schemes of Obermeier (1974) and Pestorius & Blackstock (1974).

Most of the experiments we report were conducted with static jets, both model and full scale. In these we observed that crackle is already present in the near vicinity of the jet flow and does not arise from nonlinear propagation effects. None the less the crackle spikes must owe their origin to nonlinear steepening, but in this case steepening at the source itself. We have no direct proof of the spike generation process we believe to be dominant, but draw attention to the tendency for spike-like wave forms to be generated by source processes involving finite amplitude source motions, such as those described by Ffowcs Williams (1974*b*). The mechanism of spike generation that we envisage is extremely difficult to quantify, but fairly simple to describe in a qualitative way. We envisage that the jet flow is highly unstable and that occasionally the instabilities are violent enough to 'buckle' the jet, effectively fracturing it into large eddies, or lumps of fluid, which become relatively detached from the mainstream. These lumps conserve the momentum of the parent stream and so maintain, at least initially, the supersonic velocity of the parent flow. They are shed from the stream to plough supersonically through virgin territory, and of course their path must then be impeded by bow shock waves, which resist their motion and rapidly decelerate them. Of course they cannot be absolutely decoupled from the mainstream and cannot have a distinct form. They may be more aptly thought of as supersonically moving bulges of the jet, forcing waves which pile up ahead of them, rather like the 'supersonic' section of a thick transonic aerofoil. There is no compensating tendency to form abrupt expansion waves in this process. Our view then is that the crackle spikes form in that region where the flow is disintegrating through a mixture of turbulent and highly coupled wave activity. The waves, which are strong enough to be convectively steepened within the source region, then propagate out into the far field to appear there as the compressions which cause skewness of the recorded signal and crackle.

This model of the source process is, we believe, consistent with the observations reported in the paper that the wave form, once generated, propagates with minimal change and loss of coherence. The skewness does not depend on the presence of a steady shock structure in an imperfectly expanded supersonic flow. Neither does it depend independently on the jet temperature. It is, like the sound itself, highly velocity sensitive, and scales well from engine to model conditions of $\frac{1}{10}$ scale. The skewness is greatest where the sound is greatest because the process which we outline for wave formation is the most effective jet noise producing mechanism. Finally, silencers that are effective for supersonic jets probably are so because they inhibit the formation of large-scale eddies, the natural debris of the basic jet's instabilities, which form both noise and crackle so effectively; that is why they inhibit crackle.

This work arose from the Rolls-Royce research programme aimed at the control of high speed jet noise. That programme is, in part, conducted in

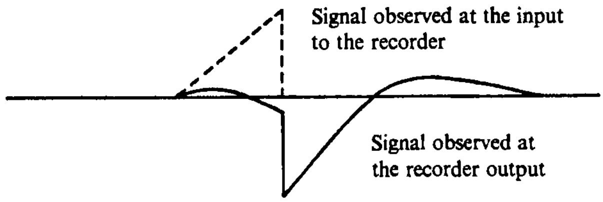

FIGURE 17. An illustration of the signal distortion caused in the a.m. recording process. The indicated signals are 10 ms segments measured on the Ampex recorder operating in the amplitude-modulated mode.

collaboration with SNECMA and the Cambridge University Engineering Department under a programme monitored by the NGTE. The co-operation of all these parties, particularly the individuals at Rolls-Royce responsible for the detailed experiments, is gratefully acknowledged.

Appendix. Experimental procedure

All the noise and performance data cited in this paper were produced at the experimental test sites of Rolls-Royce (1971) Ltd and SNECMA. The noise was measured with $\frac{1}{4}$ in. Bruel & Kjaer microphones and the signal recorded on a fourteen-channel Ampex type FR 1300 magnetic tape recorder fitted with a.m. electronics. The measurement procedures used were those in routine use at those sites. The equipment is set up in the IRIG configuration, has a signal-to-noise ratio in excess of 40 db and an accuracy of ± 1 db. Some test conditions were analysed with a 10 db attenuation of the signal recorded on tape. No significant difference could be determined between the two sets of results, thus confirming that the high amplitude excursions from the norm, which cause the crackle spikes, were reproduced without substantial clipping. The recorded signals were replayed, sometimes at a slower rate to facilitate sharper signal resolution, and analysed at the data analysis centre of the ISVR at Southampton University.

Preliminary analysis of the test data established that the noise signals were statistically ergodic. Time-average processing was therefore performed upon digitized time segments, randomly selected from the analog record of the particular test condition. The fastest digitizing rate employed was 40000 samples per second. This permitted proper definition of the selected signal history and provided useful information up to a frequency of 20000 Hz. The r.m.s. noise-to-signal ratio due to quantization error was found to be less than 10^{-3} in all the recordings analysed.

The power spectral density functions were estimated directly from the digital data after normalization to zero mean and unit standard deviation, by use of a fast Fourier transform algorithm with a Bartlett spectral window. Each estimate was determined with a resolution bandwidth equal to 40 Hz from a sample size providing 200 degrees of freedom, equivalent to a normalized standard error of 10^{-1}.

The probability density function was also estimated from normalized data over an amplitude range of ± 5 standard deviations, containing 40 class intervals.

Virtually every piece of equipment used in the measurement, recording and analysis of the signal is a.c. coupled, and this leads to a loss of low frequency response. This is such that we cannot guarantee that the shape and skewness levels of the reproduced signal are similar to those of the actual pressure wave in the sound field. Figure 17 shows how a signal with some characteristics and time scales similar to those found in the crackle spikes is affected by the lack of low frequency response. The signal is utterly transformed, only the rapid changes being faithfully reproduced. The skewness factors measured are likely therefore to be unique to this type of measurement and analysis equipment, which is in wide use throughout the international aviation community.

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