EXCESS NOISE FROM GAS TURBINE EXHAUSTS

N. A. Cumpsty
Cambridge University, Engineering Department
Cambridge, England

SUMMARY

There is evidence to show that the exhaust noise from gas turbines contains components which exceed the jet mixing noise at low jet velocities. This paper describes a theory developed to calculate the acoustic power produced by temperature fluctuations from the combustor entering the turbine. Using the turbine Mach numbers and flow directions at blade mid-height, and taking a typical value for the fluctuation in temperature, it has been possible to predict the acoustic power due to this mechanism for three different engines. In all three cases the agreement with measurements of acoustic power at low jet velocities is very good. Using a measured spectrum of the temperature fluctuation the prediction of the acoustic power spectrum agrees quite well with that measured.

1. INTRODUCTION

For pure, cold, subsonic jets, the acoustic power (PWL), or the sound pressure level (SPL) at a given angle, vary as the eighth power of jet velocity. Bushell[1] compared the measured noise from a number of jet engines at different jet velocities with the V_J^8 variation. He was able to show that almost all engines produce significantly more noise at low velocities than pure jets, and the name "excess," "tailpipe," or "core" noise is usually applied to this additional source. Although noise data have recently become available for pure, hot jets, Bushell's conclusions remain essentially valid. The general features of the exhaust noise from engines are represented by Figure 1, where it can be seen that the excess noise changes more slowly with respect to jet velocity (or engine condition) than the jet noise. Most noise measurements are made with the engine static on the ground, but when the aircraft is in flight, the reduction in the velocity difference between the jet and surrounding air normally causes a drop in the jet noise. This tends to make the excess noise even more significant than the static tests appear to imply.

The search for the source of this excess noise has exercised considerable ingenuity. The noise appears to propagate down the jet pipe and it has been shown that large bluff bodies in the jet pipe, or struts at high incidence downstream of turbines, will give excess noise and good correlations have been obtained in some cases. These correlations were unable, however, to predict all the observed noise from engines. Circumstantial evidence came to link the combustion with the noise source, but pressure transducers inside the combustion chamber do not appear to show the very large pressure fluctuation which would be required to give the acoustic power radiated. It therefore remained something of a mystery to explain how the combustion could produce such large acoustic powers. Recently, Cumpsty and Marble[2] have produced a model which assumes that the fluctuations in the temperature of the gas leaving the combustion chamber interact with the turbine to produce the noise. The present paper is based on this earlier work and applies the calculation method to three current commercial engines, the Rolls Royce Spey 512 and Olympus 593, and the Pratt and Whitney JT8D.

Whilst the calculation method was being developed, there were two interesting developments. Hoch and Hawkins (ref. 3, Fig. 25) showed spectra of SPL at low thrust conditions for two builds of Olympus 593 engine with different combustion chambers; one cannular, the other annular. The spectra were strikingly different, with the annular combustion chamber giving the lower values, and this gave fairly conclusive evidence for the importance of the combustion process.

At roughly the same time, Dils[4] published measurements of temperature fluctuations out of combustion chambers. He reported a standard deviation of temperature equal to about 10 per cent of the mean exit temperature over a wide range of engine conditions. It appears that this was an overestimate, and that 2 - 3 per cent is a more realistic estimate of the variation in temperature of the overall flow out of the combustor, and this value is probably true for most cannular combustors, Dils[5]. This temperature fluctuation is more or less fully correlated over the exit from the combustion chamber. In the case of annular combustion chambers, Dils reported that the behavior is quite different and a simple rule is not possible. The noise measurement of Hoch and Hawkins referred to above certainly bears out that there is a significant difference.

In the next section, the model and method of Cumpsty and Marble are briefly described. Following this, the three engines for which the comparisons are made are described, and the nature of the data and the method of using the data are outlined. Finally, the comparisons are discussed and, in the light of similarities and differences between the engines, fairly definite conclusions can be reached.

2. THE ACOUSTIC MODEL AND METHOD OF CALCULATION

The temperature of the gas stream varies as a result of the isentropic compression from pressure waves propagated at the speed of sound, as well as from temperature fluctuations convected with the flow and originating at the combustion chamber. The convected temperature variations are referred to as entropy fluctuations ($s'/C_p = T'/T$) to distinguish them from the pressure waves.

Certain salient features of the model can be summarized as follows:

(a) The blade passages are assumed sufficiently short that the flow inside them may be treated as if it were steady, so that disturbances on both sides of the blade row are in phase. This allows the precise blade details to be ignored, and the upstream and downstream perturbations are matched across the row. For frequencies below about 1 kHz (for which the acoustic wavelength at the turbine inlet will be about 3/4 m), this assumption will be very good even for large engines, except for Mach numbers very close to one.

(b) The blade pitch is assumed infinitesimal. This means that no information can be generated close the the blade passing frequency, but this is believed to be very much greater than the frequency of significant entropy fluctuations. This assumption allows rotor rows to be treated in just the same way as stators after allowing for the change in the mean flow Mach number and direction relative to the rotor. Assumptions (a) and (b) characterize it as an "actuator disc" type of solution.

(c) Although the incident entropy perturbations, s'/C_p, are assumed to be small, the deflection and acceleration of the mean flow in the blades will normally be large, and the pressure and entropy perturbations are of the same order. This appears to be a very good representation of the disturbances occurring in real turbines.

(d) In the analysis the input disturbance is assumed to be harmonic, but because the analysis is linear it can be immediately generalized to a random input.

(e) The axial velocity is taken to be everywhere subsonic, and in all practical circumstances this is the case.

(f) The flow is treated as two-dimensional so that radial variations are neglected.

(g) Although the axial chord of the blades is assumed small, the effect of the axial distance between blade rows on the phase and amplitude is explicitly included.

(h) All inefficiencies in the turbine are ignored so that the flow is treated as isentropic. The efficiency of turbines is normally close to unity.

(i) Non-dimensional acoustic power propagating downstream in the jet pipe is calculated. No account is taken of the nozzle impedance.

The method uses the conservation of mass, stagnation enthalpy (in a frame of reference fixed to the blade row), and entropy across each blade row. In addition, a Kutta condition is assumed at the blade trailing edge when the outlet flow is subsonic (i. e., the perturbation in outlet flow velocity is assumed parallel to the mean flow direction). If the flow at blade outlet is supersonic, the Kutta condition is relaxed and a choked condition of constant non-dimensional mass flow is imposed. The method is programmed in such a way that an arbitrary number of turbine stages may be considered. The time mean flow Mach number and direction into and out of each row must be specified, and so must the ratio of the speed of sound downstream of each row to that upstream of the first row and the ratio of the axial gap between rows to the wavelength in the circumferential direction.

The calculation procedure uses only non-dimensional parameters. One of these is fY/a, which is the phase speed of the pattern in the circumferential direction made non-dimensional with respect to the local speed of sound. Depending mainly on the value of fY/a are the directions of pressure and vorticity waves and the propagation or attenuation of the pressure waves in the axial direction. The entropy input disturbance consists of a circumferential standing wave pattern which is more easily treated as two traveling waves, one clockwise, the other anticlockwise. The wavelengths in the circumferential direction are restricted to integer fractions of the circumferences, but the frequency spectrum can cover a wide range and is generally continuous or broad band. Cumpsty and Marble considered entropy fluctuation into a range of fairly typical turbine blading. They found that the acoustic power propagated downstream is a strong function of fY/a and that for both isolated blade rows and stages the power is markedly increased with increase in the pressure drop across the row or stage. In particular, a heavily loaded stage appears to produce much more noise than a lightly loaded one for the same blade speed. The acoustic power was found to be greater for two identical stages than one, but additional stages after this served to modify the spectrum by shifting power to lower frequencies without changing the overall power. All of these observations will be relevant for the discussion of the engine results.

3. THE ENGINE DATA USED

(a) The Aerodynamic Data

The Rolls Royce Spey 512 is a turbofan with a bypass ratio of about 0.6. The Olympus 593 is a straight turbojet being developed for the Concorde. The later prototypes and the production Olympus 593 engines have modified turbines and annular combustion chambers (for which the nature of the temperature fluctuations is not known, although their magnitude seems to be smaller), but the present work refers entirely to the earlier builds with cannular combustion chambers. The Pratt and Whitney JT8D-9 is a turbofan with a bypass ratio of about 1.0. Although both the Spey and the Olympus are now Rolls Royce engines, the Olympus was designed by Bristol Siddeley and embodies different design features, quite apart from the difference in the type of engine. Some overall features of the engines are shown in Table 1.

The engine conditions at which the turbine data were obtained were different in each case. For the Spey, the turbine data were given only at the full power condition, whilst for the Olympus they were only given for the condition corresponding to approach with a 0.63 m^2 primary nozzle, this being nearer to where the excess noise is likely to be a major problem. Data for the JT8D were obtained at both the takeoff and approach conditions and showed comparatively little alterationin the flow angles and Mach number through the turbine, which in turn, it will be shown, have relatively little effect on the noise. All the Mach number and angle data were taken to apply at low engine settings, and this must involve some inaccuracy, particularly for the Spey. Except for the JT8D calculations, the variation in estimated acoustic power with jet velocity arises only from the changes in static temperature and pressure in the jet pipe.

In addition to flow Mach number and angle, the axial separation between blade rows and the local speeds of sound are required. Because the calculation method uses actuator discs to represent the blade rows, the extent of the blade axial chord cannot be properly represented, and yet this is usually much larger than the inter-row gap. The procedure adopted was to measure the axial row separation between the blade leading edges at mid-height. This provides a systematic treatment in each case, and the overall length of the multistage turbine is correctly represented by this procedure. There is, moreover, some reason to believe that the largest effects are produced near the leading edge. The calculation actually accepts the ratio of separation, Δx, to the mean diameter, D.

The calculations are all based on the data applicable to blade mid-height. For the HP turbine, the hub-tip ratio is normally high, and this assumption is relatively good; but for the LP turbine it is less satisfactory. Most designs of turbine stage, however, produce radially more or less constant work, or pressure drop. It is therefore probably more accurate to treat the stage as if it were everywhere of the mean height design than it would be for an isolated blade row.

(b) Noise Data

The problems of obtaining useful estimates of rear-arc excess broad band noise were similar in each case. At high thrusts the jet noise predominates in all cases, but at reduced thrust the compressor or turbine tones tend to protrude into the overall noise, and the present theory makes no attempt to predict these. In the case of the Spey and Olympus it was possible to eliminate most of the effect of these on overall acoustic power by only calculating the power over the rear arc; the turbine tone frequencies were above the range of interest here, and the levels were not high enough to affect overall level significantly. The JT8D noise, however, required an additional graphical correction of the power spectrum at the two lowest thrusts to remove the tones; at higher thrusts this was not necessary because the tests had been performed with extensive acoustic treatment in the ducting. The data for the Spey and the JT8D were obtained with microphones only a few inches from the ground and the spectra were consequently not distorted by ground reflections. When the noise is measured with microphones several feet from the ground, the distortion of the spectrum is so severe that a useful comparison of it with prediction is normally impossible. The ground reflections also introduce some uncertainty into the calculation of acoustic power from measurements; even with microphones very close to the surface, giving no distortion of the spectrum, 1 or even 2 dB error in power is not impossible. The noise data for the Olympus 593 corresponds to the 0.63 m^2 primary nozzle.

(c) Temperature Fluctuation Data

In all cases, standard deviation in temperature was taken to be equal to 2 per cent of the mean static temperature into the turbine and to be perfectly correlated over the circumferential width and radial height of the combustion outlet. These assumptions were based on the observations of Dils[5]. The data quoted by Pickett[6], measured much more recently in the Pratt and Whitney JT 3 D engine, show that the choice of the lowest relevant frequency is crucial in determining the measured level of σ_T/T.

When the majority of the calculations were performed the frequency spectrum of the temperature fluctuation was not known with any confidence. Dils[4] showed the amplitude to be quite significant at 300 Hz, but beyond this the response of the instruments was possibly inadequate. For this reason the spectrum for each engine has been assumed flat ("white") from 0 to 1000 Hz. This could not be rigorously justified, but it is consistent, and the upper frequency bounds the region where this type of excess noise was believed to be important. The acoustic power was summed from 20 to 1000 Hz. Any variations in the temperature spectrum will have some effect on the overall acoustic power (OAPWL), because the response of the turbine is a function of frequency, although this is fairly small, but the effect on the spectrum of acoustic power is large. The temperature power spectral density published very recently by Pickett[6] was obtained using improved techniques. This shows a very nearly linear decrease in level with frequency in the range 0 - 1 kHz (beyond which it decreases very rapidly), and over this range there is a drop of 16 dB. By integrating this spectrum it is possible to adjust the spectra and overall levels predicted assuming a flat spectrum, and it turns out that the changes in overall acoustic power caused by this are very small.

The circumferential width of the correlated area allows a spatial resolution into Fourier components of different circumferential wavelength Y_n:

$$\sigma_T(y)\, e^{i\omega t} = \left(\sigma_{To} + \sum_{n=1}^{N} \sigma_{Tn} \cos \frac{2\pi y}{Y_n}\right) e^{i\omega t} = \left(\sigma_{To} + \sum_{n=1}^{N} \sigma_{Tn} \cos \frac{ny}{D}\right) e^{i\omega t} \quad .$$

The form of this disturbance is a series of standing waves in the circumferential direction. For the purpose of the calculation it is easier to resolve each component into two equal traveling waves rotating in opposite directions; thus

$$\cos \frac{ny}{D} e^{i\omega t} = \frac{e^{i\omega t}}{2} \left(e^{i \frac{ny}{D}} + e^{-i \frac{ny}{D}} \right) .$$

The component σ_{To} corresponds to the circumferentially uniform or plane wave case, for which $Y = \infty$. The calculation must be repeated for each value of Y_n because the effect of axial distance depends on this.

4. THE CALCULATION PROCEDURE

For each wavelength of temperature disturbance a calculation is carried out at a range of frequencies for the wave system rotating in each direction. The computer program provides the acoustic power propagated down the jet pipe at each frequency and wavelength, non-dimensionalized with respect to the speed of sound and static pressure, flow area and the magnitude of entropy fluctuation in the manner described by Cumpsty and Marble. Where the pressure pattern at the downstream side of the turbine is below cut-off no power can be transmitted. For cases of small flow Mach number, and assuming a high hub-tip ratio, the criterion for cut-off is that $fY/a = 1$. As the circumferential wavelength is reduced, cut-off occurs at higher frequencies: assuming an upper frequency limit of 1000 Hz, it means that wavelengths less than one quarter of the circumferences have no significance. Some confusion arises for the plane wave case, corresponding to σ_{To}, for which $Y = \infty$ and all frequencies are above cut-off. For this case $fY/a = \infty$, but as a practical realization it has been found adequate to take $fY/a = 100$.

Figure 2 shows the non-dimensional power from the Spey for each of the relevant circumferential wavelengths, plotted against frequency. It is clear that the plane wave carries the largest amount of acoustic energy, and that the shortest wavelengths carry only very small amounts. In calculating overall power, the results such as those in Figure 2 are summed after multiplying by the appropriate Fourier component amplitudes. This total corresponds to only one combustion chamber, and since the fluctuation from each is assumed to be uncorrelated with the others, the total acoustic power is obtained by multiplying this sum by the number of combustion chambers.

5. DISCUSSION OF RESULTS

Figures 3, 4, and 5 compare the measured borad-band acoustic power from the exhaust of the Rolls Royce Spey and Olympus 593, and the Pratt and Whitney JT8D with the predictions of the present model for noise due to the entropy fluctuations. For the Spey and Olympus, the aerodynamic input corresponds to the calculated point with the highest jet velocity. The change in overall power for the JT8D which is attributable to the aerodynamic changes between takeoff and approach settings is only about 3 dB. This helps justify the extrapolation for the Spey; in fact, with a lower bypass ratio, the alteration in aerodynamic conditions for the Spey is probably smaller.

The predicted acoustic powers generally agree well with the measurements. The estimates for the Spey appear high by about 2 dB, whereas those for the Olympus are low by about 2 dB. The high level for the Spey may largely be explained by the aerodynamic extrapolation, but for all the engines, the assumed value of σ_T/T may well be wrong by 50 per cent, which would produce an error of 3 dB in the prediction. Finally, the measurement of acoustic power could be wrong by 1 or 2 dB. In many respects the most convincing aspect of the comparison is the similarity in the variation with jet velocity of the predicted acoustic power from the JT8D, approximately $V_J^{1.5}$, with the observed trend for very low velocities.

The discrepancy of about 2 dB between the Spey measurement and prediction was initially thought to be explained by the real spectrum of temperature fluctuation differing from the "white" spectrum assumed. Figure 6 compares the measured acoustic power spectrum from the Spey with a prediction using the "white" input temperature spectrum and one using the power spectral density measured in the JT 3D. (As an approximation, the power spectral density has been taken to be inversely proportional to frequency with a 16 dB drop from 0 to 1 kHz. The overall value of σ_T/T is equal to 0.02 in both cases.) The "white" spectrum leads to a marked deficiency in predicted noise at the low frequency and an excess at high frequencies compared with the almost flat measured noise spectrum. The sloping temperature spectrum leads to a large improvement at low frequencies, but again a slight overprediction at the mid-frequencies. With the same standard deviation of the overall signal, the power spectral densities of temperature fluctuation for the "white" spectrum and the sloping measured spectrum are equal at about 400 Hz, which is close to the frequency at which the response of the turbine is largest. The net effect is that the peak third octave levels of predicted acoustic power are altered very little by the change in input spectrum, and the overall acoustic power is virtually identical for the two. In view of the arbitrariness of the assumed value of σ_T/T, and the fact that the temperature spectrum was measured in a quite different engine, the agreement shown in Figure 6 is surprisingly good.

Figure 7 compares measured and predicted power spectra for the JT8D at a low exhaust velocity. There should be some similarity between the combustion chamber of the JT8D and JT3D and the temperature spectrum for the latter should be more closely applicable to the former than to the Spey. The agreement between the noise spectra measured and predicted using the measured temperature spectrum is good, particularly in the middle of the frequency range where the agreement is extraordinary. Because the agreement is so close in this range it leads one to suppose that other mechanisms may dominate the measured noise above and below it. At the very low frequencies it is very likely that jet noise is dominant, whilst above about 700 Hz one of the many other excess noise sources may be in evidence. Because the peak levels of predicted noise are almost equal and at the same frequencies for the two temperature spectra, there is, as with the Spey, almost no alteration to the overall acoustic power.

Comparing the measured and predicted levels of acoustic power in Figures 3, 4, and 5 tends to mask the variation from engine to engine. In making this comparison, it is useful to compare the predicted overall acoustic power non-dimensionalized so as to remove effects of size, jet pipe conditions, and the magnitude of σ_T/T. Table II shows the appropriate non-dimensional power for the Olympus 593, Spey, and JT8D. The acoustic power decreases in that order, and it is instructive to ask why. The key would seem to be the stage pressure ratio. Cumpsty and Marble showed the stage loading or pressure ratio to greatly affect the noise level and also that many similar stages do not produce significantly more noise than two. From Table I it is clear that the average pressure ratio per stage for the Olympus 593 is greater than for the Spey, which in turn is greater than for the JT8D. However, the fact that there are three low pressure (LP) stages in the JT8D, compared to two in the Spey, further decreases the ratio for the downstream stages which contribute most directly to the noise. To check the validity of this explanation, non-dimensional power was calculated when the two LP stages in the Spey were replaced by three identical, 50% reaction stages to give the same total LP work. Table II shows the level was considerably reduced.

Figure 2 shows that the majority of the acoustic power is produced in the plane-wave mode. Pickett*[6] showed that for this mode the acoustic intensity is approximately proportional to the square of the mean pressure drop across a blade row. The variation in predicted acoustic power with engine condition for the JT8D can be seen from Table II, and the overall turbine pressure ratios are shown in Table I. The square of the ratio of the pressure ratios at take-off and approach is 1.9, whilst the ratio of the overall acoustic power at take-off and approach is 2.3. The relatively small difference between these ratios is partly attributable to the off-loading of the latter stages at approach conditions, but is mainly because the true relation between the turbine aerodynamics and the acoustic pressure is more complicated than a proportionality based on pressure ratio.

The results obtained allow some interpretation of the significance of the temperature fluctuation as a noise source. It seems clear that for the

---

* This manuscript, ref. 6, became available when most of the work described in the present paper was completed. Pickett considers the sound generation by entropy fluctuations convected into a <u>single</u> blade row, represented by an actuator disc.

Olympus 593, at least for the early versions before an annular combustion chamber was fitted and the turbine modified, the levels of noise produced by temperature fluctuations are sufficiently large that they are significant at approach jet velocities even whilst the engine is stationary. The measurement of Hoch and Hawkins(3) showing the change in noise from the Olympus 593 with a change in combustion system proves this to be the case. In flight, this source might well dominate the rear arc noise at approach. The high levels are attributed to the large turbine stage pressure drops. The situation for the Spey 512 is less clear, but it would seem that in flight the tempetature fluctuation produces enough noise to be quite significant at approach. For the JT8D it seems that the temperature fluctuations definitely do not produce significant noise levels when the engine is static and running at typical in-service operating thrust conditions. It seems just possible that in flight, with a forward speed of, say, 100 m/s, the excess noise at approach thrust would be comparable to the jet noise.

The discussion has so far avoided the possible implications of this noise source for modern high bypass ratio engines. One reason for this is that all these engines use annular combustion chambers and no data comparable to that for cannular combustors could be obtained. The evidence of Hoch and Hawkins points to a distinct noise advantage in having an annular combustion system, but this result is isolated, and it would be premature to base too much on it. The overall design considerations of the high bypass engines do, however, allow some generalization to be made. Unless the fan is driven via a gear train, a severe constraint is imposed in the LP turbine, essentially because the large, cold fan requires that the smaller, hot LP turbine rotates more slowly than its aerodynamic optimum. This in turn means that the LP turbine stage pressure drops must be relatively low and the number of stages relatively large. These, it will be recalled, are just those conditions* likely to lead to low levels of acoustic power being produced by temperature fluctuations. Indeed, calculations performed using data for a high bypass ratio engine show this to be the case. This, combined with the tentative evidence on annular combustion chambers, suggests that with the trend towards high bypass ratio engines, the generation of noise by temperature fluctuations may be on the decline. This trend could be immediately reversed if high bypass ratio engines using a geared fan are introduced.

This paper has assumed that the noise mechanism involves convected entropy fluctuations interacting with the turbine. An alternative hypothesis assumes that the pressure fluctuations occur in the combustion chamber itself and that these propagate through the turbine. Whilst the agreement of the measurements and predictions shown here is strong support for the model adopted, it is not yet definitive, and is unlikely to be so until experiments aimed solely at separating the effects are performed. Because the pressure fluctuations inside the combustion chamber itself are affected by the pressure and entropy waves incident on the turbine, it is not easy to separate cause and effect. At the present time we do not appear to have reliable measurements published of the pressure variations in combustion chambers, but those there are show strong peaks at frequencies corresponding to resonances in the combustion system. The fact that these peaks are not normally very evident in the measured noise spectrum is

---

*For the earlier bypass engines, a similarly beneficial effect occurs compared with the straight jet engine; it is this which primarily leads to the variations between the Olympus 593, Spey, and JT8D.

interpreted as some indication that the generation of sound in the combustor itself is not the dominant mechanism.

6. CONCLUSIONS

(1) Circumstantial evidence linking excess noise with the temperature fluctuations out of combustion chambers is supported.

(2) The model of sound generation by the interaction of temperature fluctuations with the turbine proposed by Cumpsty and Marble appears to be valid for the three engines considered.

(3) Good agreement is obtained between predicted acoustic power and the measured values at low jet velocity assuming $\sigma_T/T = 0.02$, a flat, or "white," temperature spectrum up to 1000 Hz and fully correlated variation over a combustion chamber outlet. The acoustic power from this source varies with jet velocity to approximately the 1.5th power, and this is similar to the measured trend at low jet velocities.

(4) The predicted spectrum of noise obtained with the flat temperature spectrum does not match the measured spectrum at all well. Using a measured temperature spectrum, however, the agreement can be greatly improved. The change in temperature spectrum barely affects the overall acoustic power.

(5) The pressure ratio across each stage (particularly the low pressure stages) strongly affects the level of acoustic power generated by the temperature fluctuation; in fact, the acoustic power appears to be roughly proportional to the square of the turbine pressure ratio. For a given pressure ratio across the turbine, much more noise is produced when there are few stages, with large stage pressure drops, compared with more stages

and lower pressure ratio. The results for the three engines calculated strongly support this.

(6) For a high bypass ratio engine, the constraints on turbine loading inherent in the design (provided the fan is not geared) mean that the noise generation mechanism described here is not expected to be very significant.

REFERENCES

1. Bushell, K. W. "A survey of low velocity and coaxial jet noise with application to predictions," J. Sound and Vibration, V. 17, no. 2 (1971), pp. 271-282.

2. Cumpsty, N. A. and F. E. Marble. "The generation of noise by the fluctuations in gas temperature into a turbine," Cambridge University Engineering Dept., Report CUED/A Turbo/TR 57 (1974).

3. Hoch, R. and R. Hawkins. "Recent studies into Concorde noise reduction" Paper 19, AGARD Conference Proceedings, Noise Mechanisms (Sept. 1973).

4. Dils, R. R. "Dynamic gas temperature measurements in a gas turbine transition duct exit," ASME Paper 73-GT-7 (1973).

5. Dils, R. R. Private communication (November 1973).

6. Pickett, G. F. "Turbine noise due to turbulence and temperature fluctuations," presented at the Eighth International Congress on Acoustics, London (July 1974).

TABLE I

	Spey 512	Olympus 593-3B	JT8D-9
Bypass Ratio	0.6	0	1.0
No. of HP Stages	2	1	1
No. of LP Stages	2	1	3
Turbine Overall* Total-Static Pressure Ratio			
Take Off	9.0		7.5
Approach		6.2	5.5
No. of Combustion Chambers	10	8	9

* These values are very approximate and are intended only for qualitative comparison purposes.

TABLE II

Engine	Condition	Non-dimensional Power $\frac{\text{acoustic power}}{(\sigma_T/T)^2 \cdot A \cdot a \cdot p}$
Rolls Royce Spey 512	take off	$114 \cdot 10^{-4}$
Olympus 593-3B	approach	$240 \cdot 10^{-4}$
Pratt & Whitney JT8D-9	take off	$82 \cdot 10^{-4}$
	approach	$36 \cdot 10^{-4}$
Rolls Royce Spey with 3 LP turbine stages of 50% reaction	take off	$64 \cdot 10^{-4}$

NOMENCLATURE

a	speed of sound
A	area just downstream of the turbine
C_p	specific heat at constant pressure
D	mean diameter of turbine
f	frequency, Hz
n	number of harmonic in circumferential direction
p	static pressure
s	entropy
T	static temperature
V_J	jet velocity
x	axial distance
y	circumferential distance
Y_n	circumferential wavelength
Δx	axial separation between blade rows
σ_T	standard deviation in temperature of overall flow out of a combustion chamber
ω	radian frequency

ACKNOWLEDGMENTS

This work has been heavily dependent on the cooperation of the aeronautics industry. The author wishes to thank Rolls Royce (1971) Ltd. for aerodynamic and noise data for the Spey 512 and Olympus 593, Pratt and Whitney Aircraft for aerodynamic data on the JT8D, and the Boeing Commercial Airplane Company for noise measurements from the JT8D. He would in particular like to express his gratitude to R. R. Dils of Pratt and Whitney Aircraft whose guidance on combustion chamber behavior was invaluable.

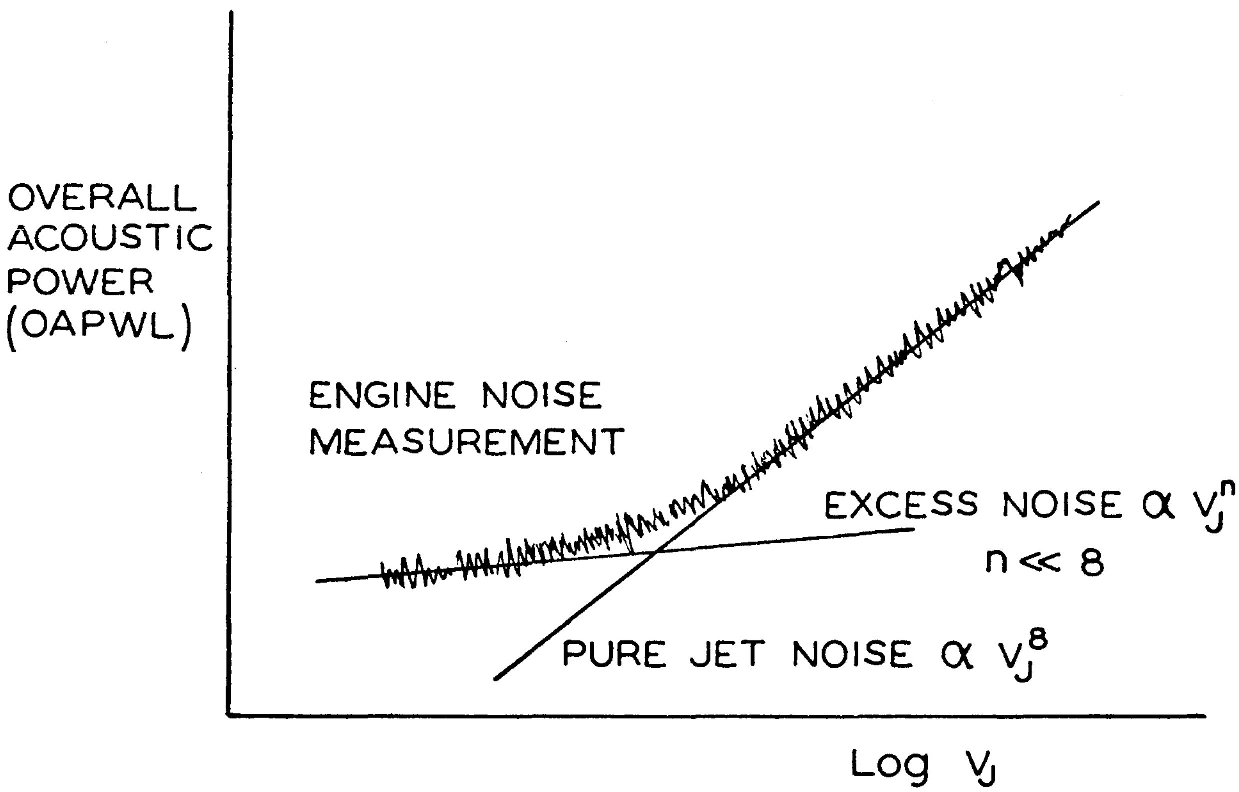

Figure 1. Schematic representation of variation with jet velocity of rear arc noise from a jet engine.

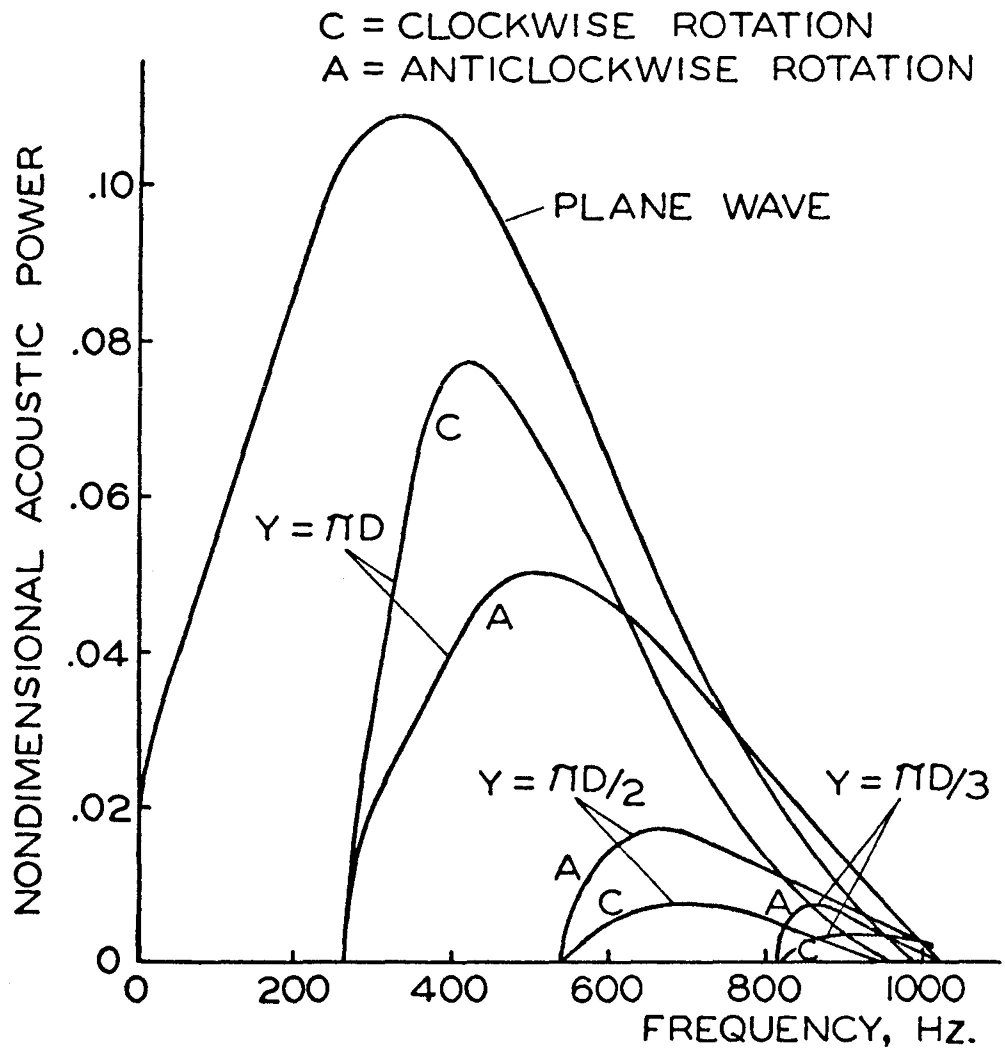

Figure 2. Non-dimensional acoustic power for the Rolls Royce Spey produced by each Fourier component of temperature fluctuation.

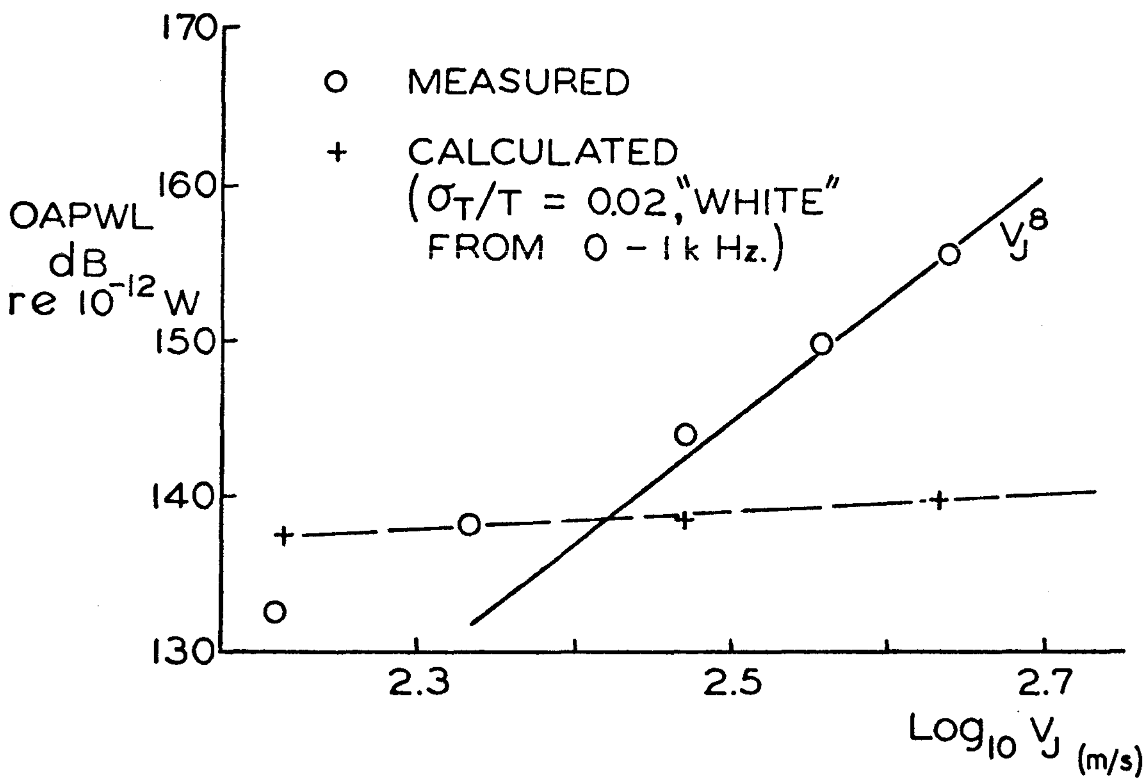

Figure 3. Predicted and measured rear arc overall acoustic power (OAPWL) for the Rolls Royce Spey 512.

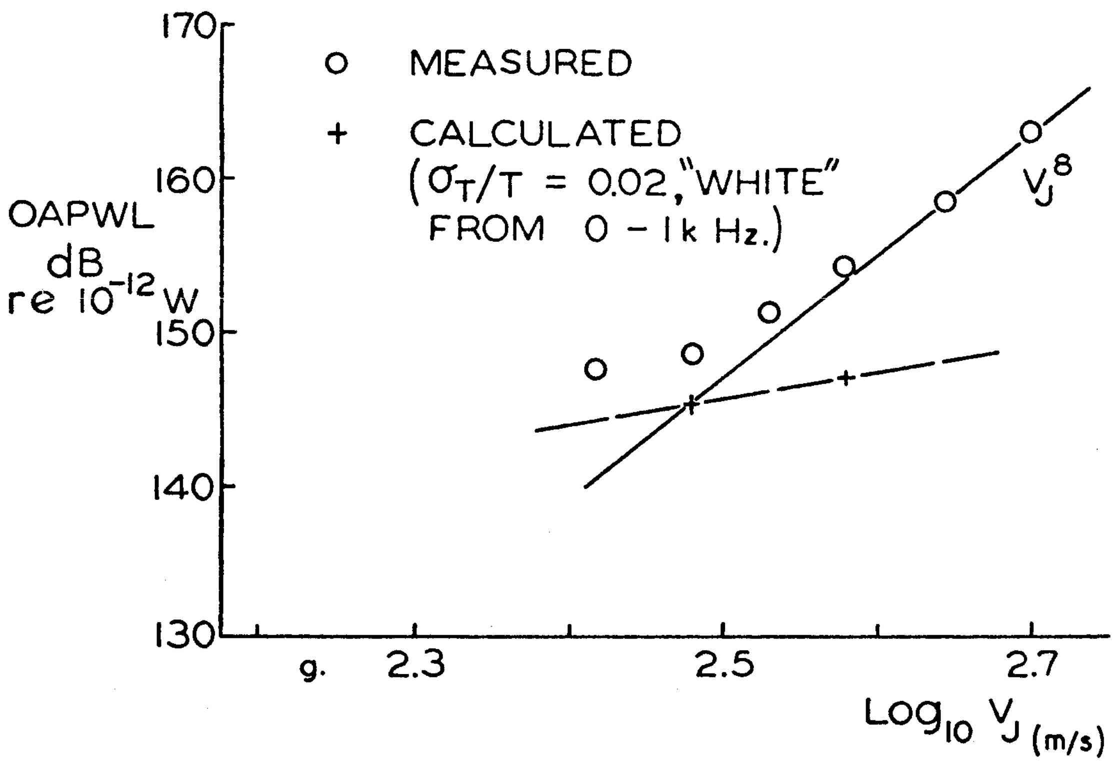

Figure 4. Predicted and measured rear arc overall acoustic power (OAPWL) for the Rolls Royce Olympus 593 (primary nozzle 0.63 m^2).

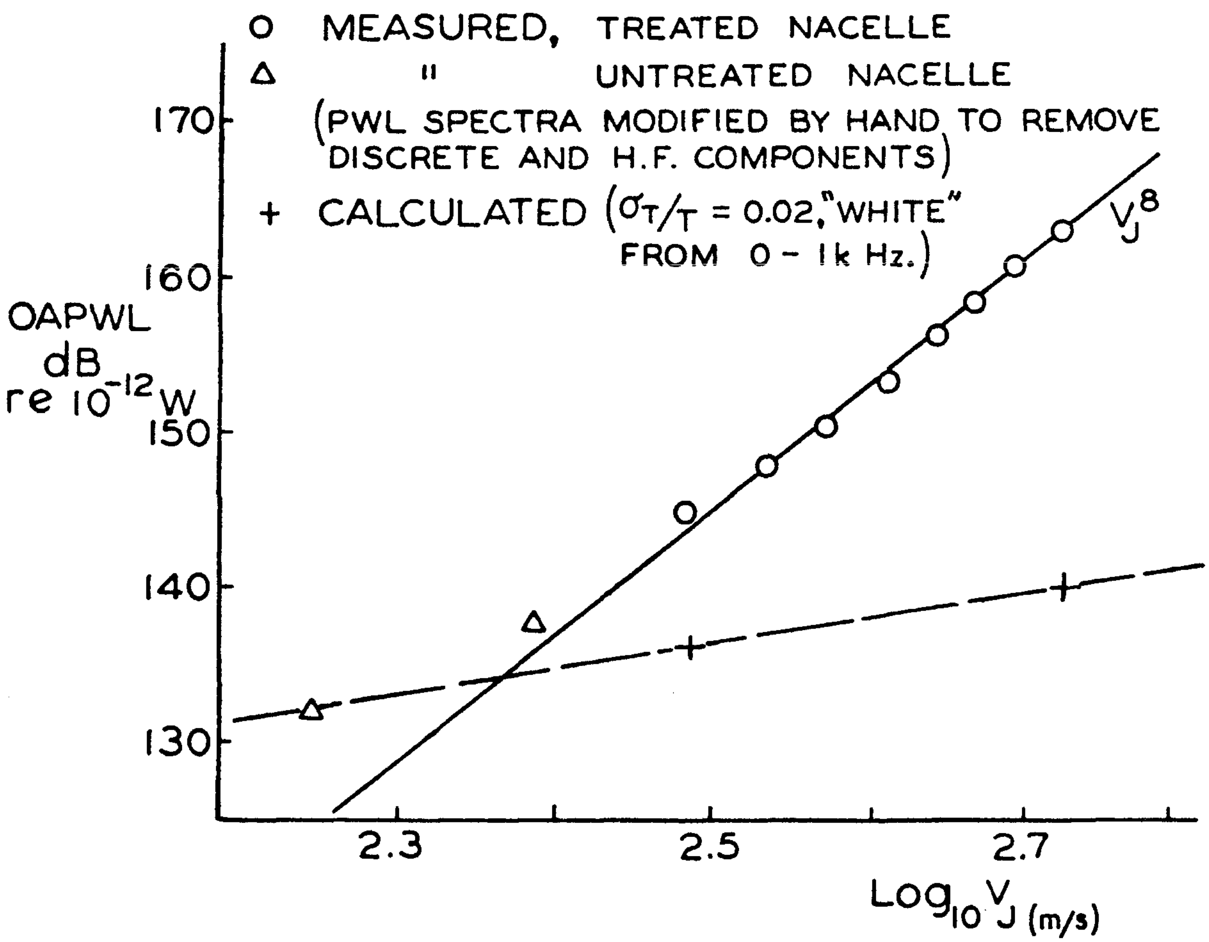

Figure 5. Predicted and measured rear arc overall acoustic power (OAPWL) for the Pratt and Whitney JT8D-9.

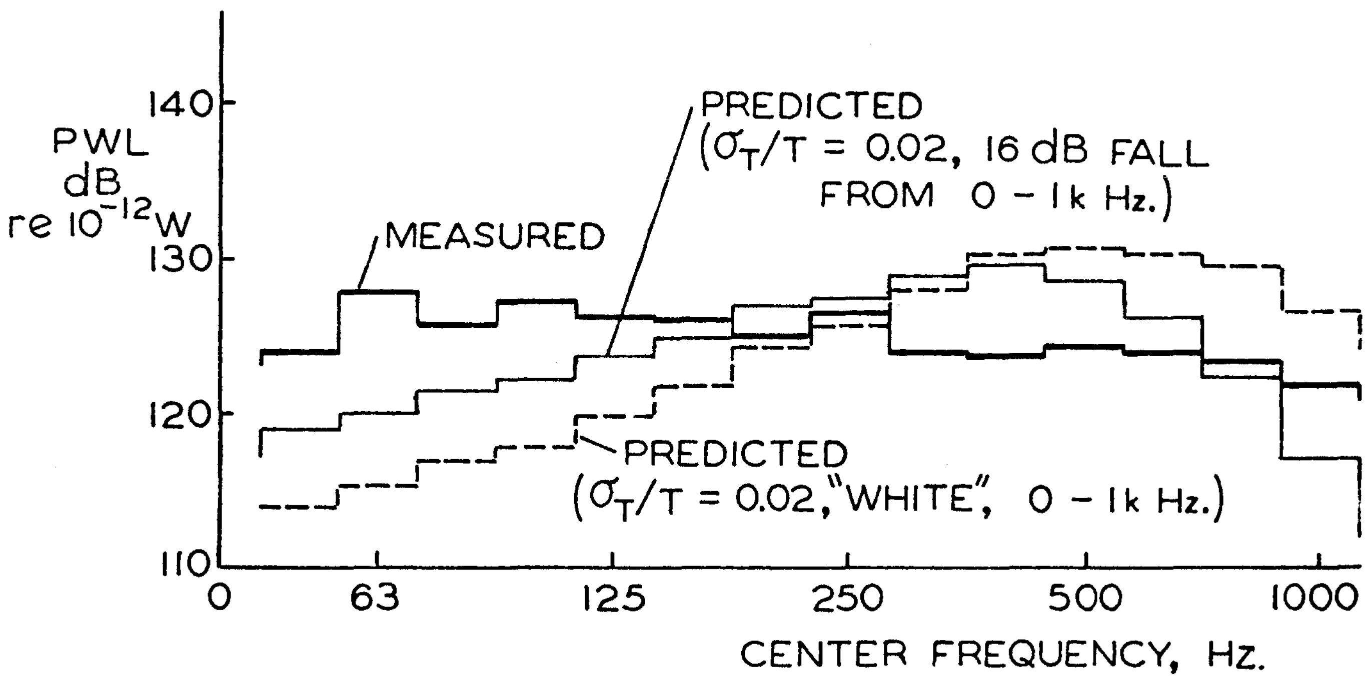

Figure 6. Predicted and measured third octave spectra of rear arc acoustic power for the Rolls Royce Spey 512 (jet velocity 216 m/s).

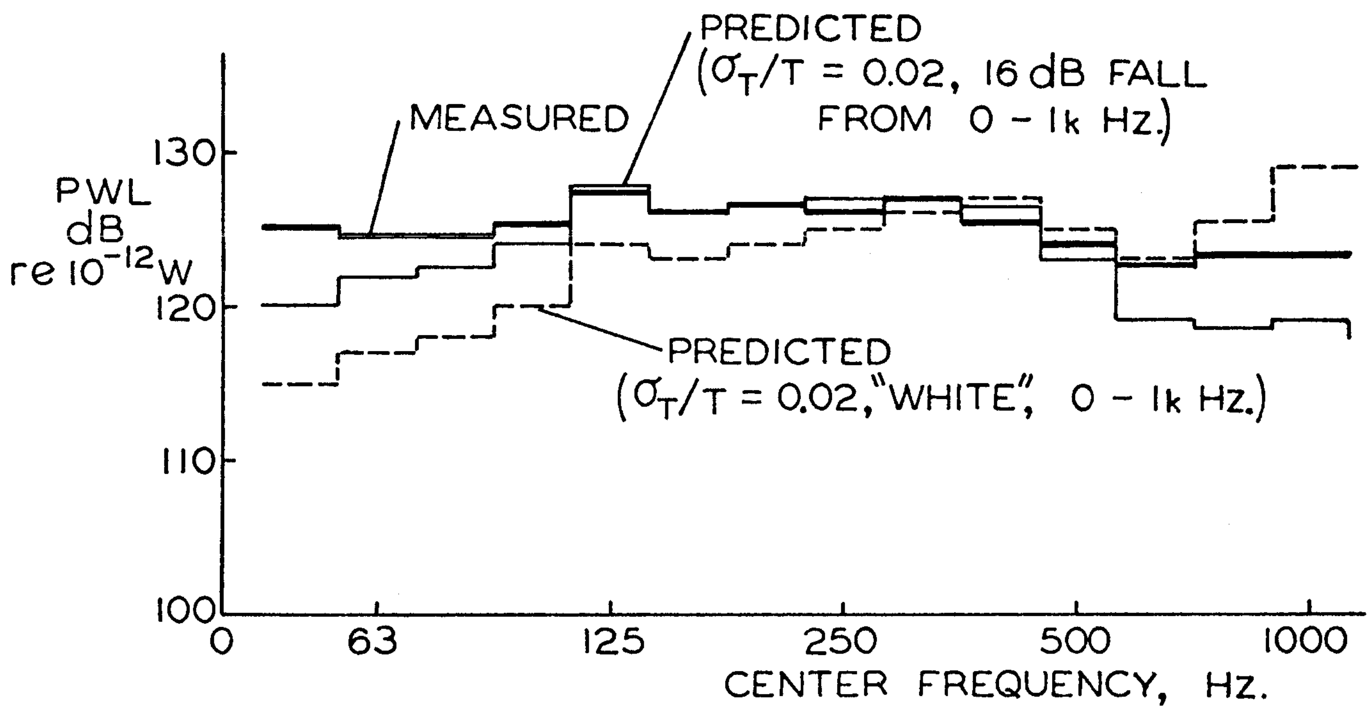

Figure 7. Predicted and measured third octave spectra of rear arc acoustic power for the Pratt and Whitney JT8D-9 (jet velocity 275 m/s).