The Noise of a Pulse Jet[*]

(A Written Contribution)

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SUMMARY

Some measurements of the noise of a pulse jet working in the open have been made Octave analyses show that the bulk of the noise energy is contained in the fundamental, the source approximating to the classical simple acoustic source This results in a relation for the mean noise level in decibels,

$$\mathrm{Db} = 10 \log_{10} \frac{1}{32} \frac{\rho_0 c}{r^2 c^2} \left(V_{max} - V_{min}\right)^2 f^2 s^2 \times 10^9 \text{ above } 10^{-16} \text{ watts/cm}^2$$

where ρ_0 is the ambient air density, c the velocity of sound and V that of the jet of exit area S and pulsation frequency f, r being the distance from the source (The units are c g s , for which $\rho_0 c = 42$) This gives a good approximation to the mean noise level, in practice the level decreasing as the angle from the jet stream is increased, and the character of the noise also becoming rather less unpleasant to the ear Although noise due to the intake of air past the valves, and the valves themselves, is undoubtedly present, it has not been considered separately, since there is no indication suggesting that it is appreciable in comparison with that of the pulsating exhaust Its existence, however, should not be overlooked

Since the generator of the acoustic energy can be likened to a simple source, the " efficiency " of the process is high, about 1% compared with a simple jet where a quadrupole field is more appropriate For a thrust of about 18 lbs , measurements indicate acoustic energy of the order of 400 watts

A second flatter and lower peak is also present in the spectra, being attributed to aerodynamic noise of the jet Although swamped by the other noise, its level is higher than that of a steady " cold " jet producing the same thrust by 25 or 30 db

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[*] Formerly University of Southampton paper 10th October, 1952 Communicated by Professor E J RICHARDS

Since the pulsating flow is an essential characteristic of this form of prime mover, the problem of noise reduction at source is severe A certain amount of cancellation by the mutual interference of two units might be achieved if it is possible for two units to run in close proximity to each other at a definite frequency

1 INTRODUCTION

The pulse jet is a mechanism, having no major moving parts which provides a thrust by virtue of an intermittent discharge of gases through an orifice The mode of operation is characterised by a pulsating flow, alternatively opening and closing the air intake vents, admitting air for an intermittent combustion so producing the propulsive jet and maintaining the resonance of the process by pressure reflection at the exit the operation is dependent upon the resonant properties of the flame tube and tail pipe assembly

The basic simplicity of the unit is attractive, being most suitable for short endurance work in view of the fairly low efficiency The pulsating flow, however, produces a large noise output, and the work of this note was performed to obtain some idea of the severity of the noise problem so raised

2 THE UNIT AND TEST ARRANGEMENTS

The unit for which the noise measurements were made was a comparatively small experimental version It was run at a sub-normal rating of 18 lbs thrust for convenience, and although this and other features were perhaps different from typical operating conditions this fact is immaterial in the present investigation which is concerned largely with the fundamentals of the generation of the sound Although technical details of the unit are as yet confidential, the writer was kindly provided with sufficient data to enable a comparison with the theory evolved to be made

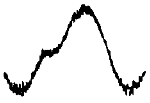
The test site* was in the open, well removed from buildings and other objects, the unit being mounted about four feet from the ground Measuring stations were marked out at a 50 ft radius from the jet exit, at angles of 10°, 30°, 60°, 90°, 135° and 180° from the direction of the jet The 10° position was made possible by a wind of strength about 15 knots blowing from the 135° direction

A Standard Telephones and Cables Objective Noise meter, Type 74100 A was used in conjunction with the two sets of overlapping octave filters The moving coil microphone, covered in a muslin shield as protection against the wind, was held by its stem at arms length above the measuring points A preliminary test, in which the waveform obtained from a crystal microphone was displayed on a cathode ray oscilloscope, was also made

3 TEST RESULTS

As a preliminary the waveform of the sound produced was displayed on the cathode ray oscilloscope, the microphone being placed at 90° to the jet, and at about 30° The waveforms obtained are as shown in the sketch

(*a*) at 90°



(*b*) *at* 30°

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* At Messrs SAUNDERS ROE Ltd , Research Unit Eastleigh Airport

The non-appearance of the higher harmonic content at the 90° station might possibly be attributable to the presence of a plate steel shield placed between the unit and the microphone, used as a safety screen on the rig (No such screen was present in the later measurements)

The results of the octave analyses of the noise at the various measuring points at 50 ft radius are given in Table 1 and Figure 1 Owing to the high peak noise level, the total noise energy is about $\frac{1}{4}$ db higher than the larger peak The units used are decibels above a sound pressure of 0 0002 dynes/cm^2,

$$\text{Db} = 10 \log_{10} {}^{\text{E}}\!/_{\text{E}_{\text{o}}}$$

where E_{o} is the reference energy level, E being the measured value It should be noted that the points of figure 1 indicate the measured energy passing through the octave filters (duly corrected for microphone response, amplifier and filter characteristics) , as is usual these points have been joined by straight lines for clarity, these lines having themselves no specific meaning

The first thing to note about the noise spectra is that they are quite unlike those of ordinary jet engines, the dominating characteristic being a large amount of energy radiated at the pulsating frequency of 120 cycles/second The noise level falls off rapidly on either side of this frequency, but rises again on the upper side to form a rounded maximum centred on about 1000 c p s The spectra have similar shape in the various positions, the intensities of both peaks being greatest at about 30° and falling steadily away as the pulse jet unit is circumnavigated, to a value about 10 db lower for the higher low frequency peak in a direction dead ahead of the unit and rather less than this for the higher frequency peak Although the harmonic content does not increase noticeably as the jet axis is approached (contrary to the indications of the observed waveform) the quality of the sound becomes appreciably harsher and is distinctly more unpleasant

We shall now examine the noise output in more detail, and then see how the interference between two units may result in a modified directional distribution the possibilities of reducing the noise at source seem to be very limited if the resonant properties of the unit are not to be materially affected

4 GENERAL CONSIDERATIONS

It can be seen from the spectra that the noise of a pulse jet falls into two main sections Firstly there is that noise directly associated with the pulsations of the device, and then there is the band of higher frequency noise centred on about 1000 c p s The latter may be the jet noise proper, *i e* , that resulting from the *turbulence* of the flow after the manner of a simple jet, although the cyclic changes in the flow due to the periodic discharge will clearly modify the structure of the turbulence

The directionality of this noise is similar to that of normal jets, *i e* , falling off with increasing angle from the jet stream direction, by an amount in this case of about 5 db between 30° and 135° The decrease in noise level very close to the jet, *i e* , at the 10° position, is a characteristic which has been noted for the noise of the jet issuing from a jet engine Although

TABLE 1

PULSE JET NOISE MEASUREMENTS

Octave levels above 0 0002 dyne/cm^{2} measured at radius of 50 ft from exit, 0° being in the direction of the jet

Filter No	1 1	1 2	2 1	2 2	3 1	3 2	4 1	4 2	5 1	5 2	6 1	6 2	7 1	7 2	8 1	8 2
Octave Band cycles/sec	37 5 75	50 100	75 150	100 200	150 300	200 400	300 600	400 800	600 1200	800 1600	1200 2400	1600 3200	2400 4800	3200 6400	4800 9600	6400 12800
Station																
10°	95	102	116	115 5	107	103 5	96	97	102	100	98	95 5	90	87 5	81	79
30°	96	102	118	115 5	105	104 5	96	101	104	104	104	100 5	98	92 5	90	85
60°	94	101	115	113 5	100	96 5	90	93	96	99	97	94 5	91	87 5	82	80
90°	92	98	113	111 5	100	95 5	91	95	100	97	97	93 5	89	85 5	82	81
135°	87	94	106	106 5	93	90 5	90	95	98	99	97	95 5	90	85 5	82	79
180°	86	100	107	107 5	94	86 5	91	98	101	98	99	97 5	87	82 5	77	73

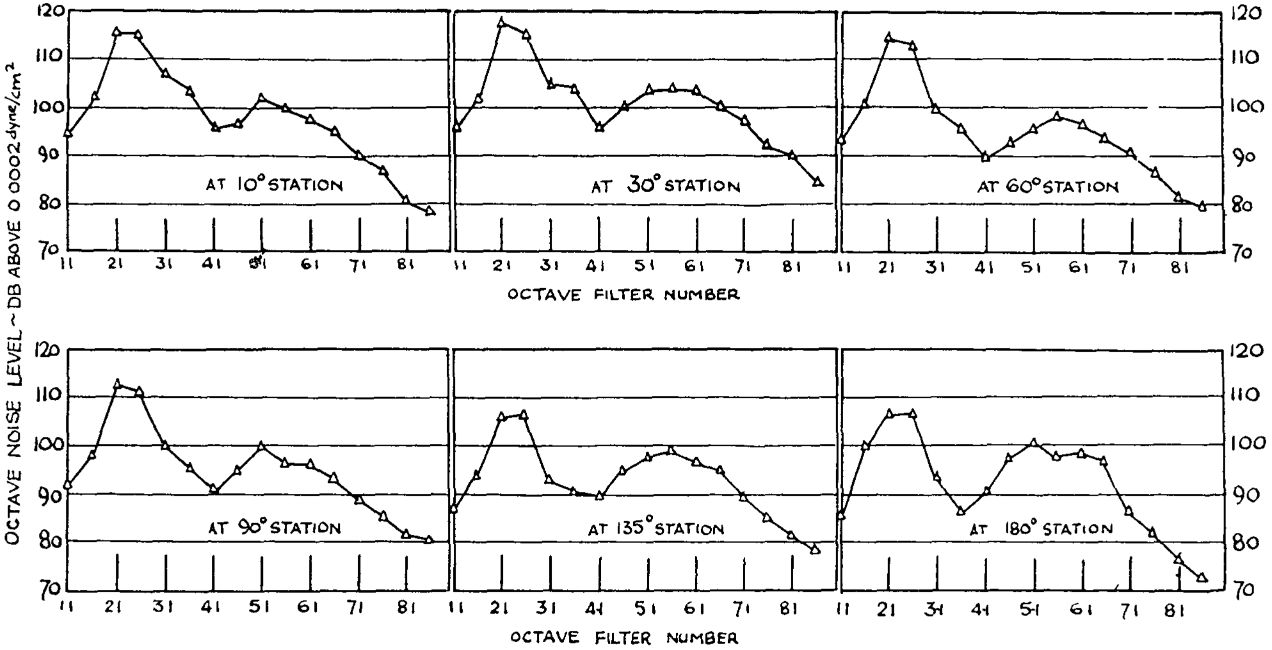

Fig 1 Measured Spectra of Pulse-jet Noise (Octave Analyses)

(See Table 1 for filter frequencies)

the frequency is not far different from that which might be expected of an ordinary jet, *i.e.*, of the order of 0.2 V/d, the maximum does not increase in frequency as the angle from the jet is increased as in the case of a simple jet.

The aerodynamic noise produced in this way is between 25 and 30 db more than that which would be expected from a jet of two inches diameter exhausting cold air so as to produce the same thrust. Although the density of the cold jet will be considerably the greater the velocity is about half the mean velocity of the pulse jet. The influence of these differences, together with the large disparity in temperatures, make a fair comparison difficult to make.

However, the noise produced in this way is at a lower level than that associated with the pulsations, and is inaudible against the background of the latter. This low frequency noise is easily the dominant noise, and acoustically the most difficult to alleviate by absorption or reflection. It will therefore be considered in rather more detail.

The flow from a pulse jet can be looked upon, roughly, as a steady flow together with a superimposed oscillating flow. At a distant point, the former will result in a steady drift of air so as to admit the volume of the exhaust gases from the jet. However, the latter represents the alternate creation and annihilation of mass, or volume of fluid so far as the external air is concerned. (We are here considering the efflux of the jet as the primary noise producer, and neglecting intake or valve noise.) This approximates to a simple pulsating acoustic source located at the orifice, particularly as the wavelength of the sound produced is large in comparison with the exit diameter. Now the velocity potential of such a source can be written as

$$\phi = \frac{A}{r} e^{ik(ct-r)} \qquad \text{———————(1)}$$

where A is the amplitude of the potential function, k = 2π/λ (λ is the wavelength) and r is the distance from the source. The velocity of sound is denoted by c. At a *large* distance from the source the particle velocity will be

$$v = -\frac{\partial\phi}{\partial r} = \frac{ikA}{r}\sin k(ct-r) \qquad \text{———————(2)}$$

and the sound pressure

$$p = \rho_o \frac{\partial\phi}{\partial t} = \rho_o \frac{ikcA}{r}\sin k(ct-r) \qquad \text{———————(3)}$$

from which the acoustic power is obtained as

$$E = 4\pi r^2 \rho_o c \frac{k^2A^2}{2r^2} \qquad \text{———————(4)}$$

The amplitude of the rate of fluctuation of fluid volume across any *small* spherical boundary of radius r enclosing the source, is

$$4\pi r^2 \frac{A}{r^2} = Q, \text{ say} \qquad \text{———————(5)}$$

so that (4) simply becomes

$$E = \frac{1}{8\pi}\,\rho_o c\;k^2Q^2$$

$$= \frac{\pi}{2}\,\rho_o c\;\frac{Q^2f^2}{c^2} \qquad \text{———————(6)}$$

where f is the frequency

In practice the value of Q can be approximated to, for the fundamental, by taking the amplitude of the velocity fluctuation at the exit, *i e*,

$$\frac{1}{2}\left(V_{max}—V_{min}\right)$$

in conjunction with the exit area S Thus

$$E = \frac{\pi}{8}\,\frac{\rho_o c}{c^2}\left(V_{max}—V_{min}\right)^2 f^2S^2 \qquad \text{———————(7)}$$

Upon inserting the appropriate values of the jet velocity, its exit area and pulsation frequency, the theoretical total acoustic energy radiated away becomes

$$E = 4\ 68 \times 10^9 \text{ ergs/sec}$$ [*]

corresponding to a noise level at a radius r of

$$E(db) = 10\ \log_{10}\frac{E \times 10^9}{4\pi r^2} \qquad \text{———————(8)}$$

above 10^{-16} watts/cm², or 0 0002 dynes/cm² very nearly.[**]

This gives at a 50 ft radius a calculated mean value of 112 db in free space, which is quite close to the mean measured value of 113 7 db after 3 db has been subtracted from the latter to compensate for reflection off the ground (Fig 1) It thus seems possible to estimate the intensity of the fundamental with a useful degree of accuracy , of course the harmonics cannot be found so simply in this way, but they are relatively unimportant

A useful guide to the dependence of the noise output on the pulse-jet parameters can be obtained from (7) To a rough approximation if the minimum velocity is small

$$\text{Thrust} \propto \rho V^2S$$

so that to about the same order of accuracy

$$E \propto TtSf^2 \propto Tt\,d^2f^2 \qquad \text{———————(9)}$$

where T is the thrust, t the jet temperature and d its exit diameter As before f is the frequency At altitude the variation in ρ_o and c might be taken into account also In general, T, t and f will increase together From the point of view of keeping the noise levels as low as possible for a given thrust, the jet temperature and diameter should be kept as small as possible, together with the frequency, although the effects of the latter will be offset to some extent by the greater sound insulation difficulties The most effective way would seem to be to reduce the amplitude of the exhaust

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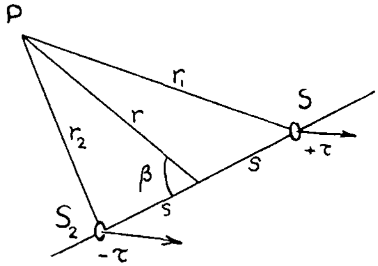
[*] c g s units are most convenient in acoustical calculations

[**] the former datum being the greater by about 0 2 db

velocity fluctuations in conjunction with a higher mean velocity (equation 7) and the greater mass flow might bring about a reduction in temperature and frequency There may be a tendency towards this for a unit in motion through the air Just what can be done along these lines is, of course, a question for the engine designer

5 On Mutual Interference



The scope of reducing the intensity of the noise at source appears to be limited the possibility of using the interference between adjacent pulse jets to obtain minima in certain directions is well worth a cursory examination The field of two adjacent jets will be considered and although the analysis could be easily extended to a larger number, such a case is unlikely to arise in practice

If the noise output is approximated to by a pair of simple sources —as indeed we have seen to be a reasonable approximation—distance 2s apart, and out of phase by a time $2\tau_0$, the total potential function at a point P (see diagram) becomes

$$\phi = \frac{1}{r_1} e^{ik(ct - r_1 + c\tau)} + \frac{1}{r_2} e^{ik(ct - r - c\tau)} \qquad \text{———————(10)}$$

and putting $r_1 = r + s \cos\beta$

$r_2 = r - s \cos\beta$

where $r >> s$ and β is the angle of the observation point P from the line joining the two sources, taken in any plane relative to the direction of the jets and if

$$q = c\tau_0 - s \cos\beta$$

then equation (10) becomes after reduction, with s/r small

$$\phi = \frac{1}{r} e^{ik(ct - r)} \; 2 \cos kq \qquad \text{———————(11)}$$

from which we can define a directionality for the fundamental of the two sources D, being a factor to apply to the arithmetical sum of the strengths of the two sources, as follows

$$D = \cos \frac{2\pi}{\lambda} (c\tau_0 - s \cos\beta) \qquad \text{———————(12)}$$

Now, if the sources are distance n wavelengths apart and out of phase by ϵ cycles

$$D = \cos \pi(\epsilon - n \cos \beta) \qquad \text{———————(13)}$$

By choosing varying values for ϵ and n we can find the resultant field for a range of conditions

The most likely state of affairs in practice is that either the units will be pulsing together (in phase) or oppositely (out of phase), i e , $\epsilon = 0, \frac{1}{2}$, respectively If then the spacing is varied from zero to half a wavelength ($n = \frac{1}{2}$) the noise reductions in decibels in one quadrant below the arithmetical sum of the noise level of two units are as shown in figure 2, the complete fields being symmetric

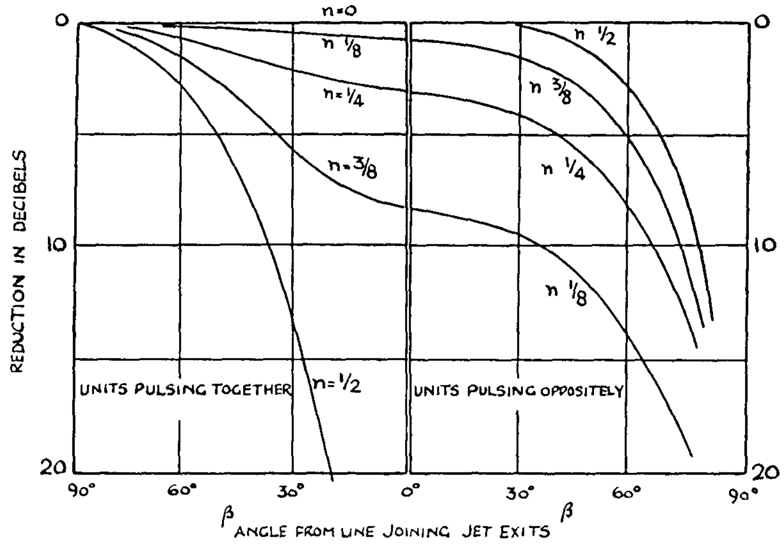


FIG 2

THEORETICAL REDUCTION IN RADIATED ENERGY OF THE FUNDAMENTAL OF THE NOISE OF TWO PULSE JET UNITS BY MUTUAL INTERFERENCE
The Units are spaced η wavelengths apart

When the units are pulsing together, there is no reduction in directions normal to the line joining them, but as the spacing between them is increased the interference progressively reduces the noise level in line with the units until at a spacing of half a wavelength complete cancellation occurs in that direction

The position is rather the reverse when the units are out of phase When superimposed, complete cancellation occurs, but as the units are moved apart the noise levels in line with them increases until zero reduction in that direction occurs at half a wavelength spacing

Practical consideration will have a powerful influence on the possible useful arrangements, particularly with regard to mutual interference between the units If two units would perform satisfactorily with the interference effects being out of phase with each unit, then the ideal case acoustically of complete cancellation, might be approximated to by making the units concentric If the opposite is more nearly true, two units half a wavelength apart and out of phase would be preferable But these are mere suppositions it is clear that any application in the manner suggested is entirely dependent upon the feasibility of running two units in close proximity at definite frequencies, especially if the units are to be spaced a specific fraction of a wavelength apart It seems probable that for satisfactory running certain conditions of phase must be satisfied, and this, best found experimentally in conjunction with thrust measurements, will decide which scheme might be considered further

6 Concluding Remarks

The dominating feature of the noise of a pulse jet is the large amount of energy contained in the fundamental corresponding to the pulsation frequency, accompanied by what is thought to be most probably aerodynamic noise at a lower level and higher frequency A more detailed analysis would be required to substantiate or refute the latter The harmonics to the fundamental were small in the case investigated, but this is not necessarily generally so since the unit was run at a de-rated thrust

The efficiency of the sound production based upon the kinetic energy of the gases is very high, of the order of 1% in comparison with a simple jet (0 01% say), being approximated to by a simple acoustic source The unit considered produced about 400 watts of acoustic energy for a thrust of 18 pounds A theoretical prediction (equation 7) gives a good approximation, the indications being that the energy of the dominating fundamental is likely to rise roughly proportionally to the thrust, jet temperature and jet exit area, and with the square of the pulsation frequency A reduction in the magnitude of the velocity fluctuations of the exhaust would be desirable for a minimum noise level, together with the factors just mentioned

The essential nature of the resonance presents difficulties from the point of view of noise reduction at source, other than by adjustment of the flow parameters, although reductions, particularly in certain directions, might be obtained by the mutual interference of two units The feasibility and success of such a method is entirely dependent upon the satisfactory operation of two neighbouring (or concentric) pulse jet units and the smallness of the harmonic content of the pulsation noise

7 Acknowledgements

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