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# ACOUSTIC ASPECTS OF A RADIAL DIFFUSER

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**The flow in a supersonic radial-diffuser is investigated experimentally and the results of the experiments are discussed in the light of existing theories From such an analysis it is concluded that a better understanding of this particular diffuser, which can be used as a sound attenuator, may lead to other applications in the field of propulsive units and jet flows*.**

## 1. Introduction

The advent of high power propulsive units in aeronautics has brought an unwelcome by-product: the noise. It was first experienced in a drastic manner at the propeller tips when these surpassed the velocity of sound, later in turbo-jet units or rocket propulsive engines. Also industrial jets operating with compressed air are powerful noise generators with all the associated side effects.

Sound generated aerodynamically has focussed attention of prominent scientists since the early 1950' s. On the theoretical side the first break-through in the understanding of the mechanism of aerodynamically generated noise was done by H. J. LIGHTHILL [1], [2] and G. M. LILLEY [3] in Great Britain followed later by A. POWELL [4] in the U.S.A. and H. RIBNER [5], [6] in Canada, just to mention a few. It was followed with greater or smaller success by considerable experimental research on both of the Atlantic like E. MOLLO CHRISTENSEN [7], A. MICHALKE [8], [9], I. JONES [10], H. RIBNER [11], W. FFOWCS [12], M. HOLLINGWORTH [13], just to quote a few earlier studies.

In spite of the progress in the understanding of the nature of aerodynamic noise when it comes to the prediction of its intensity for a particular case and to the reduction of noise by applying the existing theories it appears that they fall short of expections. They have not yet reached sufficient refinement to be

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* The Abstract was prepared by the Editorial Board.

of great use to the applied scientist, and engineer. Thus for example a multitube suppressor nozzle developed by the *Boeing Company* [14] is known to suppress the noise, yet the calculated value of the total acoustic power using LIGHTHILL's power law is equal to that of a single jet. In defence of the existing theories one should say that they point out the nature of noise generation, can help to interpret results of measurements and indicate interesting possibilities in new design.

The concept of a radial diffuser in subsonic and supersonic flows is not very well known and its application as a noise suppressor of supersonic jets new to the knowledge of the authors of this paper. Supersonic diffusers tend to diminish the noise due to the reduction of the kinetic energy of the flow. Because a normal shock has to be situated downstream of the second throat, which is open to the atmosphere the noise attenuation is not substantial.

The use of a radial diffuser would not be applicable to the turbo-jet engines during flight operation because of the reduction of the momentum flux at the exit, yet the present study indicates that the main cause of the noise reduction may not be necessarily the process of recompression. There are several other factors all working in parallel to reduce the noise in the case of such a diffuser.

This paper deals in the first instance with the experimental results of sound attenuation and the necessary details related to a supersonic radial-diffuser-silencer. In the second part the results are discussed in the light of the existing theories. It is hoped that a better understanding of this particular sound attenuator may lead to other applications in the field of propulsive units and jet flows.

## 2. Details of the experiment

### *2.1 The radial diffuser-silencer and its installation*

Fig. 1 shows a cross section of the radial diffuser. One observes in it: i) the supersonic nozzle, ii) the front plate forming the diffuser bell, iii) the adjustable back plate separated from the bell by a gap $h$, iv) a conical spike. If the diameter of the back-plate at the exit is $D$ and the diameter of the nozzle is $d$ then the area ratio of this diffuser is $4Dh/d^2$. By adjusting the back plate with the regulating screws one varies the gap $h$ and also the area ratio and the area of the second throat situated in the region of the base of the conical spike. Three typical conical spikes are also shown, as well as a rounded dome-shaped piece used originally for subsonic tests.

Fig. 2 gives a typical distribution of the internal cross-section of this diffuser along the axis for various gaps $h$. The areas $A^*$ and $A^{**}$ as function of Mach number are also drawn for all the supersonic nozzles which have a constant diameter $d = 0.8$ inch.

For a typical gap $h = 0.118$ inch and back plate diameter $D = 7.0$ inch the area ratio of this diffuser is about 5.2. The smallest recorded gap which the diffuser was operating efficiently was $h = 0.06''$ reducting the area ratio quoted above by half.

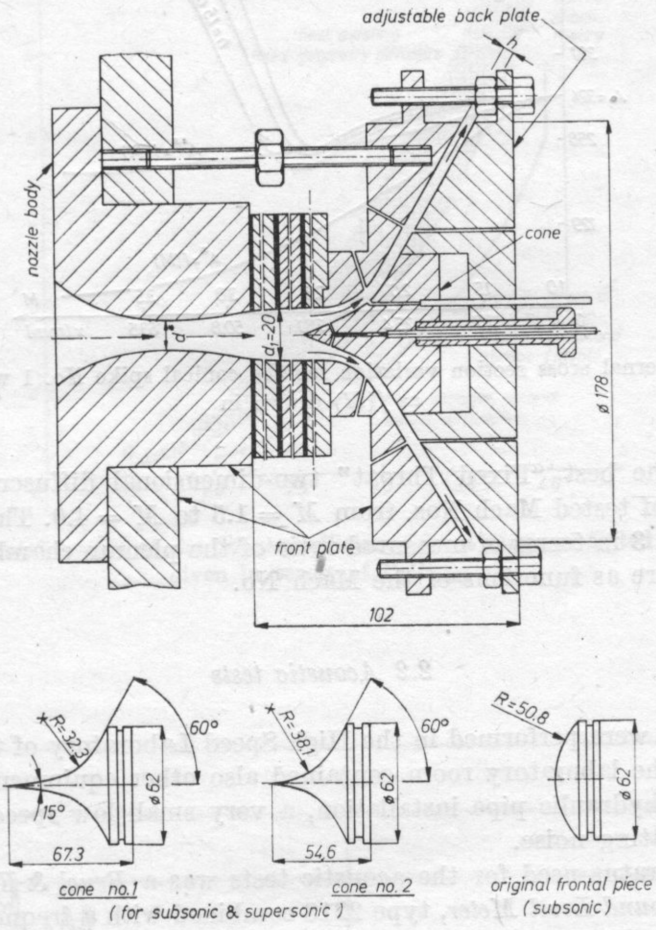


Fig. 1. A cross section of the radial diffuser with typical conical spikes and low speed rounded head

The diffuser was connected through a nozzle to a plenum chamber fed from a compressed air storage system having $T_0$ approximately at room temperature. Filling of the plenum chamber during the blow down operation through reduction valves was accompanied by a hissing noise similar to that of a pressurized water installation. No separate analysis of this noise has been done yet, although the background noise of the laboratory was recorded (sec below).

The aerodynamic characteristics of this diffuser are described separately [15]. It may be noted however that the efficiency of some configurations com-

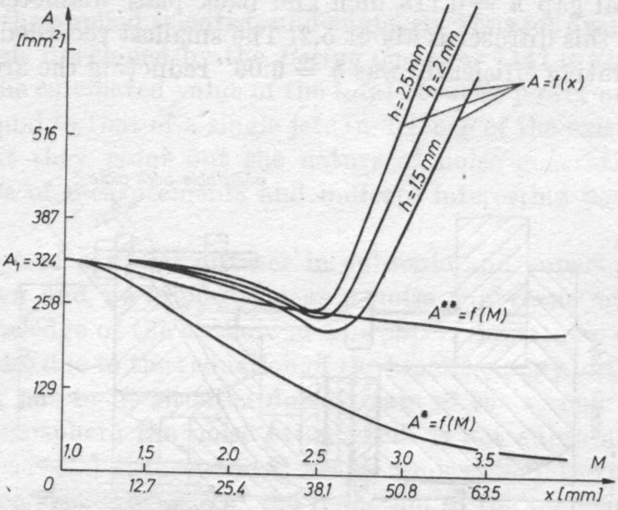


Fig. 2. The internal cross section variation for the conical spike No. 1 with $A^*$ and $A^{**}$ as $f(M)$ drawn in

pares with the best "Fixed Throat" two-dimensional diffusers through the whole range of tested Mach Nos. from $M = 1.5$ to $M = 4.0$. These results are shown in Fig. 3 in terms of measured ratio of the plenum chamber pressure to the atmosphere as functions of the Mach No.

### 2.2 *Acoustic tests*

The tests were performed in the High Speed Laboratory of the University of Calgary. The laboratory room contained also other equipment like a small water flume, hydraulic pipe installation, a very small low speed wind tunnel etc. all generating noise.

The apparatus used for the acoustic tests was a *Bruel & Kjaer Precision Intergrating Sound Level Meter*, type 2218 combined with a frequency analyzer. Also a *Bruel & Kjaer High Resolution Signal Analyzer* type 2033 with a plotter was used to obtain noise spectra. The frequency range was for most of the tests up to 20 kHz, but in some cases a microphone was used, sensitive to very high frequencies up to 50 kHz. The laboratory walls were made of cement. A typical background noise of the laboratory was recorded and is shown in Fig. 4. It does include the noise of the high pressure system required to run the nozzle.

Fig. 5 shows the results of directional tests at $M = 4.0$. The microphone was located at the level of the nozzle axis at a distance of 4.9′ from the nozzle exit and rotated through 90°. Without diffuser the highest noise level was 125 dB when on the nozzle axis. A typical "valley" of noise intersity was not recorded in the front of the nozzle which may be partly due to the bell of the diffuser

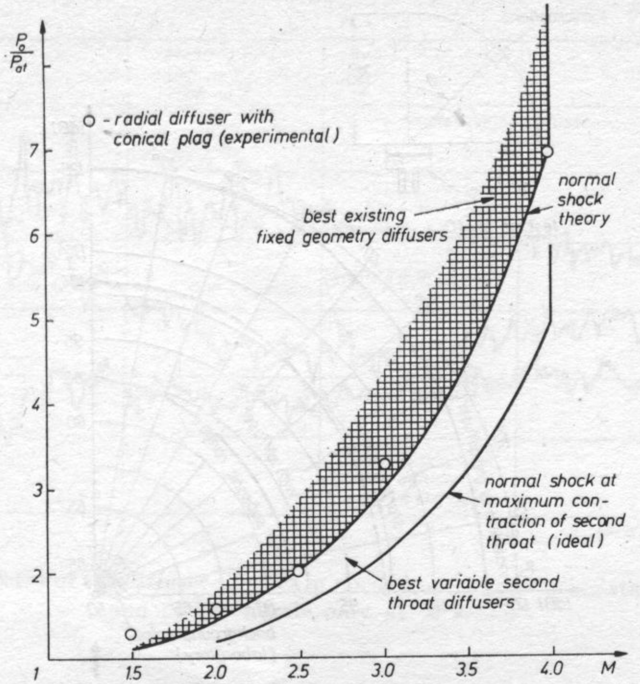


**Fig. 3. Experimental results of the diffuser efficiency for a range of tested Mach Numbers given in terms of $P_0/P_{atm}$**

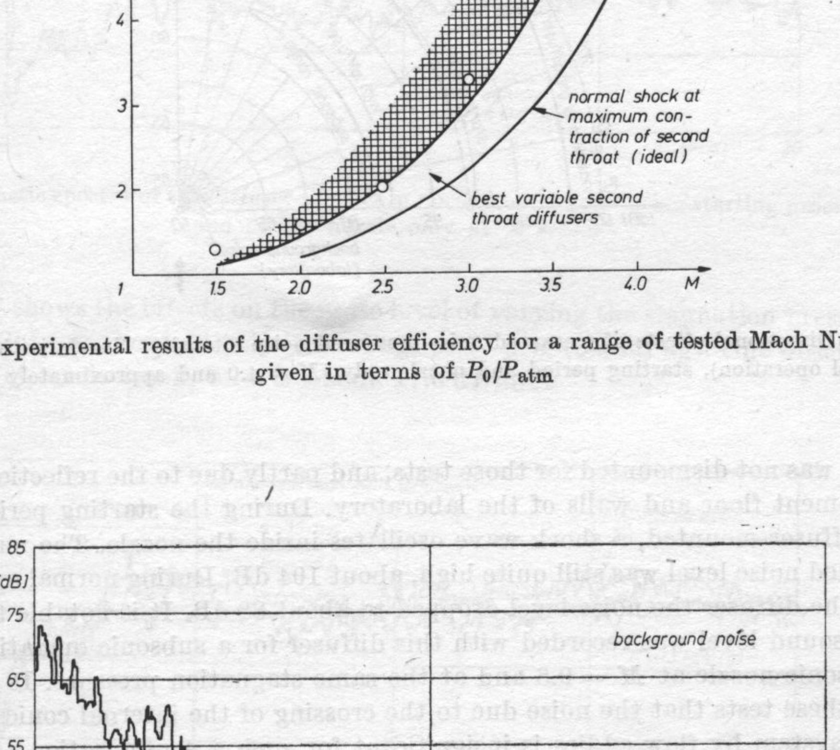


**Fig. 4. Measured spectrum of the typical laboratory background noise**

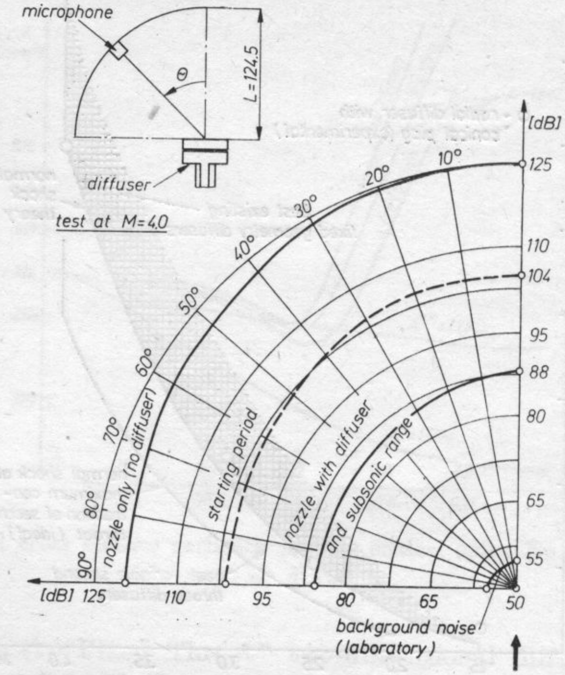


Fig. 5. Directional effects of measured noise measured noise intensity. Nozzle with diffuser (normal operation), starting period and nozzle only. $M = 4.0$ and approximately $M = 0.8$

which was not dismounted for those tests, and partly due to the reflections from the cement floor and walls of the laboratory. During the starting period with the diffuser mounted, a shock wave oscillates inside the nozzle. The maximum recorded noise level was still quite high, about 104 dB. During normal operation with the diffuser the noise level dropped to about 88 dB. It is notable that the same sound lèvel was recorded with this diffuser for a subsonic operation with a subsonic nozzle at $M = 0.8$ and at the same stagnation pressure. It appears from these tests that the noise due to the crossing of the internal conical shock wave system by flow eddies is insignificant for such a configuration. Also the directional effects are small.

Fig. 6 shows the noise spectra recorded by a microphone at 4.9′ from the nozzle exit at $M = 3.0$ with i) nozzle without the diffuser (no back plate), ii) diffuser during the starting operation, iii) diffuser during normal operation. One observes that the diffuser in condition (iii) cuts off the low frequency range noise which is the most painful for the ear. It should also be noted that the minimum gap $h$ at the diffuser exit coincided with the most efficient operation and the lowest noise level. The optimum gap varied accordingly to the internal configuration associated with various conical spikes. Its range was between 0.06 inch (1.5 mm) and 0.12 inch (3.0 mm).

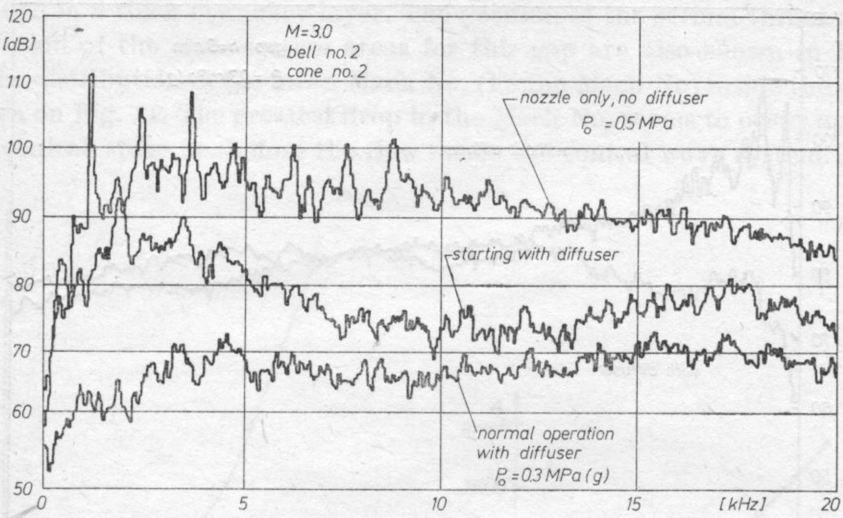


Fig. 6. Acoustic spectra of the diffuser-silencer in normal operation during starting procedure and of the nozzle only at $M = 3.0$

Fig. 7 shows the effects on the noise level of varying the stagnation pressure at $M = 3.0$ from about 44 psig (0.3 mPag) to 73 psig (0.5 mPag). One observes that this effect is small, and is about 17.0 dB/mPa.

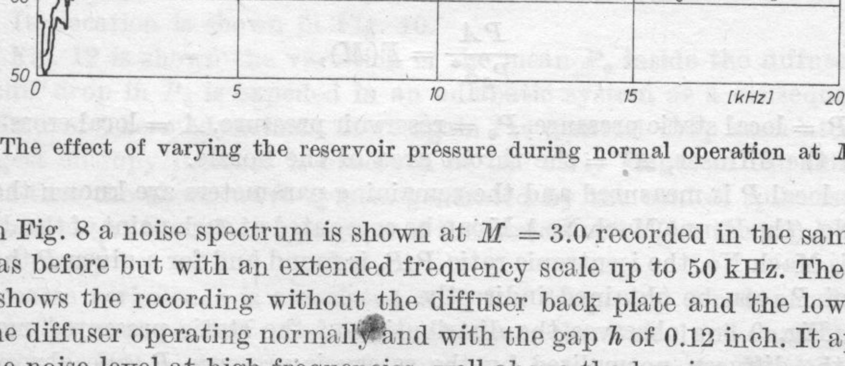


Fig. 7. The effect of varying the reservoir pressure during normal operation at $M = 3.0$

On Fig. 8 a noise spectrum is shown at $M = 3.0$ recorded in the same condition as before but with an extended frequency scale up to 50 kHz. The upper curve shows the recording without the diffuser back plate and the lower one with the diffuser operating normally and with the gap $h$ of 0.12 inch. It appears that the noise level at high frequencies, well above the hearing range, remains approximately the same. The difference of an order of magnitude is recorded however at lower frequencies within the hearing range.

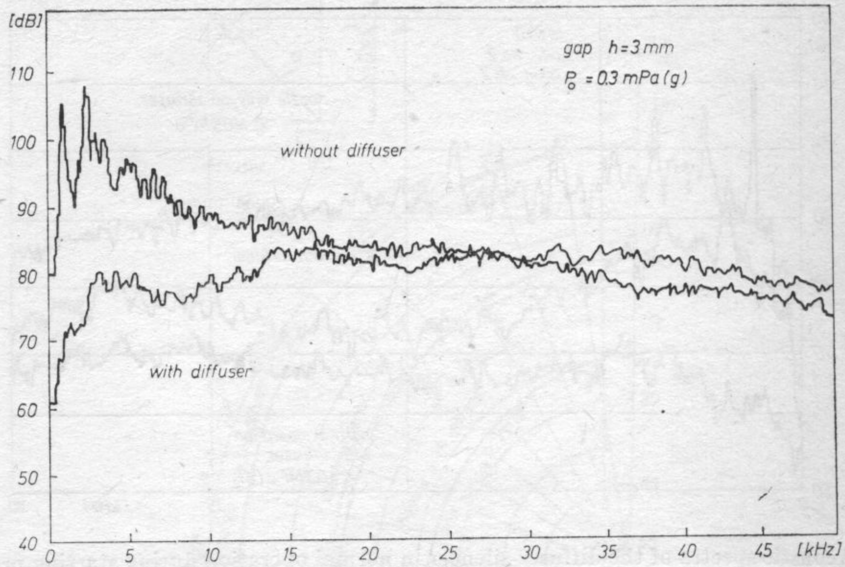


Fig. 8. Aerodynamic noise spectra at $M = 3.0$ with and without the diffuser for an extended range of frequencies up to 50 kHz

### 3. An analysis of the internal flow conditions

To understand better the unusually effective sound attenuation of this diffuser pressure measurements were made in the diffuser and in the nozzle for various flow conditions and the internal geometry was carefully considered in each case. The most important results are discussed below.

The computed values of the internal Mach. No. and the local stagnation pressures discussed below are mean values obtained indirectly making use of the equation of continuity and based on the property of the function

$$\frac{PA}{P_0 A^*} = F(M),$$

where $P$ = local static pressure, $P_0$ = reservoir pressure, $A$ = local cross-section area in the diffuser, $A^*$ = the throat area of the nozzle.

As local $P$ is measured and the remaining parameters are known the mean Mach No. (the Fanno Mach No.) $M$ can be computed at each point of the diffuser. For this Mach No. the isentropic ratio $P/P_0$ is found and for a given $P$ the mean value of $P_0$ can be obtained indirectly.

In Fig. 9 one observes the distribution of the static pressured measured inside the diffuser, normalized by the reservoir pressure $P_0$ one observes the strongest rise in the static pressures close to the diffuser exit (at $X = 3.38''$), presumably downstream of a weak shock wave located below the second throat embedded in a thick boundary layer. The position of the second throat and the distribution of the cross-section areas for this gap are also shown in Fig. 10.

The distribution of the mean Mach No. (Fanno Mach No) inside the diffuser is shown on Fig. 11. The greatest drop in the Mach No. seems to occur upstream of the conical spike i.e. before the flow meets the conical wave system. May be

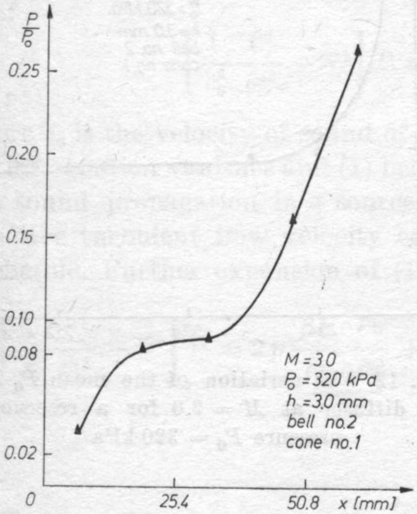


**Fig. 9.** Static pressure distribution in the diffuser at $M = 3.0$

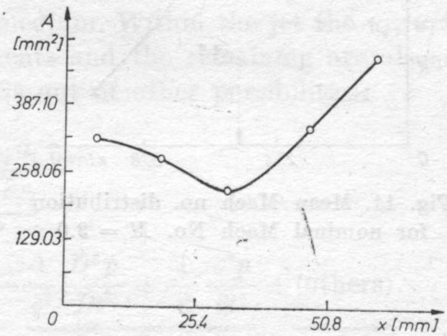


**Fig. 10.** Area distribution and position of the second throat for $h = 3$ mm Bell. No. 2, Cone no. 1

this is due to the slight roughness at the joint of the plates regulating the distance between the exit of the nozzle and the noise of the spike. Thus the conical waves occur at a comparatively small Mach No. Such a wave system is very weak and the eddies leaving the nozzle crossing them would generate a weak noise source. One notes that the Mach No, crosses $M = 1.0$ downstream of the second throat. Its location is shown in Fig. 10.

In Fig. 12 is shown the variation of the mean $P_0$ inside the diffuser. The monotonic drop in $P_0$ is expeded in an adiabatic system as a consequence of the II Law of Thermodynamics. Here again the greatest drop associated with the largest entropy increase is observed at the early stages of the flow that confirms that the shock wave system generated by the conical spike is weak.

Fig. 13 shows the relative position of the conical spike [for the gap $h = 0.12$ inch (3.0 mm)].

A coarse turbulence is associated with low frequency aerodymical noise. In this design of the diffuser the distance between the conical spike and the wall of the diffuser bell is steadily reduced up to the point when the gap $h$ becomes constant. This is shown in Fig. 14 for $h = 0.12$ inch. Thus the transversal size of the eddies moving in the diffuser is in this case reduced 4-folds (assuming

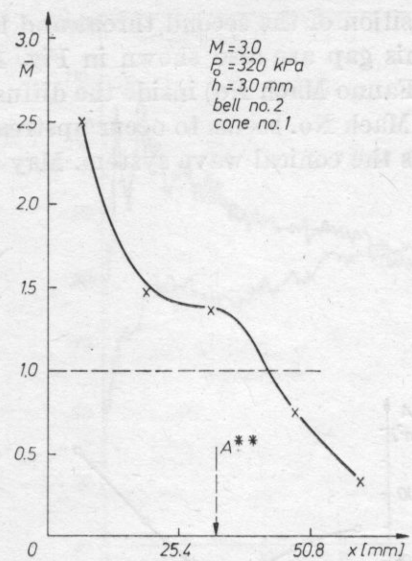


Fig. 11. Mean Mach no. distribution for nominal Mach No. $M = 3.0$

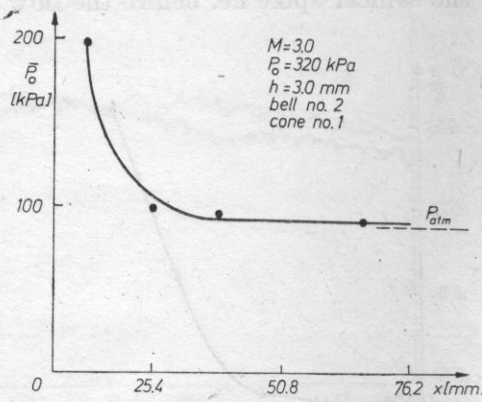


Fig. 12. The variation of the mean $P_0$ in the diffuser at $M = 3.0$ for a reservoir pressure $P_0 = 320$ kPa

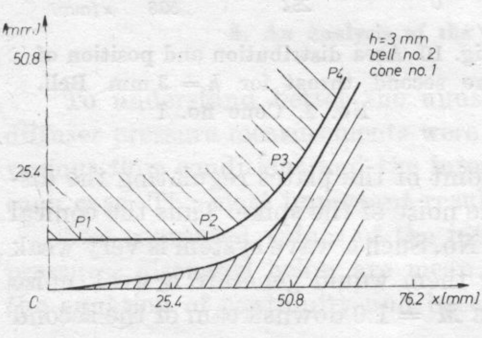


Fig. 13. The position of the conical spike No. 1 relative to the nozzle exit plane at $X = 0.0$ and of the pressure taps

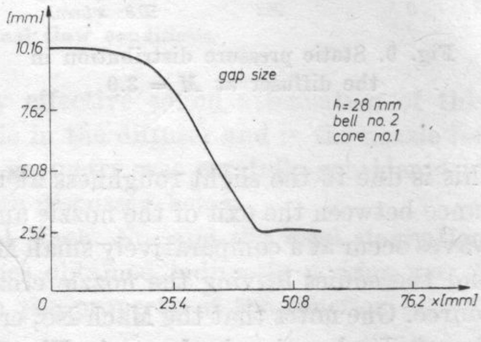


Fig. 14. The gap size inside the diffuser assumed initially as radius of the nozzle for $h = 2.8$ mm (0.11 inch)

that the initial width is equal to the nozzle radius). This also helps to understand the reduction in the low frequency noise levels as indicated by the acoustic measurements.

## 4. Theoretical aspects of sound generated aerodynamically

### *4.1 A review of the fundamental features of the current theories*

It appears that one of the inherent weaknesses of all the aerodynamical sound theories is the essential ambiguity in identifying the physical causes and sources of the observed noise field. The confidence in any conjectures in this regard can only be established by examining the details of sound production in very simple flows that are reasonably well known. Unfortunately only few compressible flow fields belong to this category. Progress in aerodynamic noise theory has been achieved by a formal but rather arbitrary source identification. LIGHTHILL's [1] full equation restated in pressure terms is

$$\left[\frac{1}{c_0^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right] P = \frac{\partial^2 p\, u_i u_j}{\partial x_i \partial x_j} - \frac{\partial^2}{\partial t^2}\left[p - \frac{P}{c_0^2}\right], \tag{1}$$

where $c_0$ is the velocity of sound of the ambient air. Outside the jet the R.H.S. of this equation vanishes and (1) becomes a homogenous wave equation describing sound propagation in a source free medium. Within the jet the $u_i$, $u_j$ are effective turbulent flow velocity components and the remaining are also not negligible. Further expansion of (1) yields out of other possibilities:

$$\left[\frac{1}{c_0^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right] P = \underbrace{2p\frac{\partial U}{\partial y}\frac{\partial v}{\partial x}}_{a} + \underbrace{p\frac{\partial^2 u_i u_j}{\partial x_i \partial x_j}}_{b} - \underbrace{\frac{1}{c^2}\frac{D^2 p}{Dt^2} + \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2}}_{c} + \underbrace{\text{(others)}}_{d}. \tag{2}$$

The transversely sheared flow $U(y)$ or $U(x_2)$ has a superimposed turbulent component $u_i (i = 1, 2, 3)$ and $x_1, x_2 = x, y$, $v = u_2$ and $c$ is the velocity of sound within the jet field.

The term ($a$) is a source responsible for noise due to shear

The term ($b$) is the "self noise" source due to turbulence

The term ($c$) is due to the convection of the sound waves but is not a source as can be seen by transferring the term ($c$) to the L.H.S.

The term ($d$) is due to other sources not classified above real or equivalent in the mathematical sense. The solution of LIGHTHILL's equation gives the famous eighth power law of noise intensity $I \sim U^8$ (true for subsonic flows).

RIBNER [16] has shown that the above presentation of LIGHTHILL'S equation leads directly to a from very similar to the often quoted LILLEY's wave equation

$$\frac{1}{c^2}\frac{D^2 p}{Dt^2} - \nabla^2 p - 2p\frac{\partial U}{\partial y}\frac{\partial v}{\partial x} = p\frac{\partial^2 u_i u_j}{\partial x_i \partial x_j} + \text{(others)} \tag{3}$$

which is identical with Eq. (2) after rearranging the terms. One observes above that the wave convection term ($c$) and the mean flow shear term appear on the L.H.S. LILLEY'S equation has been used widely to describe the jet noise with the argument that it represents more correctly the physics of noise generation because the R.H.S., the "self noise" term is considered as "real" noise source and note merely mathematically "equivalent".

This short discussion emphasizes the previous observations that the same results can be obtained without identifying exactly the sources of noise. Is has been also observed by RIBNER [16] that the sources of noise in Eq. (2) are not unique and many more source term expansion have been published. The acceptable variety of sources as well as "equivalent sources" in the mathematical sense have contributed to a great confusion for many years.

### *4.2 Some guidelines from the theory*

The experimental scientist who looks for guidance on noise abatement from these general equations like (2) and (3) can expect much less in this area his fluid mechanics counterpart who uses Navier Stokes equation for boundary layer problems. It appears that there is a general consensus that the "self noise" term (*b*) in Eq. (2) is an unmistakable real source of aerodynamic noise generation. Thus any device which would reduce the turbulence level or the size of the eddies would be beneficial. Fig. 15 gives a schematic view of a high speed jet without wave patterns, in which two regions are distinguished. Region *A*,

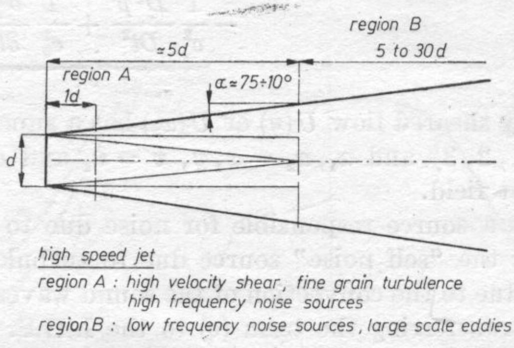


Fig. 15. Diagram of a subsonic jet with regions *A* and *B* related to high frequency and low frequency noise sources corresponding to fine grain and coarse scale turbulence respectively

very close to the exit of the jet, is characterized by nigh frequency noise sources, fine grain turbulence and high velocity shear. In region *B*, at about $5d$ distance from the jet exit, low frequency noise sources prevail as well as large scale eddies. In this context the aerodynamical noise theory indicates that very compact noise sources are inefective [17] the measure of smallness is the acoustic wave length $\lambda$. One may assume for the sake of the argument that sources smaller than $(1/4)\lambda$ are not very effective. On the other hand those larger than $(1/4)\lambda$ are more powerful sound generators. This is illustrated in Fig. 16 for a velocity of sound of 340 m/s. A reduction in the size of the eddies due to a narrowing gap inside the diffuser should contribute to the compactness of the noise sources a situation very different to that of a free jet.

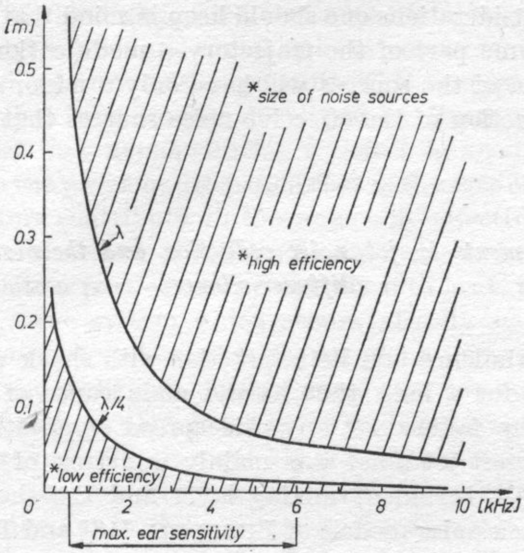


**Fig. 16. The acoustic wave length as a function of the frequency compared to the size of efficient noise sources assumed larger than λ and to the inefficient ones assumed smaller than (1/4) λ**

If one believes in the shear term of Eq. (2) as a real noise source a reduction in the transversal component $v$ along the trajectory and of the sheared gradient $dU/dy$ could contribute to the noise abatement. These two factors occur inside the diffuser because of the narrowing gap and the continuous reduction in the mean flow velocity $U$. The "self noise" term ($b$) in Eq. (2) can be explained in physical terms as an instantaneous pressure rise due to a collision between two adjacent eddies. In a three dimensional flow if the streamlines are strongly diverging transversally to the mean flow direction such collisions between two adjacent eddies should be less frequent thus reducing the "self noise" source intensity. A situation occurring within the diverging part of the radial diffuser.

With reference to the "other sources" ($d$) in the bracket of Eq. (2) and (3) a most powerful contribution to noise generation are vortices crossing a fixed shock wave pattern. Advantage is sough in this diffuser by decreasing the shock wave strength through a system of conical waves instead of plane waves.

Any boundary layer separation causes turbulence and vorticity which is the main noise source particularly if combined with shock waves. It boundary layer separation could be avoided by making the streamlines diverge between themselves due to three-dimensional effect without diverging from the wall as is the case in two-dimensional configurations this could also contribute to a reduction in the generation of noise.

LIGHTHILL's equations (2) and (3) do not explicitly contain effects of viscosity. Its role is still debated it appears that moderate friction combined with small size eddies could be beneficial to reduce the noise level.

In all these considerations one should keep in mind that if real noise sources are active along some part of the trajectory a modification of that trajectory further downstream of the sources will have only a minor effect. It is only by suppression or reduction of the effective noise sources that positive gains may be achieved.

### *4.3 Recent developments in jet noise reduction and their relation to the radial diffuser-silencer*

The role of turbulence and its interaction with shock waves has been recognized in theory for a long time as the main cause of aerodynamic noise supersonic jets. The failure for any widespread application of the existing theories to the aircraft jet noise was mainly due lack of detailed knowledge of the supersonic jet turbulent mixing layer and the shock structure itself. The theoretical shock noise models of LIGHTHILL [18] and RIBNER [19] employ integrals requiring a detailed knowledge of the shock strength, their position and of the turbulent components of the flow related to the stress tensor upstream of each shock cell. It is worth mentioning that according to these theories the "self-noise" source is associated with high pitch while the shear flow is responsible of low pitch noise sources.

On the experimental side interesting new development are to be noted. One of them is the use of a porous centerbody inserted in the jet exit. It has been first suggested Maestrello [20], [21] and afterwards further developed by BAUER [22], KIBENS and WLEZIEN [24]. Although the noise reduction by the porous centerbody in subsonic flow is disputed, a considerable in the noise level has been confirmed in supersonic condition when shock waves in the flow field. The centerbody the shock waves strength and their structure and also does not allow the jet to coalesce and produce focussing of the compression waves. Friction on the centerbody and mixing reduce gradually the energy of the jet without high noise penalty. Also SEINER and NORUM [25] have shown that the jet noise intensity in axi-symmetric flow increases in streamwise direction and reaches a maximum between the third and the sixth shock cell. Similarly TANNA et al. [26] have shown that a major reduction in noise is associated with the elimination of a highly organized shock structure.

It appears that the geometry of the centerbody also modifies the characteristics of the shear layer in such a way as to reduce the noise.

Similarly noise reduction by using a multi-jet suppressor nozzle or corrugated nozzles developed by the Boeing Co. [14] is most likely due to a change in the mixing pattern of the flow and a reduction in the scale of turbulence when the flow crosses a honeycomb-like multitube structure.

It may be also noted that most of the acoustic theories have not taken viscosity into account and its role remains up till now obscure. CANTRELL et al.

[27] and MORFEY [28] have suggested that acoustic energy is not always conserved and that sound sources and sound sinks can occur in regions of flow which is not potential and where viscosity prevails. This concept of acoustic sink in flow with viscosity has been further developed by BECHERT [29] who applied it successfully to jet flow demonstrating a defect in acoustic energy.

It appears from the previous discussion that in the case of the radial diffuser-silencer several factors contribute to the unusually effective noise attenuation and these may be enumerated as follows not in order of importance: i) Initial friction losses dissipate a part of energy directly into heat. ii) The conical spike produces a conical wave system which occurs already at a lower Mach No. than the nozzle. This system is weaker than a plane wave system and because of the closeness of the walls and quickly narrowing gap few shock wave cells can develop. iii) Streamlines diverge while the walls converge beyond the second throat. The waves are embedded in a quickly growing boundary layer. Such a wave system is not prone to be a strong noise source when crossed by the eddies. iv) A monotonic reduction in the gap size in the direction of motion together with flow deceleration reduces the size of the eddies and the turbulence scale as well as the shear stresses. These two factors affect the self noise source as well as the shear noise source and this reduces effectively the low pitch part of the spectrum. v) The mixing pattern is completely altered as compared to the free jet. The presence of the walls tends to dissipate the energy through viscosity into thermal motion. The concept acoustic sink may be important in this context. vi) A great part of the kinetic energy is conserved due to recompression and therefore less is available for acoustic dissipation also low speed flow emerges from the exit.

## 5. Concluding remarks

It should be mentioned that this type of diffuser-silencer conserves energy by recompression and works on a different principle than muffler type nozzles [30]. It is not clear however what role in noise attenuation is played by successful recompression as is the case in this diffuser. Low speed flow at the exit of this silencer makes it not applicable to aircraft to aircraft in flying conditions or to suppress the noise of industrial jets. A design is already in progress to maintain the same internal features only with a higher velocity at the exit. Preliminary tests of this diffuser-silencer on a four stroke engine indicated sound reduction comparable to a standard muffler with the difference however that for higher exit flow velocities the efficiency of the engine increased because of its discharge to a partial vacuum, while with a muffler the efficiency decreases.

More systematic research is required for this promising sound attenuator, and the role of the size of the jet must be assesed.

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