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Acoustic aspects of a radial diffuser(*)

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THIS PAPER describes experimental research on the acoustical aspects of an axially-symmetrical radial diffuser. Tests were made at high subsonic and supersonic speeds at the diffuser entry, using compressed air. The results are analysed from the point of view of the internal flow and Lighthill's theory of sound generated aerodynamically. The outstanding feature of this diffuser is not only a high efficiency in subsonic and supersonic ranges but also extreme shortness and powerful sound attenuating capacity. The noise level of a supersonic nozzle at $M = 4.0$ was reduced from about 110 dB to 80 dB. Recommendations are made for further development.

Praca przedstawia wyniki doświadczalnych badań zjawisk akustycznych w dyfuzorze radialnym o symetrii osiowej. Badania były prowadzone w zakresie wysokich szybkości poddźwiękowych oraz nadźwiękowych aż do liczby Macha $M = 4{,}0$, przy użyciu sprężonego powietrza. Wyniki są analizowane z punktu widzenia przepływów wewnętrznych oraz teorii Lighhilla dźwięku generowanego aerodynamicznie. Cechą charakterystyczną tego dyfuzora jest nie tylko jego wysoka wydajność aerodynamiczna oraz krótkość, lecz także ogromne tłumienie hałasu aerodynamicznego. Przy liczbie Macha $M = 4{,}0$ natężenie hałasu dzięki użyciu dyfuzora spada ze 110 decybeli do 80 decybeli. Przedstawiane są również sugestie odnośnie do dalszego rozwoju badań w tej dziedzinie

Работа представляет результаты экспериментальных исследований акустических явлений в радиальном диффузоре с осевой симметрией. Исследования проведены в интервале высоких дозвуковых и сверхзвуковых скоростей вплоть к числу Маха $M = 4{,}0$, при использовании сжатого воздуха. Результаты анализируются с точки зрения внутренних течений и теории Лайтхилла звука, генерированного аэродинамически. Характеристическим свойством этого диффузора является не только его высокая аэродинамическая эффективность и короткая длина, но также большое затухание аэродинамического шума. При числе Маха $M = 4{,}0$ интенсивность шума, благодаря использованию диффузора, уменьшается с 110 децибеллов к 80 децибеллам. Представлены тоже предположения, касающиеся дальнейшего развития исследований в этой области.

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 appeared 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 the attention of prominent scientists since the early 1950's. On the theoretical side the first break-through in the understanding

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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 sides 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 expectations. They have not yet reached sufficient refinement to be 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, and they 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 is new to the knowledge of the authors of this paper. Classical supersonic diffusers tend to diminish the noise due to the reduction of the kinetic energy of the flow. Since 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

Figure 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 diamater 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

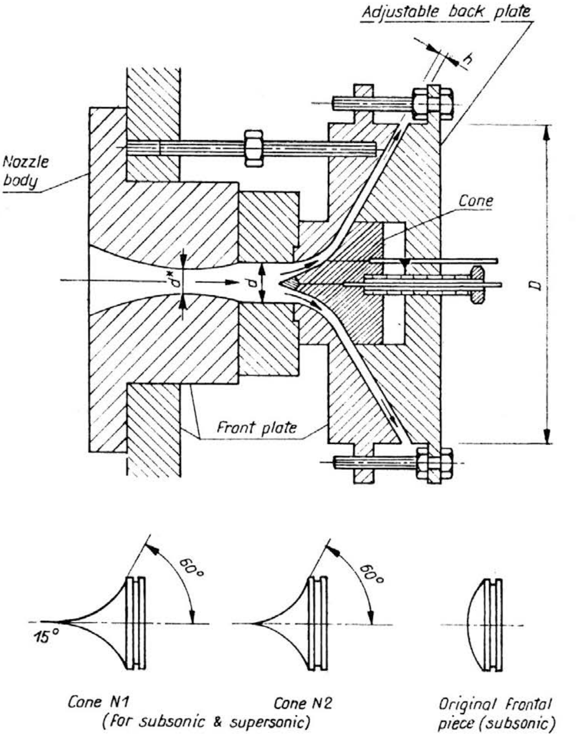

FIG. 1. A cross section of the radial diffuser with typical conical spikes and a low speed rounded head.

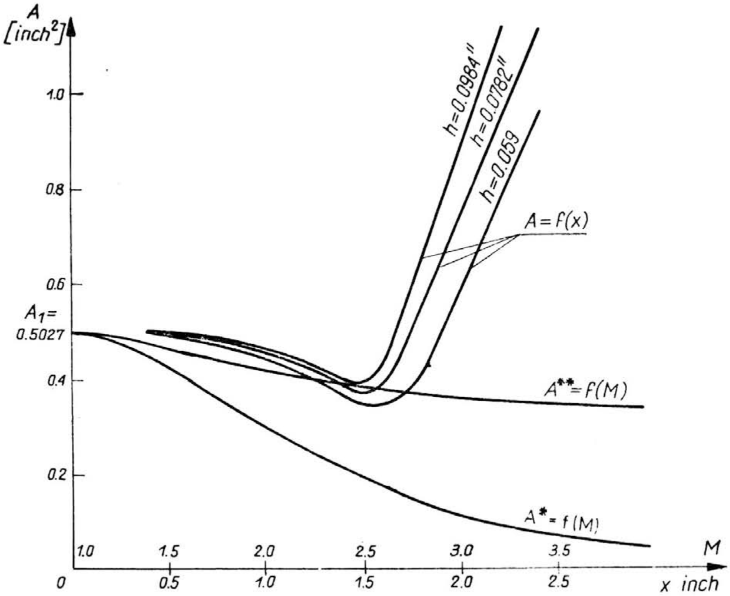

FIG. 2. The internal cross section variation for the conical spike No. 1 with A^* and A^{**} as $f(M)$ drawn in.

spike. Three typical conical spikes are also shown, as well as a rounded dome-shaped piece used originally for subsonic tests.

Figure 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 a function of the Mach number are also drawn for all the supersonic nozzles tested in this study. It has 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 at which the diffuser was operating efficiently was $h = 0.06''$ reducing approximately the area ratio quoted above by half.

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 (see below).

The aerodynamic characteristics of this diffuser are described separately [15]. It may be noted, however, that the efficiency of some configurations compares with the best

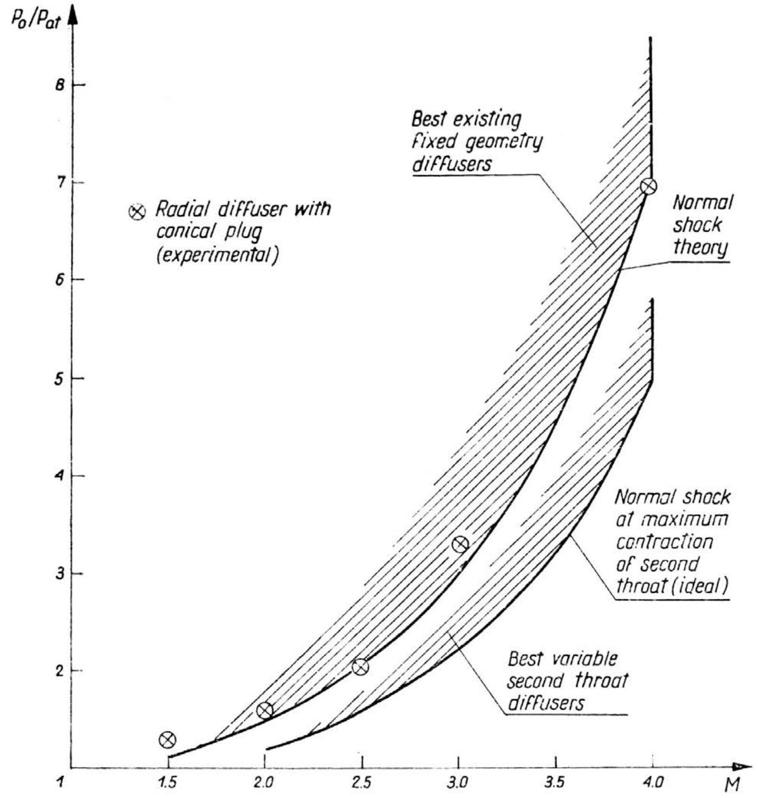

FIG. 3. Experimental results of the diffuser efficiency for a range of tested Mach Numbers given in terms of P_0/P_{atm}.

"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 P_0 to the atmosphere P_{atm} as functions of the Mach No.

2.2. Acoustic tests

The tests were performed in the High Speed Laboratory of the University of Calgary. All the acoustical measurements were made in the near-field of the jet (see Fig. 5). 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.

Standard diffusers for supersonic nozzles are open to the atmosphere and their noise level is marginally different from a nozzle without diffuser, thus comparisons of the noise level of a nozzle with this radial diffuser and a nozzle without it are valid (see Fig. 8).

The apparatus used for the acoustic tests was a Bruel and Kjaer Precision Integrating Sound Level Meter, Type 2218 combined with a frequency analyzer. Also a Bruel and 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 extending this range 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 not include the noise of the high pressure system required to run the nozzle.

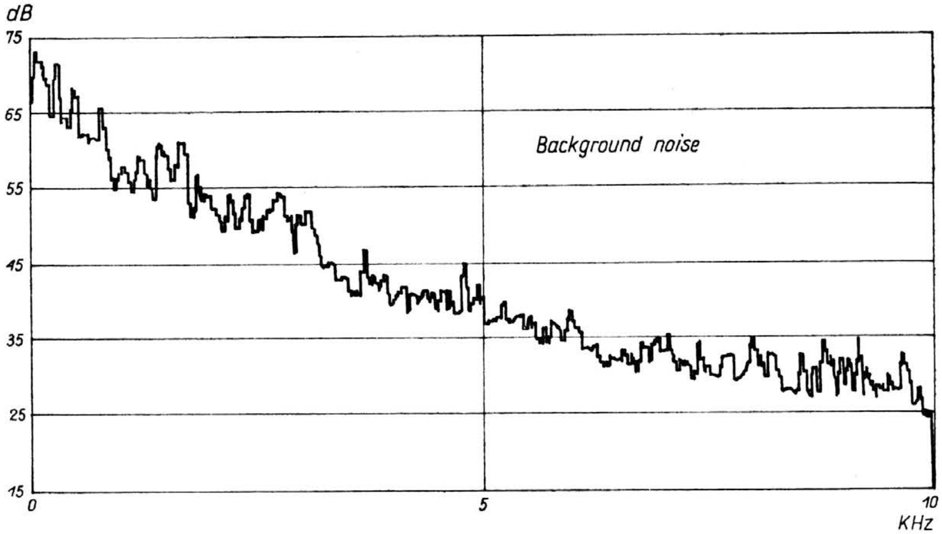

Fig. 4. Measured spectrum of the typical laboratory background noise.

Figure 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 a diffuser the highest noise level was 125 dB when on the nozzle axis. A typical "valley" of noise intensity was not recorded in the front of the nozzle which

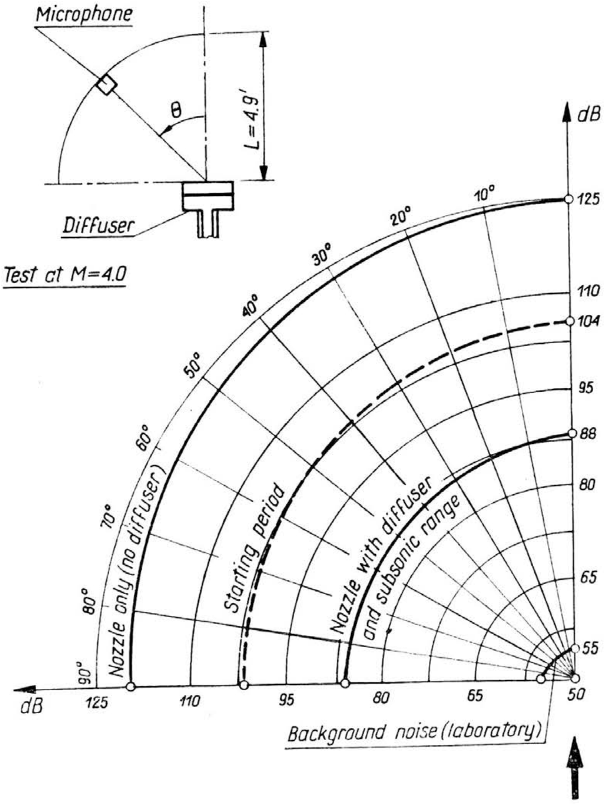

FIG. 5. Directional effects of measured noise intensity. Nozzle with diffuser, (normal operation), starting period and nozzle only. $M = 4.0$ and approximately $M = 0.8$.

may be partly due to the bell of the diffuser 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. In these conditions 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 level was reduced 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.

Figure 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).

Figure 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.

In 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

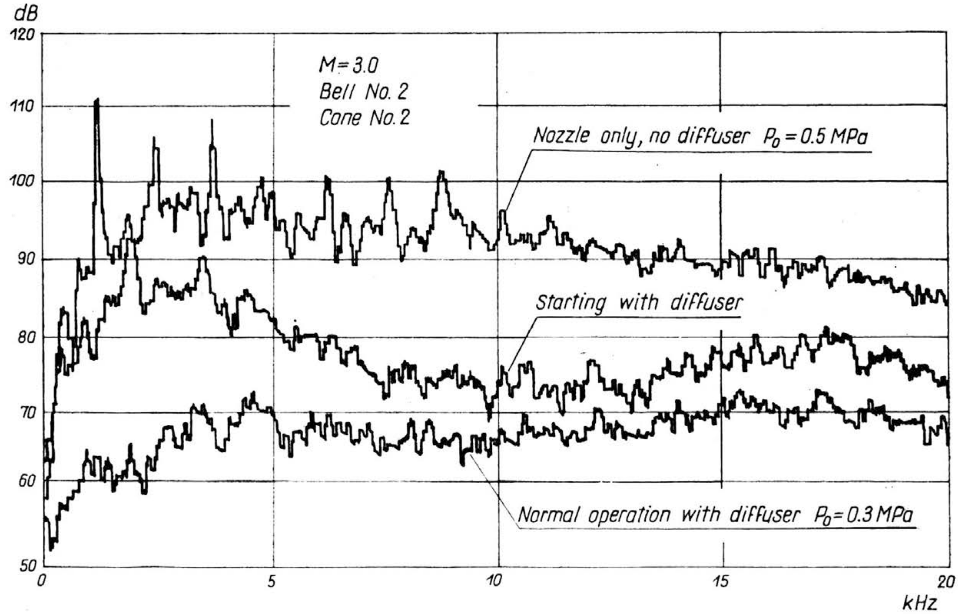

FIG. 6. Acoustic spectra of the diffuser-silencer in normal operation during starting procedure and of the nozzle only at $M = 3.0$.

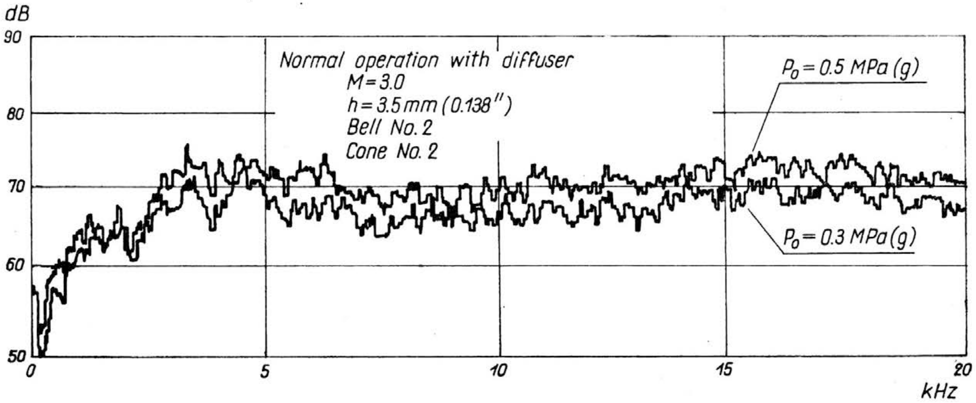

FIG. 7. The effect of varying the reservoir pressure during normal operation at $M = 3.0$.

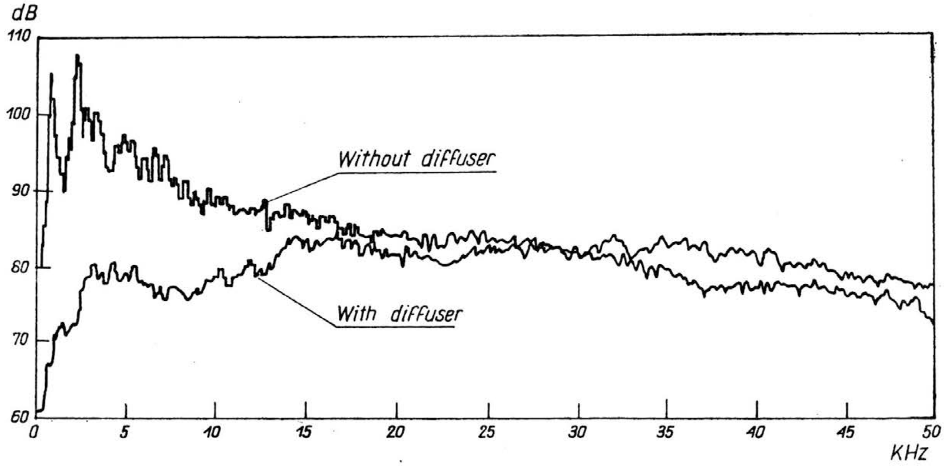

FIG. 8. Aerodynamic noise spectra at $M = 3.0$ with and without the diffuser for an extended range of frequencies up to 50 kHz.

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.

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 vaious 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 energy combined, leading to the expression

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

This function is tabulated in Ref. [31] (Table B, pp. 614–620) and can be used for adiabatic duct flow with friction and shock waves. (For more details, see pp. 104 and 170 of the above reference). The basic assumptions in developing this function are: i) the mass flow up to the throat A where the flow is isentropic equals mass flow downstream of the throat where the flow is adiabatic only. ii) Equating the two mass flows results in the tabulated Mach Number function. iii) If the $(A/A^*)(P/P_0)$ product can be estimated, a unique average Mach No. $\overline{M}$ is obtained (called sometimes the Fanno Mach No.) which takes into consideration all the adiabatic losses including shock waves, boundary layer effects, etc.

It follows that as A is a known cross-section area in the duct with friction at any specific station, A^* is a known throat area of the nozzle, P_0 is a known plenum chamber pressure and P is a measured static pressure at a given station. The above function can be evaluated and the mean Mach No. $\overline{M}$ estimated at, say, section A. This Mach No. is related through a hypothetic recompression from P to $\overline{P}_0$ which is isentropic, thus $\Big(\frac{\overline{P}_0}{P} = \left(1+\frac{\gamma-1}{2}\overline{M}^2\right)^{\frac{\gamma}{\gamma-1}}$ where $\overline{P}_0$ is the average total pressure at the given section. Thus the variation of total pressure can be estimated by measuring static pressures only, what is experimentally much easier then making pitot traverses in an inaccessible and curved passage.

In this way the mean Mach No. $\overline{M}$ and mean local total pressures $\overline{P}_0$ were computed and are shown in Figs. 11 and 12, respectively.

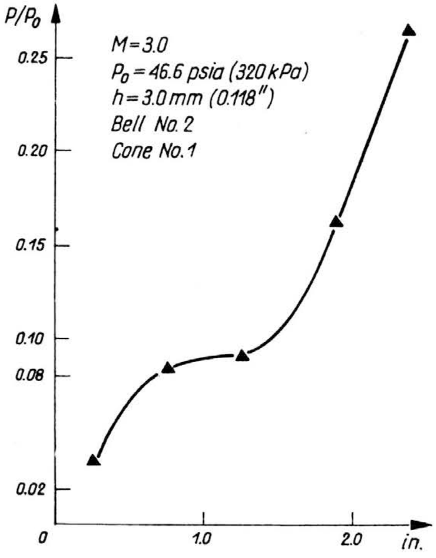

FIG. 9. Static pressure distribution in the diffuser at $M = 3.0$.

In Fig. 9 the distribution is shown of the static pressures 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 $X = 1.4''$), presumably downstream of a weak shock system located behind 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 Mo. (Fanno Mach No.) inside the diffuser is shown in Fig. 11 and the drop in the average value of $\overline{P}_0$ in Fig. 12. As the tip of the conical spike is very close to the nozzle exit (see Fig. 13), the biggest drop of the average Mach No. $\overline{M}$ and local mean total pressure $\overline{P}_0$ occurs in the early passage of flow through the

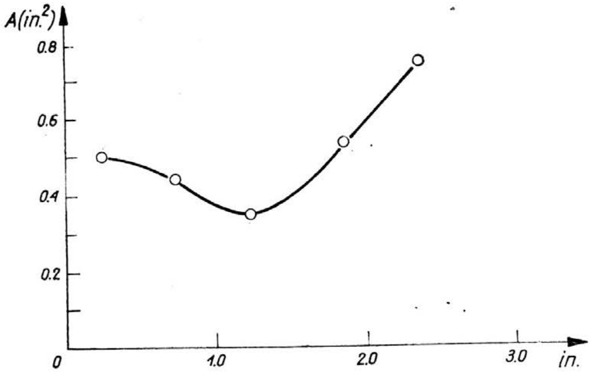

FIG. 10. Area distribution and position of the second throat for $h = 3$ mm Bell No. 2, Cone No. 1.

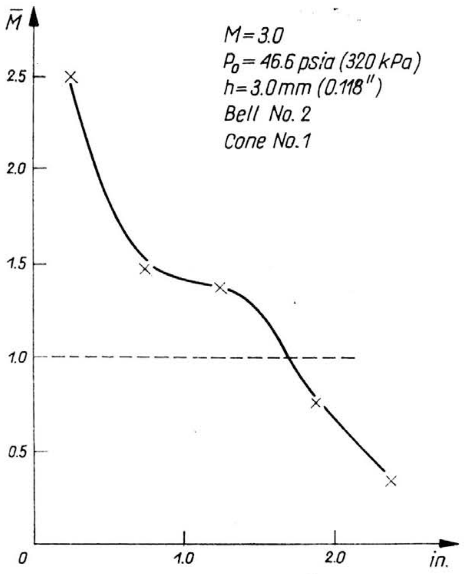

FIG. 11. Mean Mach No. distribution for nominal Mach No. $M = 3.0$.

conical wave system induced by the spike. It appears that this continuous wave system produces a continuous increase in entropy i.e. transformation of the kinetic energy directly into heat, probably is not generating acoustical energy. Also the stability of the conical wave system helps not to produce acoustic disturbances usually associated with wave oscillations. One notes that the Mach No. crosses $M = 1.0$ downstream of the second throat. Its location is shown in Fig. 10.

Figure 13 shows the relative position of the conical spike [for the gap $h = 0.12$ inch (3.0 mm)] and static pressure taps position.

A coarse turbulence is associated with low frequency aerodynamical 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

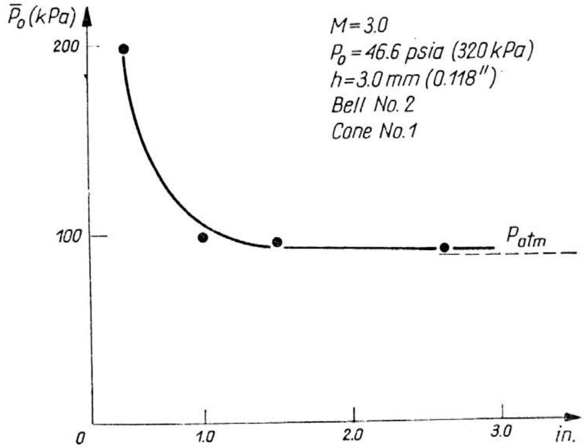

FIG. 12. The variation of the mean P_0 in the diffuser at $M = 3.0$ for a reservoir pressure $P_0 = 320$ kPa.

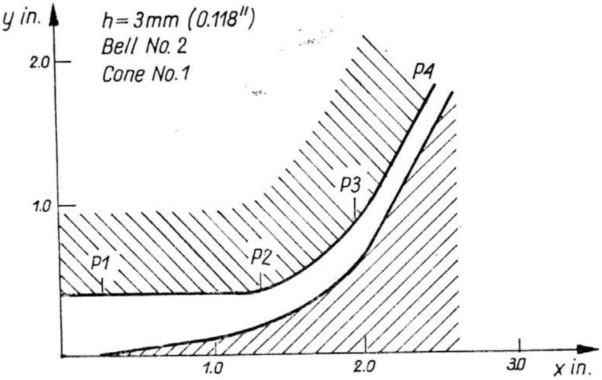

FIG. 13. The position of the conical spike No. 1 relative to the nozzle exit plane at $X = 0.0$ and of the pressure taps.

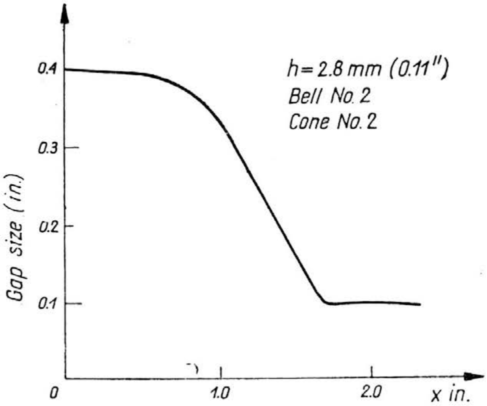

FIG. 14. The gap size inside the diffuser assumed initially as radius of the nozzle for $h = 2.8$ mm (0.11 inch).

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 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

Although an annular jet is dealt with in this study and Lighthill's theories do not apply to such a configuration, nevertheless a qualitative discussion of the acoustic characteristics of this diffuser in the light of Lighthill's theory is valuable because the noise generation mechanism is similar.

It appears that on the 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 the aerodynamic noise theory has been achieved by a formal but rather arbitrary source identification. Lighthill's [1] full equation restated in pressure terms is

$$\left[\frac{1}{c_0^2}\frac{\partial^2}{\partial t^2}-\nabla^2\right]P=\frac{\partial^2 \varrho u_i u_j}{\partial x_i \partial x_j}-\frac{\partial^2}{\partial t^2}\left(\varrho-\frac{P}{c_0^2}\right), \tag{4.1}$$

where c_0 is the velocity of sound of the ambient air. Outside the jet the R. H. S. of this equation vanishes and to the first order (4.1) becomes a homogeneous 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 terms are also not negligible. Further expansion of Eq. (4.1) yields out of other possibilities:

$$\left[\frac{1}{c_0^2}\frac{\partial^2}{\partial t^2}-\nabla^2\right]P=\underbrace{2\varrho\frac{\partial U}{\partial y}\frac{\partial v}{\partial x}}_{a}+\underbrace{\varrho\frac{\partial^2 u_i u_j}{\partial x_i \partial x_j}}_{b}-\underbrace{\frac{1}{c^2}\frac{D^2 p}{Dt^2}+\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2}}_{c}+\underbrace{[\text{others}]}_{d}. \tag{4.2}$$

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 form very similar to the often quoted Lilley's wave equation:

$$\frac{1}{c^2}\frac{D^2p}{Dt^2} - \nabla^2 p - 2\varrho\frac{\partial U}{\partial y}\frac{\partial v}{\partial x} = \varrho\frac{\partial^2 u_i u_j}{\partial x_i \partial x_j} + [\text{others}] \tag{4.3}$$

which is identical with Eq. (4.2) after rearranging the terms. One observes above that the wave convection term (*c*) and the mean flow shear term appearing 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 a "real" noise source and not merely "mathematically equivalent".

This short discussion emphasizes the previous observations that the same results can be obtained without identifying exactly the sources of noise. It has been also observed by RIBNER [16] that the sources of noise in Eq. (4.2) are not unique and many more source term expansions 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

Although more parametric studies are required to assess the main causes of the unusual acoustic behaviour of this diffuser, some probable causes will be discussed here without attempting to list them in their order of importance.

The experimental scientist who looks for guidance on noise abatement from the general equations like Eqs. (4.2) and (4.3) can expect much less in this area than his fluid mechanics counterpart who uses the Navier Stokes equation for boundary layer problems. It appears that there is a general consensus that the "self noise" term (*b*) in Eq. (4.2) 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. Figure 15 gives a schematic view of a high speed jet without wave patterns, in which two regions are distinguished. Region *A*, very close to the exit of the jet, is characterized by high frequency noise sources, fine grain turbulence and high velocity shear. In region *B*, at about 5 *d* distance from the jet exit, low frequency noise sources prevail as well as large scale eddies. In this

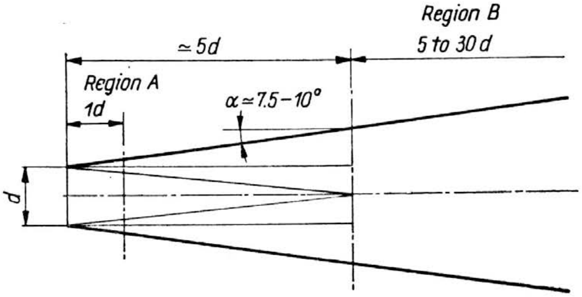

FIG. 15. Diagram of a subsonic jet with regions *A* and *B* related to high frequency and low frequency noise sources corresponding to fine grain and coarse scale turbulence, respectively. High speed jet. *Region* A. High velocity shear. Fine grain turbulence. High frequency noise sources. *Region* B. Low frequency noise sources, large scale eddies.

context the aerodynamical noise theory indicates that very compact noise sources are ineffective [17], the measure of smallness is the acoustic wave length λ. 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.

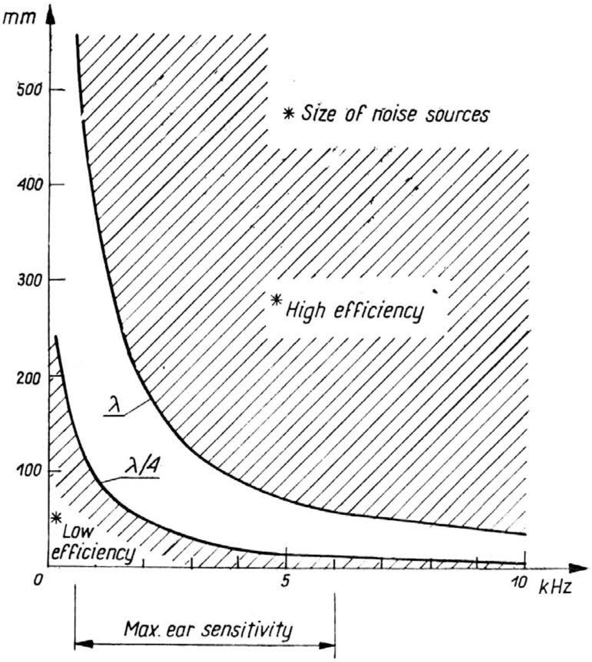

FIG. 16. The acoustic wave length as a function of the frequency compared to the size of efficient noise sources assumed larger than λ and to the inefficient ones assumed smaller than $1/4\ \lambda$.

If one believes in the shear term of Eq. (4.2) 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. (4.2) 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. This situation occurs within the diverging part of the radial diffuser.

With reference to the "other sources" (*d*) in the brackets of Eqs. (4.2) and (4.3) a most powerful contribution to noise generation are vortices crossing a fixed shock wave pattern. Advantage is sought in this diffuser by decreasing the shock wave strength through a system of conical waves instead of plane waves.

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

Lighthill's equations (4.2) and (4.3) do not explicitly contain the effects of viscosity. Its role is still debated but 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 in supersonic jets. The failure for any widespread application of the existing theories to the aircraft jet noise was mainly due to 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 "selfnoise" source is associated with high pitch, while the shear flow is responsible for low pitch noise sources.

On the experimental side interesting new developments are to be noted. One of them is the use of a porous centerbody inserted in the jet exit. It was first suggested by 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 reduction in the noise level has been confirmed in supersonic condition when shock waves appear in the flow field. The centerbody reduces the shock waves strength and their structure and also does not allow the jet too 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 stremwise 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 accociated with the elimination of a highly organized shock structure.

It appears that the geometry of the centrebody 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 patterns of the flow and a reduction in the scale of turbulence when the flow crosses a honeycomb-like multitube structure.

It may also be 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] [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 flows 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 but not in order of importance: i) Initial friction losses dissipate a part of energy directly into heat and reduce the Mach No. ii) The conical spike produces a conical wave system which occurs already at a Mach No. lower 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 of "acoustic sink" may be important in this context. vi) A great part of the kinetic energy is conserved due to recompression and therefore is less 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 the muffler type silencer [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 aicrcraft 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 increases 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 assessed.

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