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Technical Evaluation Report on AGARD Specialists' Meeting on "Aircraft Engine Noise and Sonic Boom"

by
John O. Powers and M. Pianko

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TECHNICAL EVALUATION REPORT

on

AGARD SPECIALISTS' MEETING

on

"AIRCRAFT ENGINE NOISE AND SONIC BOOM"

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by

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The Proceedings of this Joint Fluid Dynamics Panel and Propulsion and Energetics Panel (33rd) Meeting, which was held at the Franco-German Research Institute in Saint-Louis, France, from 27 to 30 May 1969, are published as AGARD Conference Proceedings No. 42.

AGARD Advisory Report 22, also published with the same title as the present report, is the technical evaluation report written by Professor W.R. Sears of Cornell University on behalf of the Fluid Dynamics Panel.

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1. INTRODUCTION

The Joint Meeting of the Fluid Dynamics and the Propulsion and Energetics Panels held in Saint-Louis, France, from 27 to 30 May 1969, to discuss the problems of aircraft engine noise and sonic boom was an essential and timely action. During the 1960's, the urban acoustic environmental levels have been increasing at the alarming rate of roughly one decibel per year and world-wide cooperation will be required to halt further escalation. The noise sources discussed in the May AGARD Meeting were those generated because of civil and/or military transportation requirements and, therefore, fall into the category of "necessary noise". As such, the challenge to the technical community is quite clear; the transportation modes must be developed while exercising all available acoustic techniques to ensure that the impact on the acoustic environment is a minimum.

The meeting provided an excellent technical exchange among members of the NATO nations. The subjects of aircraft noise generation and aircraft noise reduction techniques were discussed in detail. As could be anticipated, the major manufacturing nations contributed the bulk of the presentations but active participation was shared by all. Thirteen papers discussed aircraft noise sources mechanisms and source reduction, while two papers discussed acoustic path control, and three were directed towards the impact on the receiver. The heavy balance of presentations, toward the subject of the noise source, is not considered by the present reviewers to represent an optimum approach to the problems of noise control, for either civil or military air transportation. It is believed that this problem should be approached in a systematic manner using an appropriate combination of the avenues available to the acoustician; namely, by source control, path control, and by compensating for the impact on the receiver. Because of this rationale, the evaluation of the aircraft engine noise portion of this AGARD Meeting will be presented in terms of that approach.

2. GENERAL REMARKS

The first paper of the conference by Lilley (1)* was intended to be introductory in nature. The author, after a brief introduction to aircraft noise related problems, presented a detailed mathematical discussion of a unified treatment of aerodynamic noise. The eloquence of the mathematical model was exhibited by its ability to relate to both the problems of sonic boom and jet noise. As is typical of problems dealing with turbulent fluid flows, recourse to much experimental data is necessary to utilize the mathematical method to obtain useful results. An assessment of this paper was complicated by the use of many symbols which were not explicit enough and the mathematic formulations which were not always distinct or homogeneous. The thrust of the introductory paper, however, was to present a status report on the current theoretical state-of-the-art which was defined as being "still in its infancy". As an introduction to the physical mechanisms of aerodynamic noise, this paper was somewhat deficient, but the deficiency was rapidly offset by the subsequent papers.

The aircraft noise sources which are discussed in this review were related to the core engine flow or to the rotating engine components. The mechanisms of the core engine flow sources were explored with regard to internal and external noise generation. As such, problems at both extremes of the Lighthill velocity range were considered and physical explanations for the departure from the conventional eight power velocity law were advanced. The papers dealing with rotating machinery noise sources, in general, reflected some of the recent dramatic advances in reduction or control of these sources. The implementation of these advances in nacelle acoustic liner technology is expected to be comparable to the impact of the high bypass engine with respect to aircraft engine noise reduction. These noise reduction procedures, which are quite powerful, will not negate the need for residual noise control by operational procedures or by acoustic land use planning as long as the primary source of aircraft propulsion is turbojet machinery.

2.1 Aircraft Noise Source

A physical example of the practical combination of the many aircraft noise sources was found in the closing paper of the conference by Bair (34). While it was very limited in detail, it gave an indication of the potential magnitude of the military and civil air transport noise problems of the very near future. The paper, describing a few noise measurements of the C-5A, clearly indicated that unless additional quieting techniques are incorporated in the design of large aircraft, the resultant noise levels will be excessive. The C-5A represents an upper bound in size of the next generation of subsonic aircraft but is, in no sense, an advanced acoustic design. The 8 to 1 bypass ratio is the most acoustically favorable design feature which apparently resulted in an appreciable lowering of the jet noise levels and causes the noise signature to be dominated by the forward radiated fan noise. The latter characteristic is manifested by the rapid decrease in noise level after the maximum level of a flyover. This shortening of the flyover duration will be reflected when translating the Perceived Noise Levels to Effective Perceived Noise Levels in accordance with the recently published FAA noise regulation (see A under REFERENCES). However, the presented C-5A measured noise levels, when extrapolated to the appropriate measurement locations, are not likely to meet the required levels of that regulation.

2.1.1 Noise Prediction

Acoustic design for the purpose of compliance with aircraft noise certification regulations is developing as a requirement for most countries engaged in air commerce. It, therefore, becomes necessary to develop prediction techniques of sufficient accuracy so that the aircraft performance character-

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* Nos. in brackets are the paper reference nos. as in AGARD Conference Proceedings No. 42 and as listed under REFERENCES at the end of this report.

istics are not degraded for the purpose of ensuring an acoustic design margin. Two papers (9) and (21) were responsive to the need for advanced prediction techniques. The first paper by Kobrynski (9) addressed the problem of prediction of aircraft jet noise. This semi-empirical study attempted to correlate theoretical jet noise estimates for fixed and moving jets with a large amount of experimental data. Formula considered to be suitable for the estimation of jet noise to meet certification requirements were presented. The correlations for different polar angles apparently were quite good; however, it was stated that the Doppler effect was not properly incorporated. The future users of the method would be well advised to explore this factor before more generalized application of the method is contemplated. The second paper discussing prediction techniques presented by Duponchel (21) considered the total problem of noise estimation for turbojet and turbofan aircraft. The method was presented in the form of design curves based on results taken from existing aircraft. These design curves encompassed the parameters necessary to estimate forward and aft radiated fan and compressor noise, as well as jet noise, including coaxial jets in a fixed or moving frame of reference. The indicated accuracy of prediction was of the order of $\pm$ 3 decibels which is truly an accomplishment for such a generalized method. The final parametric curve of the presentation related the difference between EPNdB and PNdB to the distance from the aircraft. This correlation, by chance, was very similar to a correlation prepared by members of the United States Aircraft Industry Association for use in noise certification discussions. While this curve and the complete prediction method appear to be successful for the present generation low bypass ratio turbofan or turbojet aircraft, it is believed that the validity of application to the new generation, advanced technology aircraft is yet to be established.

2.1.2 Jet Noise Source

The majority of the papers presented dealing with noise source mechanism addressed the generation of jet noise, related to both subsonic and supersonic jet flows. Ffowcs Williams (8), presented an eloquent and highly mathematical analysis of the acoustic radiation from a moving jet. The basic formulation of the expression for the radiation intensity was developed as an extension of his previous theoretical works and as such provides a complete analytical description of the parameters involved. Considerable manipulation of the initial expression for the intensity was necessary for application to a specific conceptual model before a reduced expression was obtained which explicitly demonstrated the influence of aircraft speed on the source radiation. In retrospect, the reviewers believe that the author could have enhanced the impact of his presentation by more closely relating his analysis to potential physical advances in the area of jet noise control.

An excellent experimental paper by Lush (31) did, in fact, attempt to relate the theoretical analysis of Lighthill (B under REFERENCES) and Ffowcs Williams (8) to model jet test data taken for large variation of the experimental parameters involved. The correlation necessarily required important assumptions with respect to a number of little known parameters such as - e, the anisotrophy factor, α, the turbulence frequency ratio, and the most important, Q, the ratio of strength of lateral to randomly orientated quadrupoles. It was pointed out by the authors that lack of knowledge of these parameters can result in differences in the normalized frequency spectrum and it is to be speculated that additional correlations would improve the understanding of the relative contributions of the parameters involved. While the general correlation is quite good when compared with classical presentations of jet acoustic data, it would appear that the modified Doppler factor - F - was varied over a limited range with respect to the emission direction factor -θ- and that further data would be desirable.

The subject of jet noise mechanisms was considered by Gordon (6) in a most interesting perspective. The analysis dealt with the influence of up-stream turbulence on the noise produced by a low speed jet. The significance of this problem is obviously related to the current generation of new technology engines which, as a result of the high bypass ratios, are operating at considerably reduced jet velocities. To realize the full acoustic promise of the low flow velocities, it would be beneficial if the acoustic radiation continued to be reduced in accordance with an eighth power velocity law. Experimental evidence unfortunately indicates that there is a transition to a sixth power velocity law with the attendant higher sound power levels. The author very explicitly demonstrated that this results from the presence of internal dipole noise sources which may be correlated with the pressure losses in the system. It is anticipated that these experimental results and their correlations will be useful in defining studies of these problems and will eventually lead to a more complete realization of the acoustic potential of the high bypass ratio aircraft engine.

Martlew (7) demonstrated how the jet shock wave structure was manifested in the far field as the noise mechanism of a jet flow operating at supercritical speeds. The demonstration was shown as the result of model tests in anachoic chamber with appropriate measurements exhibiting clearly the effect of pressure ratio and directionability of the acoustic radiation. Using subcritical jet flow test results as a base, it was possible to show the distinction between the pure discrete frequency acoustic production phenomenon referred to as "screech" and the phenomenon referred to as "forward throw" which is manifested by the increase in level of the high frequency part of the spectra. The later, in turn, was a strong function of angle from the jet axis, increasing with that angle. The correlation of the frequency of peak sound pressure level with a parameter related to the jet velocity and the shock cell length was indeed an interesting approach. The author concluded that this correlation supported the hypothesis that the increase in high frequency noise is attributable to convection of disturbances through the regularly spaced shock system. This noise mechanism was shown to be as much as 10 dB greater than that of the subcritical jet and was further shown to be reduced by approximately 5 dB by the use of a plug nozzle operating at an intermediate supercritical pressure ratio.

A second paper dealing with jet flows operating at supercritical speeds presented by Westley (23) concentrated on the mechanism of "screech". This paper was an extension of a previous paper given in the 1968 Toronto Symposium on Aerodynamic Noise and while the first paper dealt with the two symmetrical and spiral modes of jet oscillations, the second dealt primarily with the symmetrical mode. The authors described a unique experimental arrangement which could be utilized to obtain instantaneous distribution of screech pressure. Applications of their techniques could be used to define near field pressure distribution for investigations related to acoustic fatigue. The experimental results indicated that the third and fourth shock cells produced the strongest acoustic radiation. In addition to the pressure distribution data, an excellent schlieren movie of a jet operating in a screech condition provided further visual insight into the shock cell oscillation mechanism.

2.1.3 Fan and Compressor Noise Source

While the majority of the papers addressing noise source mechanisms dealt with jet noise, by contrast, the few papers dealing with fan and compressor noise mechanisms did contain some discussion of methods of reducing the resulting acoustic radiation. The noise reduction methods were based on the comparatively recent and rapidly advancing technology of nacelle acoustic treatment. The potential of acoustic absorbing techniques is being exploited in most of the emerging generation of aircraft designs and, hopefully, will contribute appreciably to the reduction of airport noise problems.

An interesting qualitative description of the noise generation associated with the shock wave system emanating from a supersonic tip speed fan was presented by Kester (19). The phenomenon has been variously described as "buzz-saw" or "combination tone" noise and is postulated to be related to the lack of uniformity of the shock wave system on the different blades of a fan. It was noted by the author that a short length of acoustic treatment in the inlet duct liner which was installed near the fan blade tips yielded as much as a 15dB reduction in the combination tone noise. This reduction, however, was accomplished without a corresponding reduction in fan discrete frequency noise which was attributed to the fact that the latter noise source is distributed over the entire fan inlet annulus as distinguished from the tip localized generation of the combination tone noise.

In a general discussion of acoustic absorber investigations Webber (17) presented a description of the installations and procedures used by Rolls-Royce to study methods of controlling the fan and compressor noise. The experimental facilities described appear to represent the most advanced equipment available for the optimization of acoustic duct design. The extent of this absorber development activity reflects the concern of the Rolls-Royce Company for the reduction of the currently dominant fan, compressor, and turbine noise. The dominance of these noise sources was further demonstrated by the comparison presented of the component noise levels of current and new technology bypass engines. From the limited experimental results presented, it was indicated that the acoustic performance of several materials was quite similar and that other criterion, such as cost effectiveness, would be the basis for final material selection. While the paper was quite interesting in a descriptive sense, it would have been beneficial to illustrate in a more quantitative manner some of the acoustic design considerations, such as for example, the influence of flow velocity on attenuation.

The implementation of engine quieting by the application of nacelle acoustic treatment techniques was the subject of the paper presented by Rekos (35). This paper described an on-going NASA program with the Boeing and McDonnell Douglas Companies to develop acoustic treatment configurations for the B-707 and the DC-8 aircraft. The author presented the considerations related to material and design detail selections as well as several potential inlet configurations. Ground test results indicated that the noise reductions in the landing configuration may be as much as 13 to 16 PNdB for the B-707, and 9 to 11 PNdB for the DC-8. These objectives appear to be realizable for these two JT3D powered aircraft because the jet floor is sufficiently below the fan and compressor noise levels. Since the presentation of the paper, it has been reported that the reduction levels of the ground tests were also realized in flight test. The excellent success of this program in demonstrating the acoustic feasibility of these treatment configurations represents a significant step towards the quieting of existing aircraft. Considerations of economic viability and consistency with airworthiness requirements remain to be demonstrated; however, before the practicability of further activity related to treatment of existing aircraft can be established.

2.1.4 Design For Noise Source Control

The presentation by Morgan (18) was based on the concept that "quiet" should be continually factored into the design of engines and aircraft from the time of conception to the time of delivery of the flight test article. The methods of implementing this design concept at the General Electric Company were discussed by the authors in a very general review paper. The General Electric acoustic facilities, theoretical and experimental programs, and test results from ground and flight experiments were all shown as contributing elements of an integrated procedure for obtaining the maximum suppression of the important noise engine sources. The correlations between estimated and measured component noise generation appeared to be quite remarkable as was the correlation between predicted and measured over-flight aircraft noise. As is often the case, the reviewers must speculate if the cases presented were just well chosen or if the procedures can be relied upon to give consistently good results.

A second paper by Rekos (33) dealing with a complete acoustic design, described the NASA "Quiet Engine" program. The concept of the program was to develop the appropriate engine cycle using all available suppression techniques. Accordingly, the high bypass ratio was used to minimize jet noise and then the remaining problems were to minimize fan and compressor noise. This, in turn, was accomplished by eliminating inlet guide vanes, reducing fan tip speeds and increasing spacing between rotors and outlet stators. The objectives of this program, which seem very ambitious, were to realize 16 to 24 PNdB reduction of the jet noise and 15 to 17 PNdB reduction of the aft radiated fan noise when compared to the JT3D engine. It is interesting to point out that the "quiet engines" of this program will be of the thrust category of the JT3D, but the acoustic technology, if successfully demonstrated in hardware tests, will be generally applicable to engines of other thrust ratings.

2.2 Acoustic Path Control

The control of aircraft noise by alteration of the acoustic path between the source and the receiver is a technique which is daily employed in airline operations. It was, therefore, somewhat surprising that only two papers addressed the subject directly and only one other paper touched briefly on the subject. Some of the path control techniques, such as those related to air traffic routing, are applicable only to local situations and, therefore, are of limited general interest. Other techniques, such as the power reduction takeoff and the two-segment glide slope approach procedure mentioned in (22), apparently do offer considerable potential, with respect to noise reduction, and further exploitation of this potential is to be encouraged.

Of the two papers dealing in detail with the acoustic path, the paper by Thomas (10), considered the influence of ground reflections on the measurement of aircraft noise. The development was an appropriate combination of theoretical and experimental studies yielding frequency dependent reflection coefficients and/or acoustic correction factors. Using these factors, jet measurements in the presence of a ground plane could be corrected for all positions of the measuring microphone relative to the jet source. The experimental correlation of the point source jet measurements made in an anachoic chamber followed the theoretical curves remarkably well and clearly exhibited the enhancement and cancelling phenomenon of the direct and reflected acoustic signals.

The second paper dealing with the acoustic path control was that of Pianko (24) who is a co-author of the present conference review. Accordingly, the following comments should be attributed to the other author of this review for objectivity. Pianko's discussion was addressed primarily to the use of power cutback as a means of noise reduction. The mathematical development of the expressions for the thrust reduction point associated with optimum noise reduction indicated an applied knowledge of the practical problems involved. It was shown that the location of the cutback point with respect to a measuring station was very significant and that large variations in the measured values could be realized with only small changes in the location of cutback. The noise reduction potential during power cut was also evaluated for changes in several operational and configurational parameters. A final point made by the author which was of considerable interest was that the apparent acoustic benefits from power cutback for an overthrusted aircraft were evaluated to be numerically larger when expressed in terms of PNdB rather than in terms of EPNdB.

2.3 Acoustic Impact on Receiver

The subject of the acoustic impact on the ground receiver was accorded a minimum of attention in the AGARD Conference. Why this should be the case is not clear to the reviewers since control of the land usage in the airport vicinage is considered to be an effective means of avoiding aircraft noise problems. Actually, the paper by Hoover and Cochran (3), presented by Powers, contained the only discussion of airport designs for noise control purposes. That paper, while limited in technical depth, contained many interesting ideas and general acoustic considerations. The subject of aircraft certification as planned in the United States was reviewed and present noise levels were compared to the future noise limits. It was indicated that reductions of aircraft noise levels in excess of 10 EPNdB are to be expected from the coming generation of large gross weight subsonic aircraft. It was further indicated that the supersonic transport aircraft would be in a different category from a certification standpoint because of the different operational and noise characteristics. Some additional discussions of the SST acoustic characteristics, for example, quantitative results dealing with the noise reduction possible from a sonic throat in the engine inlet or a tradeoff evaluation of configurational considerations which reduced noise by improving airport performance while reducing range performance, would have increased the technical benefit of the paper. The final considerations of the paper were directed to airport land use planning and suggested several means of implementing land use programs. These programs will become necessary to accommodate the residual noise after application of all other noise reduction techniques; however, the cost involved for existing airports may be prohibitive and sensible acoustic land use plans should be instituted before airport construction is initiated.

The remaining paper related to the acoustic receiver was presented by Hay (22) and was devoted to a detailed discussion of the electronics of a real time analysis. The instrumentation described was capable of analyzing the one-third octave bands of the acoustic signal in real time and averaging spectral data over prescribed time increments. As described signals could be instantaneously recorded, stored, and played back, as desired, or transmitted to remote stations. While the accuracy of the system was a function of many variables, the system appeared to have significant value when used to analyze aircraft acoustic signals.

3. CONCLUSIONS

Based on the papers presented at this AGARD Meeting on Aircraft Noise, it was apparent that there was an appreciable awareness, among the members of the technical community, of the severity of this problem. The concentration of the participants was on techniques for reduction of aircraft noise at the source. There appears to be a reasonable resource of knowledge on basic engine design parameters which may be manipulated to optimize "quiet" in design and, more specifically, there have been many recent advances in the field of nacelle acoustic treatment which can be included in future designs. The field of jet noise acoustics has been the subject of many sophisticated analyses; however, it is obvious that much basic work is in need to increase the knowledge and understanding of jet acoustic mechanism in the sub and super Lighthill flow velocity regions. Not only is understanding of the mechanisms needed, but means of altering this acoustic source to achieve significant noise reduction is essential. These two flow velocity regions are most important in relation to the problems of the high bypass ratio and the supersonic turbojet engines. If means of lowering the noise generation at these jet speeds cannot be found, we will have defined the acoustic barrier or truly the lower bounds for aircraft noise generation.

4. RECOMMENDATIONS

This AGARD Meeting on Aircraft Noise was a successful interchange of much valuable technical information. It is believed that the NATO Member Nations were able to develop a realistic assessment for the over-all current state of aircraft acoustic art. Hopefully, the interchanges can lead to some degree of standardization of terminology and, hence, an improvement of communication between the technical workers in this important, though somewhat specialized, field.

It is recommended that a future meeting, after a suitable number of years - say three to five - could readdress the subject and, using the present meeting as a base, could evaluate the progress made in the intervening time. Surely, the current escalation of the noise levels in the environment will have been stopped and hopefully there will be a deescalation of those noise levels.

As a final recommendation, it would be desirable at a future assemblage of this eminent group of acousticians, that an improvement in the balance of the papers could be realized. To obtain solutions to aircraft acoustic problems, a proper balance of improvements at the source, path, and receiver is surely essential.

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