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Technical Evaluation Report on the AGARD Fluid Dynamics Panel Symposium on Fluid Dynamics of Jets with Applications to V/STOL

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AGARD Advisory Report No.187

TECHNICAL EVALUATION REPORT

on the

AGARD FLUID DYNAMICS PANEL SYMPOSIUM

on

FLUID DYNAMICS OF JETS WITH APPLICATIONS TO V/STOL

by

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This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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1. INTRODUCTION

From 2 to 5 November 1981 the AGARD Fluid Dynamics Panel organized a symposium on "Fluid Dynamics of Jets with applications to V/STOL" at the Fundaçao Calouste Gulbenkian, Lisbon, Portugal. Co-chairmen of the programme committee of the symposium were Prof. A.D. Young and Dr. B. Quinn.

31 papers, including five review papers were grouped into six sessions :

I Jet interactions with neighbouring surfaces
II Jet structure and development
III Windtunnel simulation of flow field, forces moments
IV Injection and thrust augmentation
V Theoretical models and their assessment
VI Invited brief contributions.

The papers are published in AGARD conference proceedings no. 308. This document being already available for a thorough study of the papers, the purpose of this report is limited to a brief overall analysis of the papers presented as well as a survey of the conclusions and recommendations that can be deduced therefrom. Many of the comments in this technical evaluation report have already been made by the author in his summary remarks at the end of the symposium.

2. GENERAL OBSERVATIONS

The majority of the papers presented at the symposium described experimental investigations of an exploratory nature, aiming at a better understanding of the different types of complex three-dimensional turbulent flow phenomena that are associated with jets. On the other hand only a few papers reported on activities in the field of the development of prediction methods.

The papers on experimental investigations were practically all from universities. The large national research institutes and the industries hardly contributed to the symposium. It is quite usual that the universities are engaged in the type of exploratory experiments reported at the symposium. The national research institutes generally concentrate on experiments that are set up particularly as a check on theoretical prediction methods. The latter type of experiment usually asks for a lot of details and very high accuracy and they are consequently more expensive in general.

Obviously, there is still a large need for exploratory experimental investigations on V/STOL aerodynamics. In other words the progress made in the field of V/STOL aerodynamics has not been very impressive so far.

The last meeting of the Fluid Dynamics Panel on V/STOL aerodynamics was held at Delft University in 1974. The general feeling at that meeting was that the situation in the field of research on V/STOL aerodynamics was far from promising. The majority of the papers at the 1974 symposium reported on research that was carried out quite some time before the meeting and on projects that had already been stopped at that moment. It was stated that the basic flow phenomena were well understood, but that one was still far away from sufficiently accurate theoretical prediction methods.

The fuel crisis of 1974 further diminished the interest in civil V/STOL applications. Also the activities on military V/STOL aircraft projects decreased. In Europe only the U.K. kept their interest in military V/STOL aircraft with the further development of the Harrier in co-operation with McDonnell Douglas. The activities in the U.S. were also limited. Apart from the work on the Harrier the only recent activity that resulted in prototype aircraft was the STOL transport project, which as it looks now, will probably not be continued. There seems to be a renewed interest nowadays however for V/STOL aircraft designed to operate from damage runways and from smaller ships as was mentioned at the symposium in the paper by Roberts and Anderson (29).

The absence of V/STOL projects of course decreased the budgets that were made available for research in this field and consequently the extent of the research activities also in aerodynamics. This happened especially in Europe where, particularly in France and Germany, the research on V/STOL aerodynamics came to an almost complete standstill. What has been put forward at this symposium reflects this situation. It is not surprising therefore that the progress on V/STOL aerodynamics has not been very encouraging.

Fortunately, aircraft designers in general and designers of V/STOL aircraft in particular are able to make reasonably good aerodynamic designs with only a minimum of design tools in the form of theoretical prediction methods and an experimental data base in hand. Aerodynamic design of V/STOL aircraft is still more art than science today.

As far as the experimental data base is concerned, the problem is that the number of variables and options, and therefore the number of possible shapes and parameters in the aerodynamic design is so large that such an experimental data base with enough adequate information for the designer is very hard to build up.

The designer of V/STOL aircraft is also facing a lack of powerful theoretical prediction methods. Most of the prediction methods are based on potential flow methods using empirical input to represent the propulsive flow characteristics. The existing prediction methods are very limited in their range of valid application and in the extent of their verification with experimental results.

The designer of V/STOL aircraft is obviously in a much less comfortable position than the designer of conventional aircraft who nowadays has reasonably accurate prediction methods in hand that are based on a combination of potential flow calculations and viscous flow boundary layer type calculations with additional modelling of the interaction of these two. A very important aspect of the modern design procedures for conventional aircraft is the fact that some of the methods can be used in an inverse way, which makes it possible to find the aircraft geometry for a given desired pressure distribution, and consequently to really optimize the shape of the aircraft. Such inverse methods will be unattainable in the near future for V/STOL aircraft.

The symposium showed that there are different feelings about the importance of turbulence in the description of V/STOL flow fields. Bradbury (1) in his general review suggests that turbulent mixing is not an important characteristic in the VTOL jet interference in transition and that an adequate description of the flow is given by a doublet distribution along the jet path which is obtained in an empirical way, the doublet strength being directly related to the deflection of the jet.

The suggestion of Bradbury (1) is probably correct if one is interested only in the effect of the jet on the outer potential flow at large distances from the jet. In these cases the details of the jet itself are not of interest. The deflection of the jet thrust which can be represented by the doublet distribution is the main effect whatever the deflection mechanism may be, at least for an initial jet angle of ninety degrees. The entrainment, to be represented by a sink distribution, in such a case has a smaller effect. Nevertheless the addition of the entrainment in the model can make the difference between reasonable agreement and good agreement.

For smaller initial jet angles the effect of entrainment will however become more important and if one is interested in the details of the jet, for instance because it hits a lifting surface, turbulent mixing is of course the dominating effect and has to be included in the description of the flow. A strong point for prediction models including turbulence is that the jet path is given by the model and does not have to be obtained from experimental data.

3. JET INTERACTIONS WITH NEIGHBOURING SURFACES

A detailed review of the different positive and negative jet interference effects for modern transport aircraft and military V/STOL aircraft was given by Barche (2), who points at the lack of full scale engine test data to replace the simplified assumptions used for model tests. The importance of jet nozzle velocity profile and flow angle distribution on the development of the jet was also indicated by Bradbury (1).

An interesting experiment was described in the paper by Borges and Viegas (3) who studied the shear stress field produced by single and multiple circular jets impinging on a plane surface whereby an erosion technique using sand particles was employed to evaluate the shear stress distribution.

Araûjo, Durão and Firmino (5) also investigated experimentally the flow characteristics of a jet impinging normally or obliquely on a wall. They used a laser Doppler anemometer to mesure mean and fluctuating velocity components.

Another application of the laser Doppler anemometer technique was reported by Catalano, Morton and Humphris (7). They describe an experimental investigation of an upper surface blowing configuration. The paper gives very detailed information on the effects of both a flat and a curved wall on the one, two and three point statistical properties of a co-flowing turbulent jet.

The laser Doppler technique is in principle the best method to investigate the flow in and around jets. The application of conventional measuring techniques with hot wires and pressure probes has serious drawbacks for the types of flow under consideration, where one has to measure mean velocity and turbulence at relatively large distances from a surface. The presence of probes or rakes will, in general, have an important effect in disturbing the flow to be investigated.

This is possibly not unacceptable if one is interested only in a rough description of the flow characteristics, but it is certainly not acceptable for experiments aiming at a very detailed and accurate description of the flow field for instance experiments to be used as a test case for prediction methods. Therefore there is every reason to give much attention to a further development of the laser Doppler technique and to build up adequate experience with the application of it.

The paper by Taylor and Watkins (6) describes an experimental investigation of inclined jets in a cross wind, giving pressure distributions on the flat plate from which the jet originates, the jet path and the total pressure decay along the jet path. In particular attention is given to small jet exhaust angles (15°).

Other papers in this session were those by Bourque (4) on an experimental and theoretical investigation on the interaction of two two-dimensional jets giving the position of the jets and the velocity distributions and by Zacharias (8) on an investigation of afterbody/jet interference comparing the experimentally obtained pressure drag on rotationally symmetric afterbodies with results from calculations using a finite element method and a potential flow model for the jet simulation.

4. JET STRUCTURE AND DEVELOPMENT

Two papers within this session in particular discuss the structure and modelling of turbulent jet flows. The paper by Mathieu and Charnay (9) gives an overview of the literature describing investigations on jets of different types. It is concluded that although many sophisticated experiments have been carried out, the mechanisms inherent in the development of free turbulent flows are still not completely understood. Clarification of the many questions about several aspects of the entrainment process requires further careful investigations.

The paper by Persen (14) discusses a series of very precise experiments performed in the near field of a plane turbulent water-in-water jet. The experimental data are considered in the light of classical and new theoretical assumptions.

Pontikis, Felk and Young (11) describe an experimental investigation on initially planar jets inclined to an external flow. Two configurations have been tested a two-dimensional jet and a finite span jet. Detailed measurements of mean flow and turbulence characteristics have been performed. One of the conclusions of the paper is that the turbulence characteristics and associated entrainment rates are significantly different for the upper and lower halves of the jet and that this can be explained in terms of longitudinal curvature effects. If this is correct it could mean that simple turbulence models will not give an accurate description of curved turbulent jets.

Only one single paper of the symposium deals with the problem of jet acoustics. Neuwerth (13) describes the results of an investigation on the acoustics of externally blown flaps. The importance of ordered turbulent structures to the generation of noise and the possibility of acoustic feedback phenomena are discussed.

The other papers in this session by Parikh (12) and by Khan, Mc Guirk and Whitelaw (10) will be discussed under the sessions on injection and thrust augmentation and on theoretical models and their assessment.

5. WINDTUNNEL SIMULATION OF FLOW FIELD, FORCES MOMENTS

The paper by Kotansky (16) shows how the designer of V/STOL aircraft currently uses a mixture of empirical methods and potential flow methods for the engineering prediction of ground flow fields, induced suckdown and fountain formation for multiple jet VTOL aircraft. The method is quite impressive as an engineering method but still rather primitive compared with the sophisticated methods used nowadays to design conventional aircraft.

The absence of an adequate experimental data base and sophisticated theoretical prediction methods makes the designer of V/STOL aircraft very much dependent on windtunnel testing. In using the windtunnel the designer of V/STOL aircraft is faced however with the problem of how to extrapolate the results of the tests to full scale free flight conditions.

In the case of testing of conventional aircraft the availability of calculation methods plays an important role in the interpretation of windtunnel results and in the extrapolation of those results to full scale data. They are intensively used for the interpretation of differences between free flight test data and windtunnel data. For V/STOL testing this can be a serious problem. The comparison of windtunnel data and flight test data for a V/STOL fighter aircraft was discussed by Haftmann (18).

Windtunnel testing technique itself is rather complicated for V/STOL configurations, as was discussed in the review paper by Margason (15). It is shown that relatively small variations in model geometry can have a large effect. This indicates the need for testing on large models.

The problem of wall interference effects for V/STOL windtunnel testing hardly obtained any attention at the symposium. Obviously there is not much work under way to report on. The subject has been studied quite intensively during the fifties and sixties but a reliable method of correcting V/STOL model test results is still not available. The important phenomena are the non-linear behaviour of the wall effect due to the influence of the tunnel walls on the trajectories of the jets and the complete breakdown of the test section flow with jets impinging on the walls.

These phenomena make the problem more complicated than wall interference for CTOL-model testing where in fact quite some activity is going on nowadays. Much work has to be done in the area of V/STOL wall interference. For instance careful comparative tests with some standard model in a range of windtunnels equiped for V/STOL testing would be a useful exercise as indicated by Bradbury (1) in his review paper.

Kalemaris (17) reported on static tests on models of different size of a twin turbofan V/STOL aircraft. It is shown that if the details of the airframe are accurately simulated the static tests on smaller scale models give good results.

6. INJECTION AND THRUST AUGMENTATION

A detailed description of the state of the art in the field of thrust augmenting ejectors was given in the survey paper by Quinn (19), who concludes that our knowledge of the fluid dynamics of jets mixing in a confined region is still rather poor.

The applicability of two-dimensional boundary layer methods based on eddy viscosity turbulence modelling and of two-dimensional integral methods is considered to be very limited. Three-dimensional calculation methods using $K-\varepsilon$ turbulence model equations have not been very successful so far.

The use of simple one-dimensional prediction methods presumes access to a broad data base. It is concluded however that the available experimental data do not give the information that is needed to design high performance V/STOL ejectors.

Several papers dealt with experimental investigations aiming at an improvement of the performance of ejectors by introducing a time dependency into the flow to increase the mixing rate.

Parikh (12) reported on an experiment showing that a significant enhancement of the mixing can be obtained for a confined jet when it is pulsed at an organ pipe resonant frequency of the confined tube. The paper by Viets (21) also describes the large effect that acoustic resonance can have on the performance of ejectors. The paper by Binder and Didelle (22) deals with the effect of forced pulsations and flapping motions. It is pointed out that careful considerations on overall efficiency have to take into account additional losses and power requirements for the generation of the unsteady jet.

Optimization of this type of ejector is completely dependent on experiments. Quasi-steady theories of turbulence will quite certainly fail to predict such flows. This point has been indicated several times during the symposium as an area of further study.

Other papers within this section were those by Lepretre and Portier (23) reporting on an experiment related to the development of a jet engine thrust vectoring device based on the Coanda effect and by Mignosi (20) on the optimization of an ejector system for a windtunnel. Riviello, Murolo and Torella (24) reported on ejector optimization for a turboprop and a turbojet engine.

7. THEORETICAL MODELS AND THEIR ASSESSMENT

Two papers, by Khan, Mc Guirk and Whitelaw (10) and by Baker, Manhardt, Orzechowski and Yen (26) describe numerical solutions for turbulent jets in a crossflow. The development of such methods is considered to be very important because they have at least the potential to bring the prediction methods for V/STOL aerodynamics, particularly the aerodynamics of the transition phase of the flight, to a more sophisticated level.

The investigation by Baker et al (26) deals with the calculation of the near field of a single jet in a crossflow, exhausting from a flat plate using a parabolic approximation of the Navier Stokes equations for the turbulent jet.The method can be considered as a first step to a more detailed and more accurate modelling of this important V/STOL flow problem. The results shown are very impressive. The computational simulations clearly show the experimentally documented features of V/STOL jets. In particular, lateral entrainment, axial vortex pair initiation and inducement of the wake flow into the jet region, opposite to the initial upstream crossflow direction are predicted.

The method developed so far still gives a far from complete description of the entire flow field. However, contrary to the potential flow methods using singularity distributions to represent the jet flow and its entrainment, this method is able to give a detailed description of the flow inside the jet. This is important in particular in those cases where the jet impinges on lifting surfaces such as with blown flaps.

The method of Baker er al (26) does not necessarily give a better prediction of the pressure distribution on the flat plate from which the jet is originating. The method will probably not be able to give an adequate description of the flow in the immediate vicinity of the orifice where the jet interacts with the boundary layer on the plate because the assumptions underlying the parabolic approximation of the Navier Stokes equations are certainly not fulfilled in this region.

The interaction between the jet and the boundary layer on the plate from which the jet originates will probably be small for those cases where the angle of the jet with respect to the outer flow direction is large, that is close to ninety degrees, and the ratio of the jet velocity to the free stream velocity is large, but the effect may be large for smaller angles of the jet and/or smaller velocity ratios.

Another point that is not clear is whether the turbulent jet model and a potential flow model for the outer flow can be coupled in an adequate way in general through an iteration process. It is to be expected that in many cases there will be a weak interaction between the jet flow and the outer flow. In those cases the application of a simple boundary condition will probably be sufficient to obtain a rapid convergence of such an iteration process.

There may however be other flow conditions where there is a strong interaction between the jet flow and the outer flow. Probably in such cases the coupling between the two flow fields has to be performed in an interactive way, through a type of boundary condition as used for strong interaction problems between boundary layers and the outer potential flow around a lifting surface. For a flow with strong interactions such an interactive boundary condition may be a necessary condition to obtain convergence of the iteration process. The flow conditions at smaller jet angles and smaller velocity ratios may be expected to be more critical in this respect.

It is evident that the method developed by Baker et al (26) has its limitations and that even a relatively simple flow as the one considered in the paper can not be described in every detail. For the area close to the orifice probably a less simplified version of the Navier Stokes equations such as the one used by Khan et al (10) has to be applied. Clearly the modelling of the much more complicated flow around practical multiple jet V/STOL aircraft configurations using approximations of the Navier Stokes equations is not attainable in the near future.

The development of adequate turbulence models is one of the main problems in the calculation of jet flows. The problem was mentioned in the paper by Khan et al (10) where it is concluded that in some of the calculations the turbulence modelling was responsible for over-estimating the rate of mixing. On the other hand the experience from boundary layer research shows that this point should not be over-emphasized. The numerical treatment of the flow can also be responsible for discrepancies and the numerical problems will be dependent on the choice of the turbulence model. The application of the K-ϵ model may have disadvantages in this respect.

A discussion on K-ϵ turbulence modelling is given in the paper by Donaldson and Sandri (25) indicating that this model can in principle be extended to take account of the turbulence structure as found in experiments. The need of a better co-operation between modellers and experimentalists is emphasized.

A large effort on the development of numerical methods taking account of the turbulent mixing is of extreme importance in order to make progress in the field of V/STOL aerodynamics. However, it has to be accepted that it will be a long and laborious process to reach a point where these methods can be used in the design of V/STOL aircraft.

In the mean time there is certainly need for a further development of the potential flow methods in which the jets are represented by singularity distributions. Such methods have to be considered as the main tool for the prediction of the aerodynamic chracteristics of V/STOL aircraft in the years to come.

The only paper on the development of potential flow methods for jets in a cross flow was the paper by Walters and Yen (27) describing a modification of the singularity distribution in Wooler's model in order to obtain a better agreement with the pressure distribution on the plate from which a jet normal to a free stream originates.

In developing such potential flow methods it is important to keep in mind that the fact that a better prediction of the pressure distribution on the plate is obtained does not necessarily means that a method gives a better overall description of the flow field. The pressure distribution on the plate is strongly influenced by the interaction between the jet and the boundary layer on the plate, an effect that is not described by a potential flow model. Therefore the pressure distribution on the plate is not necessarily the best yardstick. Also it is to be realized that the singularity distribution used by Walters and Yen (27) is tuned to the case of a jet perpendicular to the undisturbed flow. A further refinement will probably be necessary to give a better prediction of the flow for smaller jet angles.

8. INVITED BRIEF CONTRIBUTIONS

Two papers describe investigations on two-dimensional wall jets. The paper by Gersten, Schultz-Hausmann and Schilawa (28) deals with the theoretical prediction of buoyancy and entrainment effects on hot free jets and wall jets. An integral method is presented to predict the development of laminar and turbulent hot jets. A higher order boundary layer theory is used to predict buoyancy effects on horizontal hot wall jets.

The paper by Krause, Hänel and Hewedy (30) presents the results of studies on two wall jet configurations. Finite difference approximations of the boundary layer equations are compared with experimental results for tangential injection of a jet through a slot in a forward facing step into a turbulent boundary layer. The agreement is good except for the region close to the separation point. The influence of tangential slot injection in flow direction of a jet in an attached boundary layer on the surface pressure distribution as predicted by calculations matching finite-difference solutions of the boundary layer and the outer potential flow are shown for a transonic flow with a shock wave around an airfoil.

The paper by Ransom and Barnes (31) reports on the application of a tracer gas method for the measurement of entrainment of an axisymmetric free jet. Measured values of entrainment are used to compute the interference pressure distribution over a flat surface surrounding the jet.

A summary of a recent symposium of the AGARD Flight Mechanics Panel on the "Impact of Military Applications on Rotorcraft and V/STOL Aircraft Design" (Paris, April 1981) with respect to fixed-wing aircraft is given in the paper by Roberts and Anderson (29). It is emphasized that the performance and operational effectiveness of V/STOL configurations will depend on the successful integration of propulsion and aerodynamics.

9. CONCLUSIONS AND RECOMMENDATIONS

- The successful application of future V/STOL aircraft is dependent on improvements regarding the integration of propulsion and aerodynamics. This requires a more complete understanding of the fluid dynamics of jets.
- The present knowledge of the complex three-dimensional turbulent flow phenomena associated with jets is still very limited. As a consequence the currently applied methods for the prediction of V/STOL aerodynamics are rather primitive compared with the sophisticated methods used to design conventional aircraft.
- The development of numerical solutions for turbulent jets in a cross flow using approximations of the Navier Stokes equations is considered to be important because they have the potential to bring the prediction methods for V/STOL aerodynamics, particularly the aerodynamics of the transition phase of the flight, to a more sophisticated level.
- Much attention should be given to the development of adequate turbulence models for jets. The availability of new experimental techniques and the progress made in numerical mathematics and computer technology makes this possible. Experimental studies combined with efforts to calculate the flow will rapidly advance the understanding of turbulent shear flows and the ability to handle these flows computationally.
- The development of numerical solutions for the flow around multiple jet V/STOL aircraft configurations using approximations of the Navier Stokes equations will be a very long and laborious process. Therefore there is a need also for improvement of the potential flow methods in which the jets are represented by singularity distributions.
- Quantitative predictions of unsteady turbulent ejector flows are far beyond what will be attainable in the near future. Improvement of ejector performance will therefore be largely dependent on experiments. Extension of the experimental data base is essential.

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(6) TAYLOR, P. and WATKINS, D.J. — An investigation of inclined jets in a crosswind

(7) CATALANO, G.D., MORTON, J.B. and HUMPHRIS, R.R. — An experimental investigation of an upper surface blowing configuration

(8) ZACHARIAS, A. — An experimental and theoretical investigation of the interaction between the engine jet and the surrounding flow field with regard to the pressure drag on afterbodies

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(9) MATHIEU, J. and CHARNAY, G. — Structure and development of turbulent jets

(10) KHAN, Z.A., MC GUIRK, J.J. and WHITELAW, J.H. — A row of jets in a crossflow

(11) PONTIKIS, Y., FEIK, R.A. and YOUNG, A.D. — Experimental investigation of initially planar jets inclined to an external flow

(12) PARIKH, P.G. — Resonant entrainment of a confined pulsed jet

(13) NEUWERTH, G — Flow field and noise sources of jet impingement on flaps and ground surface

(14) PERSEN, L.N. — The near field of a plane turbulent jet

Session III - Windtunnel simulation of flow field, forces moments

(15) MARGASON, R.J. — Survey paper : Jet V/STOL wind-tunnel simulation and groundplane effects

(16) KOTANSKY, D.R. — The modelling and prediction of multiple jet VTOL aircraft flow fields in ground effect

(17) KALEMARIS, S.G. — Evaluation of the effects of model scale and test technique on jet-induced effects

(18) HAFTMANN, B. — Jet effects on forces and moments of a V/STOL fighter type aircraft

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(19) QUINN, B — Thrust augmenting ejectors : A review of the application of jet mechanics to V/STOL aircraft propulsion

(20) MIGNOSI, A. — Optimisation theorique et controle experimental d'un injecteur

(21) VIETS, H. — Unsteady ejectors

(22) BINDER, G. and DIDELLE, H. — Improvement of ejector thrust augmentation by pulsating or flapping jets

(23) LEPRETRE, M. et PORTIER, C. — Etude experimentale d'un deviateur de jet

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Session V - Theoretical models and their assessment

(25) DONALDSON, C. duP. and SANDRI, G. — On the inclusion of information on eddy structure in second-order-closure models of turbulent flows

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Session VI - Invited brief contributions

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(29) ROBERTS, L. and ANDERSON, S.B. — V/STOL aircraft and fluid dynamics

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14. Abstract

This report presents an evaluation of the papers presented during the AGARD Fluid Dynamics Panel Symposium on Fluid Dynamics of Jets with Applications to V/STOL held 2–5 November in Lisbon, Portugal. General observations on progress in the understanding of the flow phenomena associated with jets are followed by more specific comments related to the five topical sessions of the meeting: Jet Interactions with Neighboring Surfaces, Jet Structure and Development; Windtunnel Simulation of Flow Field, Forces Moments; Injection and Thrust Augmentation; and Theoretical Models and their Assessment. Conclusions and recommendations for further work drawn from the presentations and discussions at the Symposium are included.

The full text of the 31 papers presented at the Symposium is available as AGARD Conference Proceedings No.308, (ISBN 92-835-0308-2), published in January 1982.

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