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FLUERICS 39: The Fluid Mechanics of Fluidics

February 1977

TR-1798—FLUERICS 39: The Fluid Mechanics of Fluidics, by Tadeusz M. Drzewiecki

U.S. Army Materiel Development and Readiness Command
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Basic flow fields such as forced vortices, stagnation flows, jets, edge tones, weak vortices, partial and full channel flows, and nozzle flows are but a sample of what the fluidics researcher must understand in order to prepare physically meaningful models. Some of the models of fluidic devices where specific treatment of fluid phenomena is presented are discussed in this paper. For example, the coefficient of discharge for planar nozzles has been

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determined and is found to depend on a single nondimensional parameter involving the Reynolds number. The resistance of rectangular channels including the entrance losses is shown to be very adequately determined. By modelling jets in terms of their momentum flux, one can obtain quite accurate results for pressure recovery of fluidic devices wherein the jet is stagnated and turned. Dynamic effects of pneumatic and hydraulic jet flow devices can be modelled by use of lumped parameter concepts such as slug flow and moving jet boundary volumes. These types of analyses are shown to have good agreement with measured characteristics.

FOREWORD

The contents of this paper are essentially the words and slides that the author used in his oral presentation to the American Physical Society at their 28th Annual Meeting (Division of Fluid Dynamics) at the University of Maryland on 25 November 1975.

CONTENTS

FIGURES

1. INTRODUCTION

The subject of fluidics is essentially the mechanization of fluid mechanics to control devices, be they logic gates, sensors, analog amplifiers, power valves, or passive components. Such aspects of basic fluid mechanics as forced vortices, stagnation flows, jets, edge tones, weak vortices, partial and full channel flows, and converging nozzle flows are just some that the fluidics researcher must cope with when he is preparing a physically meaningful model of a fluidic component. To present in one place all the analyses and solutions and flow fields would require a book. Kirshner and Katz[1] is one such repository of information. The purpose of this paper is only to provide the reader with a rudimentary acquaintance with some of the more familiar solution techniques and the degree of accuracy that can be achieved by using such simple methods of modelling. The references quoted here will provide the reader with further information for a detailed study. As such, then, this paper is a synopsis of problem areas and analysis techniques that have led to successful implementation of engineering solutions in fluidic applications.

2. NOZZLE FLOW

In most active fluidic devices, the main flow field is a subsonic submerged jet that is formed in a converging nozzle. Most fluidic amplifiers and gates have characteristics that are strongly dependent on the discharge characteristics of the nozzle. Certainly if a nozzle is long and very resistive, with a low discharge coefficient, then the pressure recovered at the output is low compared with that imposed at the supply plenum. By the same reasoning, the average velocity of a jet emanating from such a nozzle is lower than that from a shorter nozzle; consequently, the transport delay is longer; the phase shift, greater; and the frequency response, lower. In addition, the amount of momentum lost in the nozzle certainly dictates the amount of jet deflection by either a momentum interaction or a pressure field. These arguments then dictate that the discharge characteristic of a converging nozzle be well known.

In most cases, the flow field in a planar fluidic amplifier is laminar in the converging nozzle, so that one can apply a simple superimposed (one for the sides and one for the top and bottom) momentum integral technique to calculate the displacement thickness at the nozzle

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[1] *J. M. Kirshner and S. Katz, Design Theory of Fluidic Components, Academic Press, New York (1975).*

exit. Drzewiecki[2-4] has applied this technique and has found that the results are quite satisfactory as shown in figure 1. This figure shows the discharge coefficients for a large number of different nozzle shapes. The discharge coefficient, c_d, is essentially a function only of a modified Reynolds number. This function was determined by examining the basic form of the solution for c_d.[4,5] The flow out of a nozzle is essentially the inviscid flow out of a nozzle whose area has been reduced by the displacement thickness on all four sides, or

$$c_d = \left(1 - 2\frac{\delta^*}{b_s}\right)\left(1 - 2\frac{\delta^*}{h}\right) , \tag{1}$$

where δ^* is the displacement thickness and b_s is the supply-nozzle width.

The simple momentum integral relationship known as the Karman-Pohlhausen equation defines the momentum thickness, θ, at the nozzle exit,

$$\frac{U_\infty \theta^2}{b_s \nu} = \frac{0.47}{\left[\frac{U\left(x/b_s\right)}{U_\infty}\right]^6} \int_0^{x/b_s} \left[\frac{U(\chi)}{U_\infty}\right]^5 d\chi , \tag{2}$$

where U_∞ is the nozzle exit free-stream velocity; ν is the kinematic viscosity; U is the free-stream, x-direction velocity; x is the coordinate direction, and χ is the dummy variable for the x-direction. If one notes that, at the exit, the static pressure gradient is essentially zero, then the simple relation between the displacement thickness and momentum thickness,

$$\frac{\delta^*}{\theta} = 2.554 , \tag{3}$$

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[2] *T. M. Drzewiecki, Planar Nozzle Discharge Coefficients, Developments in Mechanics, Proceedings of the 13th Midwestern Mechanics Conference, Vol. 7 (August 1973).*

[3] *T. M. Drzewiecki, Fluerics 34. Planar-Nozzle Discharge Coefficients, Harry Diamond Laboratories TM-72-33 (September 1973).*

[4] *T. M. Drzewiecki, Fluerics 37. A General Planar Nozzle Discharge Coefficient Representation, Harry Diamond Laboratories TM-74-5 (August 1974).*

[5] *T. M. Drzewiecki, A Fluid Amplifier Reynolds Number, Proceedings of the Harry Diamond Laboratories Fluidic State-of-the-Art Symposium, Vol. 2 (October 1974).*

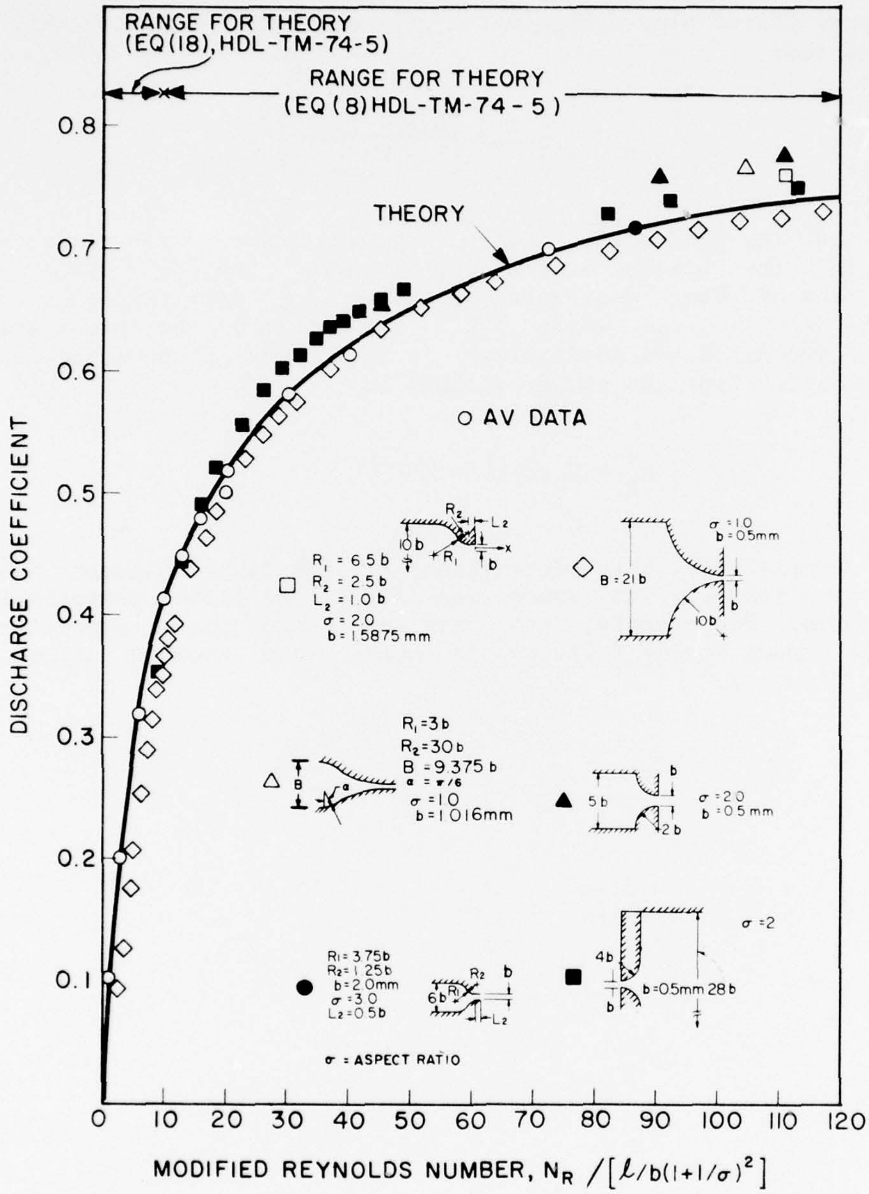

Figure 1. Comparison of theory and data for nozzle discharge coefficient for nozzles of widely varying plan view--low modified Reynolds number (from T. M. Drzewiecki, HDL TM-74-5 (August 1974)).

holds true. After some manipulation as described by Drzewiecki,[4,5] it turns out that

$$c_d \approx 1 - 3.5 \left[\frac{L(1 + 1/\sigma)^2}{N_R}\right]^{\frac{1}{2}}, \tag{4}$$

where L is the equivalent length of the whole nozzle if it were all b_s wide; σ is the nozzle aspect ratio, h/b_s; and $N_R = U_\infty b_s/\nu$. The contribution of most converging sections not more than $10b_s$ long is about $1b_s$; $L \approx 1 + L_{th}$, where L_{th} is the length of the throat straight section.[5] The discharge coefficient is thus almost a universal function of the modified Reynolds number defined as

$$N_R' = N_R/[L(1 + 1/\sigma)^2] \tag{5}$$

Not surprisingly, this definition of the Reynolds number has been found, experimentally, to reduce many fluidic amplifier characteristics to one curve. For example, the gain of proportional amplifiers of different aspect ratios falls on one curve when plotted against N_R' as shown in figure 2.[5]

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[4] *T. M. Drzewiecki, Fluerics 37. A General Planar Nozzle Discharge Coefficient Representation, Harry Diamond Laboratories TM-74-5 (August 1974).*

[5] *T. M. Drzewiecki, A Fluid Amplifier Reynolds Number, Proceedings of the Harry Diamond Laboratories Fluidic State-of-the-Art Symposium, Vol. 2 (October 1974).*

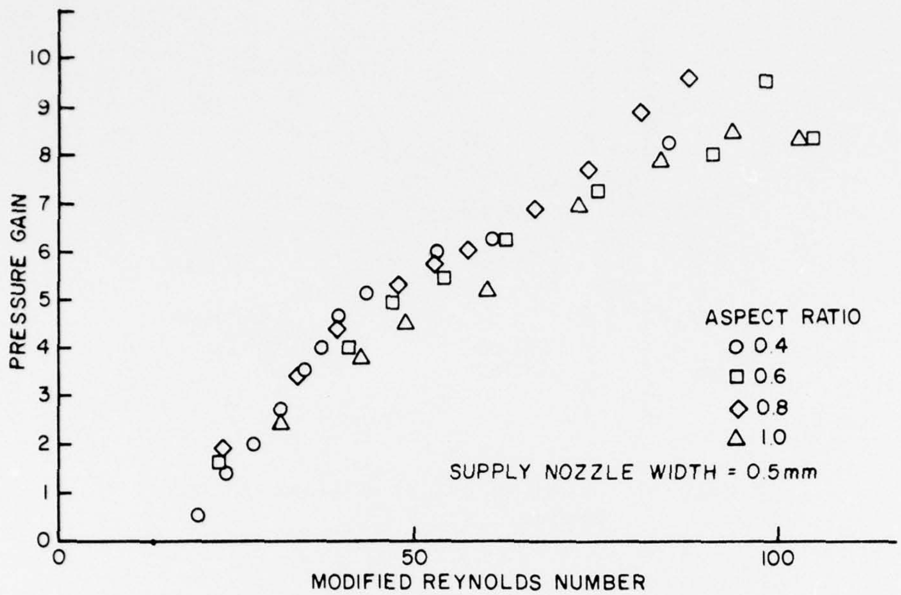

Figure 2. Laminar amplifier gain versus modified Reynolds number (data from F. M. Manion and G. Mon, HDL-TR-1608 (September 1972)).

3. JET WALL-ATTACHMENT DEVICES

Among the first fluidic devices extensively studied were the turbulent jet wall-attachment devices that form the basis for most flueric logic gates available commerically. The jet attachment to either of two or more walls gives an output in the attached position and none at the other. This forms the basis for binary logic. Consider now the flow field in a wall attachment device as shown in figure 3.

Due to the entrainment potential on either side of a planar turbulent jet, the jet attaches to one side wall or the other when perturbed in that direction. An attachment bubble is formed with a forced vortex in it driven by the velocity at the edge of the jet. Such a concept may be used in conjunction with assumptions like a constant radius of curvature jet (at any one instant of time), momentum reduction by splitter interaction with a known (Görtler) profile jet, jet motion due to momentum interaction of two inviscid jets, and control jet momentum reduction by nozzle viscous action. When such a concept is used, quite satisfactory results can be obtained when the input and

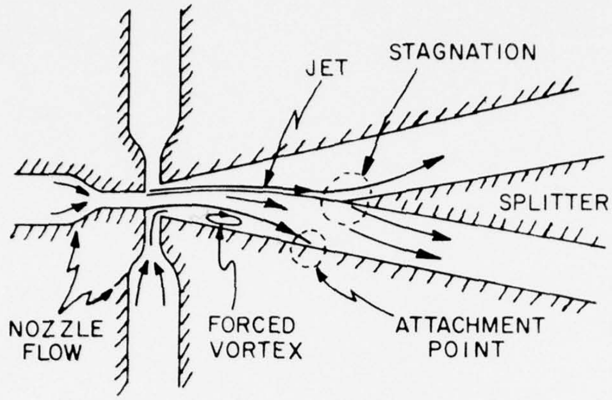

Figure 3. Attached jet in wall-attachment device.

output port characteristics are described.[6,7] Transient response can be modelled by using lumped parameter techniques for the channels and by considering the expanding bubble volume as capacitance, the viscous losses as resistance, and the fluid inertia as inductance.[6]

Figure 4 shows the type of prediction capability using such a theory, as reported in the literature.[7]

More than two attachment walls can be used. The three-dimensional diffuser section, with cross sections that range from triangles to octagons, has been successfully demonstrated by Ernst.[8] These flow patterns represent new variations of wall-attachment problems that must be solved.

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[6] *J. M. Goto and T. M. Drzewiecki, Fluerics 32. An Analytical Model for the Response of Flueric Wall Attachment Amplifiers, Harry Diamond Laboratories TR-1598 (June 1972).*

[7] *T. M. Drzewiecki, Prediction of the Dynamic and Quasi-Static Performance Characteristics of Flueric Wall Attachment Amplifiers, Fluidics Quarterly, 5, No. 2 (April 1973).*

[8] *A. Ernst, Design Method for Sequential Circuits Using Multistable Wall Attachment Elements, Proceedings of the 7th Cranfield Fluidics Conference, Stuttgart, West Germany (November 1975).*

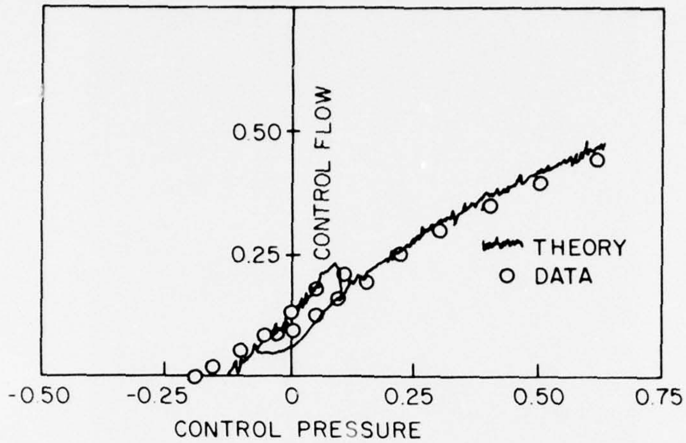

Figure 4. Input characteristic for close wall amplifier.

4. ANALOG JET-DEFLECTION AMPLIFIERS

The other important class of fluidic jet devices is analog jet-deflection amplifiers. Figure 5 is a flow-visualization photograph of the flow field of a laminar proportional amplifier.

The signal is amplified when a small differential pressure is imposed across the jet near its origin and deflects the jet. This deflection causes the high-energy stream to impart more of its energy (in the form of pressure and flow) to one output channel than the other. In the no-outflow condition, an output pressure differential of 25 times the input differential can be achieved.[9] This is thus a pressure gain of 25.

The flow fields can be analyzed in several categories. Nozzle flow is critical for two reasons. Not only must the jet momentum be known, but the stability of the flow requires that an upper limit on the Reynolds number be scrupulously observed. In addition to the nozzle flow (fig. 5), one can observe that the flow in the control channels is essentially full-channel flow through a rectangular duct. Much work has been done on rectangular-channel developing flows, but it has only

[9]*F. M. Manion and G. Mon, Fluerics 33. Design and Staging of Laminar Proportional Amplifiers, Harry Diamond Laboratories TR-1608 (September 1972).*

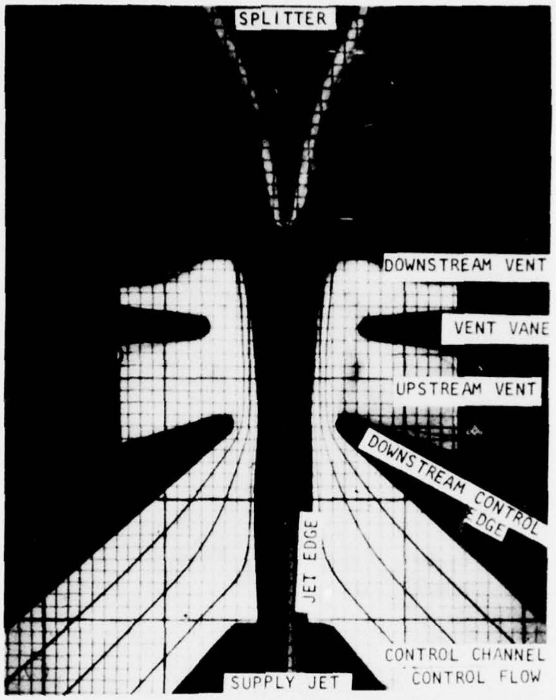

Figure 5. Dye visualization of flow field of typical laminar proportional amplifier.

recently been adapted to fluidics.[1,4,10] There is flow from the control channel through the space between the jet and the downstream edge of the control channel. This flow has been handled in the following way. In the presence of a jet-edge static pressure, the laminar jet profile at zero jet-edge pressure is distended to a shape where the velocity is increased by the value of the static head converted to a dynamic head. When the flow without the static head is subtracted from that with the static head, the flow remaining is the net flow passed through the

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[1] *J. M. Kirshner and S. Katz, Design Theory of Fluidic Components, Academic Press, New York (1975).*

[4] *T. M. Drzewiecki, Fluerics 37. A General Planar Nozzle Discharge Coefficient Representation, Harry Diamond Laboratories TM-74-5 (August 1974).*

[10] *F. M. Manion and T. M. Drzewiecki, Analytical Design of Laminar Proportional Amplifiers, Proceedings of the Harry Diamond Laboratories Fluidic State-of-the-Art Symposium, Vol. 1 (October 1974).*

aperture for a given pressure difference, and so an effective resistance can be defined as the ratio of the pressure drop to that flow.[10] A more classical flow region is that of the jet impinging on the splitter. This region is treated[10] as a uniform flow impinging on a circular cylinder or a wedge. The jet that flows between parallel plates loses momentum flux to viscous drag. When one considers a parabolic velocity profile not unlike the fully developed flow of the Poiseuille case, excellent estimates of the viscous shear and, hence, the momentum loss are obtained. When the jet impinges on the splitter, essentially one of two conditions can occur. (1) The channels are blocked by an external load, and the jet must turn about 90 deg, converting its axial momentum into a recovery pressure. (2) The flow is allowed to pass into the outlet channel, whereupon there is a partial channel inlet flow that eventually becomes a full channel flow some distance downstream. This latter condition still has to be satisfactorily solved, although recent attempts[11] have resulted in relatively good esimates of the driving potential at the receiver face.

As the viscous jet emanates from the nozzle, it entrains the flow from the surroundings due to viscous drag at the free shear boundary. When the effects of viscosity are more pronounced (e.g., when the Reynolds number becomes smaller), the jet entrains more flow; hence, it spreads out more. This spread is shown by the jet-edge dye streaks in figure 6. The photograph on the left is at a modified Reynolds number of ~ 40 ($N_R \approx 1000$); on the right, ~ 80.

As might be surmised, when the jet spreads more, it loses more momentum, imparts less pressure, is smeared out over the receivers, and lowers the gain. These deductions are substantiated by data (fig. 2), and the theoretical model,[10,11] using the ideas presented, also predicts this behavior. Figure 7 shows a typical agreement between the theory and data for the laminar proportional amplifier gain.

In figure 7(a), the gain of one amplifier is shown to increase with N_R; in figure 7(b), the output pressure differential of another amplifier is plotted versus the control pressure differential. The small-signal gain, $d\Delta P_O/d\Delta P_C$, is the slope of this curve, and if a line is drawn at the theoretical slope to twice the centered jet pressure recovery, then this represents the theory. (That is, twice the momentum impinging on the same area results in twice the pressure recovery.) The

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[10]*F. M. Manion and T. M. Drzewiecki, Analytical Design of Laminar Proportional Amplifiers, Proceedings of the Harry Diamond Laboratories Fluidic State-of-the-Art Symposium, Vol. 1 (October 1974).*

[11]*T. M. Drzewiecki, Fluerics 38. A Computer Aided Design Analysis for the Static and Dynamic Port Characteristics of Laminar Proportional Amplifiers, Harry Diamond Laboratories TR-1758 (June 1976).*

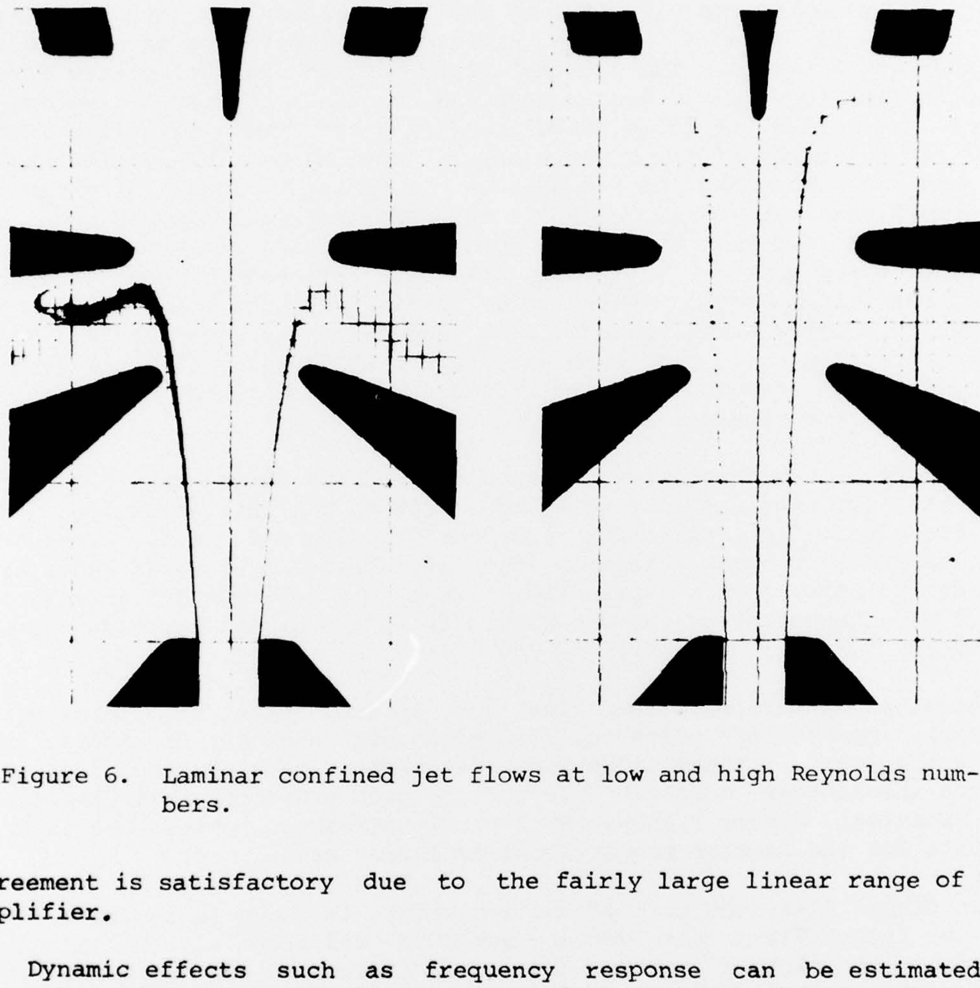

Figure 6. Laminar confined jet flows at low and high Reynolds numbers.

agreement is satisfactory due to the fairly large linear range of the amplifier.

Dynamic effects such as frequency response can be estimated by determining how fast the jet can respond to an input signal. The input channel resistance and lumped or slug-flow inertance couple with the capacitance, due to the change in control channel volume because of jet deflection, to form a resistance-inductance-capacitance second-order system. When additional phase lag is included due to the jet transport time from the control region to the outputs, the response of the jet motion at the outputs is quite adequately described. Figure 8 shows the gain and phase shift as a function of frequency (Bode diagram) as reported by Manion and Drzewiecki.[10]

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[10] *F. M. Manion and T. M. Drzewiecki, Analytical Design of Laminar Proportional Amplifiers, Proceedings of the Harry Diamond Laboratories Fluidic State-of-the-Art Symposium, Vol. 1 (October 1974).*

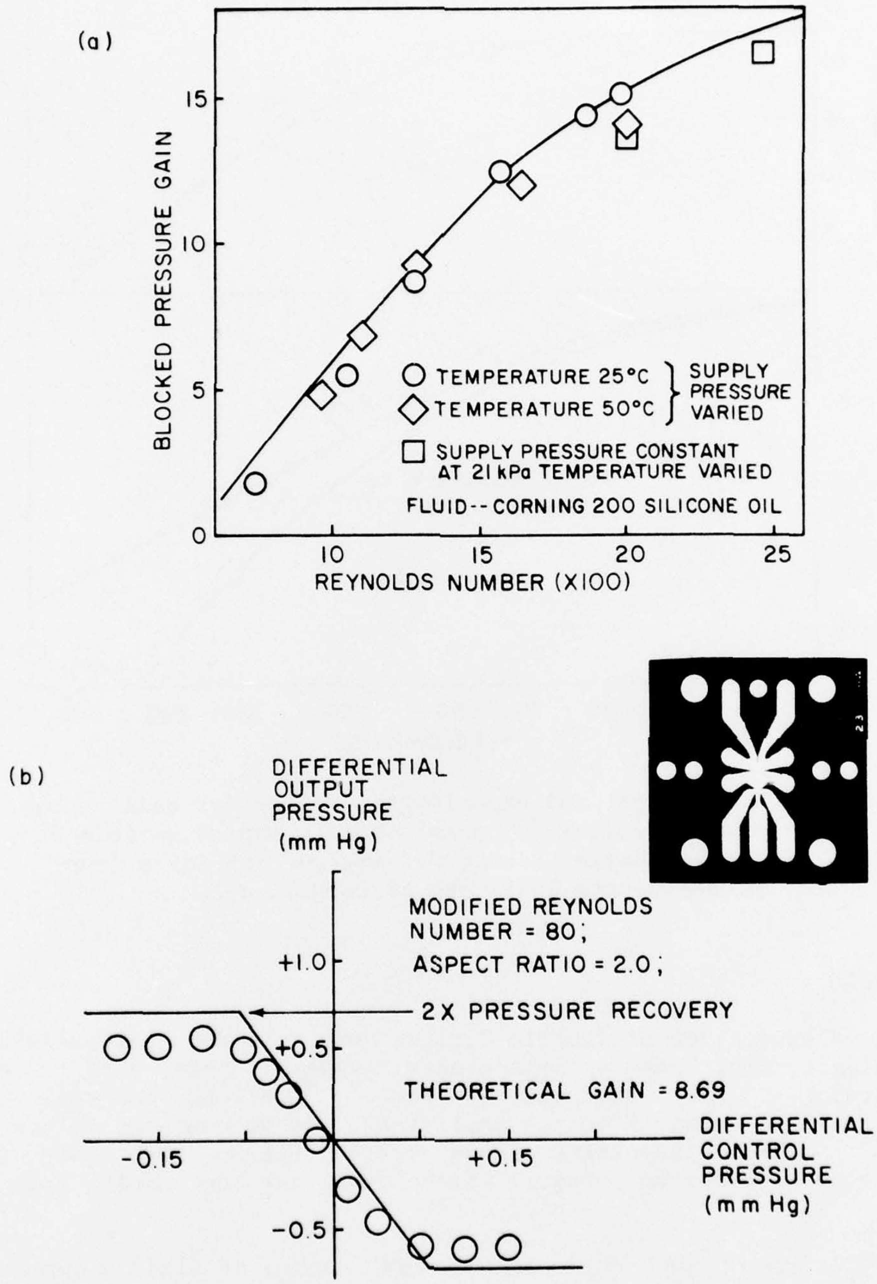

Figure 7. Typical comparisons for (a) amplifier gain of theory and data and (b) amplifier transfer characteristic.

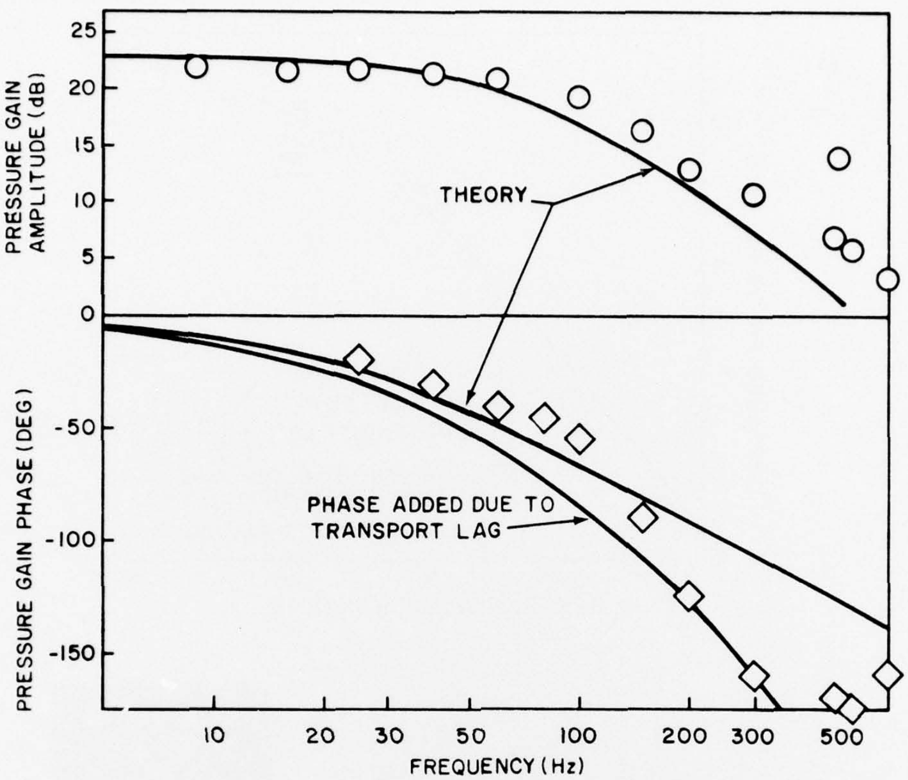

Figure 8. Theoretical and experimental values for gain versus frequency (Bode diagram), nozzle aspect ratio = 2.0, supply-nozzle width = 0.5 mm, red oil (data from Massachusetts Institute of Technology).

5. CLOSURE

Many other classes of fluidic devices have yielded successfully to some analysis. For example, impacting axisymmetric jets, used in impact modulators, have been analyzed by Katz.[1,12] Strong and weak vortex motions form the basis of vortex amplifiers (and diodes) and vortex rate sensors. Solutions involving strong vortex motion have been found mainly by using momentum integral techniques, and the results have been

[1] *J. M. Kirshner and S. Katz, Design Theory of Fluidic Components, Academic Press, New York (1975).*

[12] *S. Katz, A Static Model of Direct and Transverse Impact Modulators, Ph.D. Thesis, Oklahoma State University, Stillwater, OK (July 1970).*

applied to amplifiers and diodes.[13] The vortex rate sensor is a device in which a small angular rotation imparts a tangential velocity to a radial sink flow. The velocity causes the formation of a weak vortex. When momentum integral techniques and solutions of the simplified Navier-Stokes equations have been used, reasonable results have been obtained.[14]

One could go on and on, since flows in complex internal passages range from secondary flows in elbows and nozzles[15] to strong forced vortices in latching vortex wall-attachment amplifiers.[16] This report indicates the types of fluid mechanics problems involved in fluidics and the material available to solve these problems. Solution techniques have come a long way since the advent of the high-speed digital computer and the interactive minicomputers. Solution, however, of complex fluid problems does not have to involve complicated finite difference schemes, but rather can be achieved with a reasonable mixture of control volume, momentum integral, lumped-parameter, and other approximate techniques.

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[13] *D. N. Wormley, A Review of Vortex Diode and Triode Static and Dynamic Design Characteristics, Proceedings of the Harry Diamond Laboratories Fluidic State-of-the-Art Symposium, Vol. 1 (October 1974).*

[14] *A. J. Ostdiek, Viscous Vortex Rate Sensor, Harry Diamond Laboratories TR-1555 (November 1971).*

[15] *R. P. Trask II and T. M. Drzewiecki, Secondary Flows in Jets and Their Effects on Fluidic Components, Harry Diamond Laboratories TM-70-23 (October 1970).*

[16] *T. M. Drzewiecki, Interpretation of Surface Static Pressure Distributions in Fluid Amplifier Applications, Harry Diamond Laboratories TR-1627 (July 1973).*

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(16) T. M. Drzewiecki, Interpretation of Surface Static Pressure Distributions in Fluid Amplifier Applications, Harry Diamond Laboratories TR-1627 (July 1973).

NOMENCLATURE

b_s	Supply-nozzle width, m
c_d	Nozzle discharge coefficient, -
L	Total effective nozzle length divided by b_s, -
L_{th}	Length of nozzle throat divided by b_s, -
N_R	Reynolds number, $(b_s/\nu)\sqrt{2P_s/\rho}$, -
N_R'	Modified Reynolds number, $N_R/[L(1 + 1/\sigma)^2]$
P_c	Control pressure, Pa
P_o	Output pressure, Pa
P_s	Supply (source) pressure, Pa
x	Coordinate direction
y	Coordinate direction
U	Free-stream, x-direction velocity, m/s
U_∞	Nozzle exit free-stream velocity, $\sqrt{2P_s/s} \equiv U_\infty$, m/s
δ^*	Displacement thickness, m
Δ	Change
θ	Momentum thickness,m
ν	Kinematic viscosity, m^2/s
ρ	Fluid density, kg/m^3
σ	Nozzle aspect ratio, h/b_s, -
χ	Dummy variable for x-direction

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