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A STUDY ON PARAMETERS AFFECTING THE PERFORMANCE OF TURBULANCE AMPLIFIERS

by

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ABSTRACT

The turbulance amplifier is one of the two pure digital fluidic elements, and operates on the principle that a laminar jet issuing from a cylindrical tube will remain laminar up to a distance of approximately 100 times the diameter of the tube. If a second tube is placed in the jet path, a part of the laminar flow can be captured by it, to produce an output pressure, this pressure depending on the average velocity of the jet portion intercepted. If a control tube is placed at right angles to the main jet, disturbances can be introduced into the laminar supply jet by fluid streams of lower energy issuing from the control tube. As a result of this, output pressure will decrease in the output tube.

In the work that follows, various parameters, which have pronounced effects on the input-output relations in a turbulance amplifier are considered and in view of dimensional analysis a functional relation between these parameters is obtained.

Investigation of jet flow phenomena is based on Schlichting's solutio for circular, laminar jets in infinite flow fields; various assumptions and approximations are made to apply this solution to jet flow in a finite field-turbulance amplifiers. The analytic study of mixing of jets is based on momentum conservation principle at the point of impinge of control and supply jets. Assumptions and approximations made are verified partially by a series of experiments performed on various models, and partially by experimental data available in literature.

Input-output characteristics thus obtained are examined according to the functional relation stated above, by methods of linear regression, and a function relating output pressure to supply and control pressures as well as geometric parameters is established.

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I. INTRODUCTION

A. Background of Fluidics

Fluidics can be defined as the application of fluid power in automatic control systems to replace electronic devices, where electronic devices are impractical. The fundamental principle applicable to all fluidic devices is that a stream of gas or liquid flowing through a small hole or nozzle can be deflected from its path when hit with one or more small control streams of fluid. Regulation of force, direction and volume of the control streams can produce switching, amplification and oscillation. The combination of various fluidic elements constitutes a fluidic system, which is defined by the National Fluid Power Association, NFPA, as follows: "a fluidic system is one in which sensing, control, information processing, and/or actuation functions are performed primarily by utilizing fluid-dynamic phenomena."

Although the physical effects pertaining to fluidics have been known for a long time, the introduction of fluidics into the field of automatic control systems goes back as far as 1960. The development of fluidics is briefly viewed by Gray[(1)x] as follows:

> "The earliest reference to the use of jet amplifiers is a paper published by Coanda in 1933. In 1938 McMahan pointed out a means of control of fluid flow by the use of aerodynamic characteristics of the jet. Todd applied for a British patent on a 'mechanical relay of the fluid jet type.' Preliminary work for the control principle on a variable flow restrictor

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[x] Paranthetical references placed superior to the line of text refer to the bibliography.

> using a vortex was done by J.M. Rhoades and D.E. Cain in the early 50's. There was no significant advance in the field until 1960, when the results of research at the Diamond Ordnance Fuze Laboratories (Now Harry Diamond Laboratories) and at M.I.T. were announced. Then Horton described research on fluid amplifiers concerning stream-interaction principles, and Greenwood and Ezekiel (M.I.T.) presented fluid logic concepts. The word at DOFL, reported in control Engineering, January 1963, created an intense interest from industry."

Since then many firms have invested large sums in research and experiments to mass produce fluidic system components and although some of them have been standardized recently, most of the components are still at the laboratory stage.

Fluidic elements can be used as amplifiers and logic valves and when they are combined in a suitable manner they can be used in control actions. Fluid logic valves can be constructed practically for every purpose where it is a question of directing a liquid or gas flow. For example, they can be the outlet cone in a jet motor where the blowing nozzle in the cone controls the jet. Another field of application is in medicine, where fluidic systems are used for the control of artificial hearts. Fluidics have not yet come into any great use in industry, but growing interest in the field promisas a more practical and general use.

According to Wood[2] there are certain advantages and limitations of fluidic elements. Fluidic elements perform well under high or low temperatures, vibration and shock. Thus, they can be of great use especially in space vehicles and rockets which are subject to very high and very low temperatures, which may obstruct the proper and safe operation of electronic devices. The abscense of moving mechanical parts provides high reliability, while the simplicity of the basic devices promises low cost of production. Fluidic elements can amplify flow or pressure signals, or provide maximum gain. A single element can function as a logic element. Electronic counterparts of these logic elements, which can be used to build fluidic computers, require several active and passive elements.

Failures of fluidic systems are of three types[2]:

(a) failure of interconnection between lines;

(b) failure of the material from which the system components are fabricated;

(c) obstruction of fluid flow in ducts or orifices by particles contained in the fluid.

Response time in fluidic devices is limited with the speed of sound and is greater than in electronic devices where speed limit is the speed of light.

Fluid dynamic phenomena such as mixing of fluids, Coanda effect, wall effect, turbulance, jet flow; fluid characteristics such as viscosity; and boundary layer problems are factors to be considered in analysing the operation of fluidic systems and elements. Fluid dynamic equations which govern the above fluid characteristics and phenomena, are nonlinear and various assumptions have to be made in order to solve them both for the steady-state and transient operation of the fluidic systems and elements. Therefore, development of fluidics, up to now, has been primarily on an empirical basis. An optimum economy in the design, production and performance of a device, system or system element requires both empirical and theoretical analysis. Use of numerical analysis techniques with new electronic computers may enable time-dependent solution of the non-linear fluid flow equations, so that operation characteristics of fluidic systems and elements can be theoretically explained, in order to increase fluidic system optimization.[3]

B. Background of the Problem

Fluidic elements may be classified into two categories: active elements, which require a separate power supply and produce gain and passive elements, such as resistors, capacitors, filters and inductors. Active elements are of two basic types according to their functions: digital elements, which are used in on-off controll actions and proportional elements, which are used in continious control actions.[2] Turbulance amplifier is one of the main pure digital elements which was first developed by R.N. Auger and corp.[4]

According to Letham[5] the turbulance amplifier (fig.1) operates on the principle of the transition of a free jet between two collinear tubes from laminar flow to turbulent flow.

If a stream of sufficiently low velocity is projected from a tube of small diameter, a laminar free fluid jet can be established in ambient fluid. Such a jet can remain laminar for a distance of about 100 times the inside diameter of the tube, this distance being inversely proportional to the supply pressure. If a second tube is placed in the jet path, a part of the laminar flow can be captured by it, to produce an output pressure this pressure depending on the average velocity of the jet portion intercepted. The supply flow will be turbulent if the output tube is placed at a sufficient distance from the supply tube, and since the turbulent jet spreads more than the laminar jet, the output pressure will decrease.[4,5]

If, however, the tubes are placed at a fixed distance apart, at very low velocities the supply jet is laminar. As the supply jet velocity-supply pressure- is increased, the output pressure also increases. Then as the supply velocity is further increased turbulance occurs between the supply and output tubes. Output pressure decreases rapidly with even a relatively small further increase of supply velocity. When the supply flow becomes turbulent at the exit of the supply tube, increase in supply pressure causes increase in output pressure (fig.2). If the supply pressure is adjusted so that the supply jet becomes turbulent just before entering the output tube, very small disturbances of the supply jet cause further turbulance and large changes of output pressure. These small disturbances cause the point at which the stream becomes turbulent to shift towards the supply tube. Disturbances can be introduced into the laminar supply jet by fluid streams - control flow - of lower energy, directed at right angles to the supply flow.[4,5]

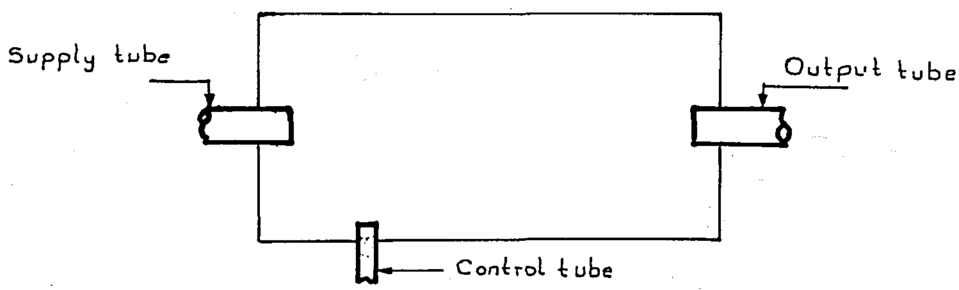

Fig.1 - The turbulance amplifier

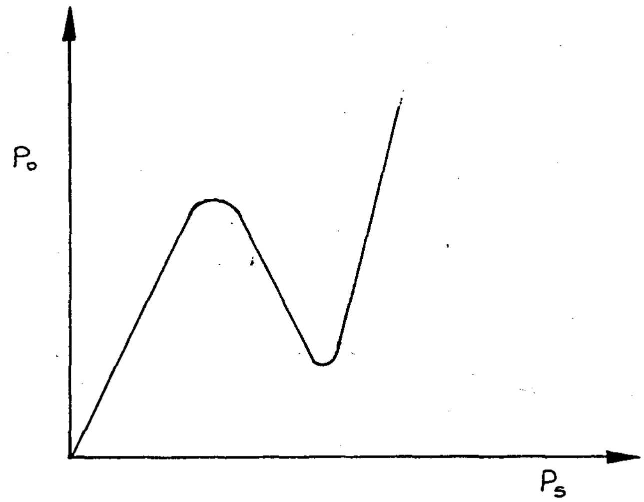

Fig.2 - Output vs. supply pressure for a turbulance amplifier.

Most turbulance amplifiers used for control purposes are operated in the range where they are not acoustically sensitive. Amplifiers have been constructed with power gains of 40 to 80. If same acoustic sensitivity can be tolerated, pressure gains of 1000 can be obtained.(6)

Although the turbulance amplifier can be used in proportional applications, its primary use is in logic circuitry, since one turbulance amplifier can drive up to 10 or more secondary units.(4)

According to Auger(4) the turbulance amplifier is a logical NOR device - that is any input (control flow) reduces the output to essentially zero. Because NOR devices can be used to construct any logic function, the turbulance amplifier can be applied to digital logic circuits as the basis for all logical functions such as AND, OR and counting circuits.

Various parameters in the design affect the performance of the turbulance amplifier. To obtain high efficiency and sensitivity, a study of these parameters seems to be essential.

II. STATEMENT OF THE PROBLEM

The following measurable quantities may be considered as the factors that affect the design and performance characteristics of a turbulance amplifier (fig.3):

(a) supply pressure, P_s, psi.

(b) input -control- pressure, P_c, psi.

(c) output pressure, P_o, psi.

(d) distance between supply and output tubes, h, inches.

(e) distance between control tube and ℄ , ω inches.

(f) distance between control tube and supply tube, ℓ, inches.

(g) supply tube diameter, d_s, inches.

(h) input -control- tube diameter, d_c, inches.

(k) output tube diameter, d_o, inches.

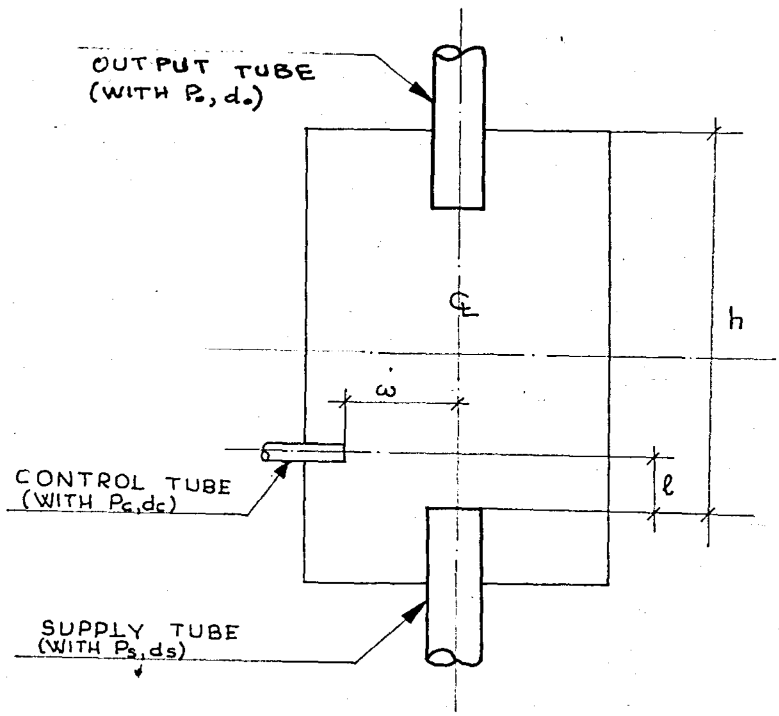

Fig.3 - Factors affecting the design and performance of a turbulance amplifier.

The turbulance amplifier is designed according to the following criteria:[4,5]

(a) usefulness: to obtain high output pressures when no control flow is applied, that is to approach $P_o/P_s = 1$ when $P_c = 0$.

(b) sensitivity: to have a high effect of control flow disturbances, that is to approach $P_o/P_c = 0$ at constant values of supply pressure and low values of control pressure.

(c) economy of power and material, that is low working pressures and small geometric sizes.

However, laminarity considerations fix the upper limit of the distance between the output and control tubes to approximately 100 times the diameter of the supply tube, whereas sensitivity increases with increasing distance between them.[4,5,6] Therefore, the selection of a supply pressure and a distance between the supply and output tubes represents a compromise between sensitivity and useful output.

According to available working pressures, measuring instruments and manufacturing facilities the supply and control tube diameters can be fixed as constant values, and output tube diameter taken equal to the supply tube diameter. The above discussion reduces the number of the stated factors from nine to six, which are, P_s, P_c, P_o, ℓ, ω, and h. Mathematically, if any variable A_1 depends on the independent variables A_2, A_3, ... , A_n, the functional equation may be written as

$$A_1 = \emptyset(A_2, A_3, \ldots\ldots, A_n) \tag{1}$$

In the case of a turbulance amplifier, eq.(1) takes the form,

$$P_o = \emptyset(P_s, P_c, \ell, \omega, h) \tag{2}$$

However, when there are more than three variables in an analysis, dimensional analysis techniques are recommended to reduce the number of variables, so that a more comprehensive presentation and analysis of data is possible.(7,8) By applying Buckingham's II- theorem, the six variables in eq.(2) may be reduced to three variables,

$$P_o/P_s = \emptyset_1\{((P_c/P_s)^a\ \ell/h), ((P_c/P_s)^b\ \omega/h)\} \tag{3}$$

Thus the object of the problem is to establish a functional relation according to eq.(3), considering the factors of usefulness, sensitivity and economy.

III. METHOD OF ANALYSIS[x]

The following criteria have been considered in the determination of geometric dimensions and the working pressures of the model:

(a) supply flow must be laminar at the exit of the supply tube

(b) geometric dimensions must be as small as possible

(c) working pressures must be as low as possible to obtain power economy

In the following section assumptions made for the determination of pressure range and size of the model are discussed in accordance with the above criteria, final results are presented and compared with practical ranges and dimensions which are given in ref.(4,5,6) and a procedure of analysis is given at the end.

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[x] Equations developed will apply to air at 70^{o}F and 14.7 psi. The following properties of air are used in all the calculations:[(9)]

Density, $\rho = 1.35 \times 10^{-6}$ slugs/in^3

Specific weight, $\gamma = 4.35 \times 10^{-5}$ lb/in^3

Viscosity, $\mu = 2.6 \times 10^{-9}$ lb-sec/in^2

Kinematic viscosity, $\nu = 2.36 \times 10^{-2}$ in^2/sec.

A. General Assumptions

1. Requirements for Model Size

Various factors were to be considered in determining the diameters of the supply, output and control tubes. Letham[5] recommends output diameter to be equal to the supply tube diameter and control tube diameter to be smaller. Manufacturing facilities and experimental equipment, mainly pressure probes and indicators that were available, set a lower limit of 1 mm. for diameters to be used. Thus selecting 1 mm. (0.4×10^{-1} inches) as control tube diameter, supply and output tube diameters were chosen as 2 mm. (0.79×10^{-1} inches).

It is also recommended by Letham[5] that, the distance between supply and output tubes should be less than about 60 times the inside diameter of the supply tube, and to have more pronounced effects of turbulance, distance between control tube and $\mathcal{C}_L$ (fig.3) should be small.[5]

2. Requirements for Working Pressure Range

If supply flow is measured at the exit of the supply tube by a pilot-tube, then the velocity of supply flow at the exit of the supply tube is given by

$$\frac{P_s - P_{ss}}{\frac{1}{2g}\,\gamma\,V_s^2} = 1 + \frac{M^2}{2.2!} + \frac{2-k}{2^2.3!}M^4 + \ldots\ldots\ldots\ldots \qquad (5)$$

assuming the flow is a reversible, adiabatic flow of a compressible perfect gas, with no shaft work[10]; whereas P_s is total (stagnation) pressure, P_{ss} is static supply pressure, V_s is velocity of supply flow and M is Mach number, all at the exit of the supply tube (fig.4).

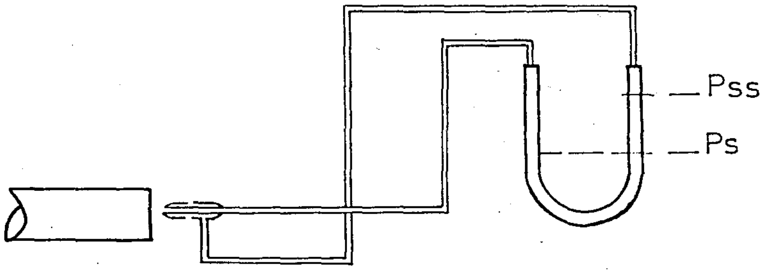

Fig.4 - Pressure measurement at the exit of the supply tube.

If Mach number is less than 0.2, eq.(5) takes the following form when written for V_s, with an error of less than one per cent[10]

$$V_s = \frac{2g}{\gamma} (P_s - P_{ss})^{1/2} \tag{6}$$

but since

$$P_s - P_{ss} = P_{sd} \tag{7}$$

where P_{sd} is dynamic supply pressure at the exit of the supply tube (fig.4), and since for laminar flow in circular tubes of very small diameter, i.e. about 0.03 inches, dynamic and static pressures may be taken approximately equal[4], eq.(6) may be written as

$$V_s = \left(\frac{g}{\gamma} P_s \right)^{1/2} \tag{8}$$

However, if supply flow is measured at the inlet of the supply tube, pressure drop across the tube for small Reynolds numbers is given by[11]

$$\Delta P = \lambda \left(\frac{L}{D} \right) \left(\frac{1}{2} \rho V_s^2 \right) \qquad (9)$$

where λ is Fanning friction factor and is equal to 64/Re; L is length, D is diameter of the supply tube; V_s is velocity of supply flow at the exit of the supply tube and ρ is density of air. Thus, if P_s' is the measured pressure, that is, supply pressure at the inlet of the supply tube (fig.5)

$$P_s' = P_s + \Delta P \qquad (10)$$

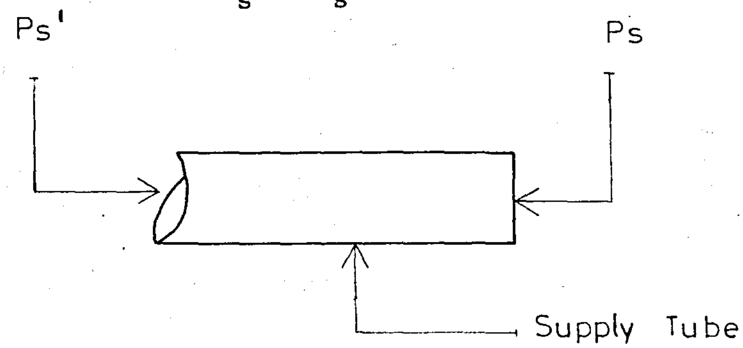

Fig.5 - Pressure measurement at the inlet of the supply tube.

Control pressures are determined on the condition that they should be less than about $\frac{1}{10}$ times supply pressures.[5]

The condition that supply flow must be laminar at the exit of the supply tube is determined according to Reynolds' number, Re

$$Re = \frac{VD}{\nu} \qquad (11)$$

where V is average velocity, D is a characteristic dimension and ν is kinematic viscosity of the fluid. Thus for the model under scrutiny, using air as the fluid, D is diameter of the supply tube.

Substituting eq.(8) for V into eq.(11) and using properties of air at 70°F and 14.7 psi

$$Re = 1.26 \times 10^5 (P_s)^{1/2} D \tag{12}$$

where P_s is supply pressure at the exit of the supply tube, psi; D is supply tube diameter, inches. Supply tube diameter was determined as 0.79×10^{-1} inches; substituting this value for D into eq.(12)

$$(P_s)^{1/2} = \frac{Re}{10^4} \tag{13}$$

Since for laminar flow in a circular tube Re must be less than 2000, the upper limit for the supply pressure at the exit of the supply tube, from eq.(13), is 4×10^{-2} psig.

B. Working Pressures and Geometric Size of the Model and Comparative Values From Literature

According to the above discussion, the geometric dimensions of the model and the range of the working pressures have been determined as follows (pressures are referred to supply and control pressures at the exit of the supply and control tubes respectively):

(a) supply and output tube diameters, d_s and d_o respectively, are 2 mm. (7.9×10^{-2} inches) each.

(b) control tube diameter, d_c, is 1 mm. (3.95×10^{-2} inches)

(c) maximum supply pressure, P_s, is 4×10^{-2} psig.(30 mm.w.c)

(d) maximum control pressure, P_c, is 8×10^{-3} psig.(6 mm.w.c)

(e) range of distance between supply and output tubes, h, is between 20 mm. and 100 mm. (0.788 inches and 3.940 inches)

(f) distance between control tube and ℄, ω (fig.3), is about 1/4 h.

(g) distance between control tube and supply tube, ℓ (fig.3), is about 1/4 h.

Practically ideal values for dimensions and working pressures for turbulance amplifiers are given in ref.(4,5,6) as follows:

(a) supply (and output) tube diameter is 0.03 inches.

(b) range of distance between output and control tubes is between 0.375 inches and 1.5 inches.

(c) supply pressure range is between 0.2 psig and 0.5 psig.

(d) output pressure is about 1/2 times supply pressure, when control flow is not applied.

(e) control pressure range is between 0.01 psig and 0.02 psig.

C. Procedure of Analysis

The analysis of the problem is based on the following procedure:

(a) investigation of P_o as a function of P_s at constant values of h,

$$P_o = f(P_s)_{h\,=\,\text{const.}}$$

This function is investigated both analytically and experimentally for the above determined model dimensions and working pressures.

(b) investigation of P_o as a function of P_s and P_o at constant values of h, ω and ℓ,

$$P_o/P_s = f(P_c/P_s)_{h,\omega,\ell} = \text{const.}$$

However due to the limited accuracy and sensitivity of the pressure indicator that was used, namely U-tube manometer, experimental analysis of the above function on the model was not possible. Thus, in order to have a basis of comparison of the analytical results, the range and dimensions of the model is changed to the range and dimensions of "the ideal" amplifier, so that analytical results are compared to experimental results given by Letham[5] and Kompass.[6]

(c) the expression

$$P_o/P_s = \phi\{((P_c/P_s)^a\ \ell/h),\ ((P_c/P_s)^b\ \omega/h)\}$$

is investigated on the same basis as part (b).

IV. ANALYTICAL APPROACH TO THE PROBLEM

The analytical approach to the problem, jet flow in turbulance amplifiers, is based on Schlichting's solution for laminar circular jets.[12] In this section Schlichting's solution is discussed and a method is devised to apply this solution to jet flow in turbulance amplifiers.

A. Schlichting's Solution for Laminar Circular Jets

Schlichting considers laminar circular jets as an example of motion in the abscense of solid boundaries, to which boundary layer theory can be applied so that it is possible to use Prandtl's boundary layer equations for steady, two-dimensional, incompressible flow of low viscous fluids with neglected body forces. Since the pressure gradient in the x-direction, dP/dX, may also be neglected as a result of the ambient pressure being impressed on the jet, the total momentum in the direction of the jet is constant. Further the jet spreads outwards in the down stream direction because of the influence of friction; however its centerline velocity decreases in the same direction. The system of coordinates is selected with its x-axis in the direction of the jet, the radial distance denoted by y, the axial and radial velocity components being u and v respectively.[12] Schlichting gives the following expressions for conservation of momentum in the x-direction, equation of motion and equation of continuity for the adopted system of coordinates and under boundary layer simplifications, respectively, as

$$J = 2\pi\rho \int_0^\infty u^2 y \, dy = \text{const.} \tag{14a}$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \nu \frac{1}{y} \frac{\partial}{\partial y} \left(y \frac{\partial u}{\partial y} \right) \tag{14b}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{v}{y} = 0 \tag{14c}$$

with the following boundary conditions

$$y = 0 : \qquad v = 0 ; \qquad \frac{u}{y} = 0 \tag{15}$$

$$y = \infty : \qquad u = 0$$

The following are further assumed[12]

(a) velocity profiles $u(x, y)$ are similar;

(b) jet width is proportional to x^n

(c) the stream function will be of the form

$$\psi \sim x^\rho F(\eta) \qquad \text{with} \qquad \eta = \frac{y}{x^n} \tag{16}$$

Since momentum in the direction of the jet is independent of x and since the inertial and frictional terms in eq.(14) must be of the same order of magnitude[12]

$$P = n = 1$$

thus

$$\psi = \nu \, xF(\eta) \qquad \text{and} \qquad \eta = \frac{y}{x} \tag{17}$$

from which

$$u = \frac{\nu}{x} \frac{F'}{\eta} \; ; \qquad v = \frac{\nu}{x} \left(F' - \frac{F}{\eta} \right) \tag{18}$$

When these values are inserted in eq.(14b),the following expression for

F, which is in terms of the stream function ψ, is obtained

$$\frac{FF'}{\eta^2} - \frac{F'^2}{\eta} - \frac{FF''}{\eta} = \frac{d}{d\eta}\left(F'' - \frac{F'}{\eta}\right) \tag{19}$$

Solution of this equation yields[11]

$$u = \frac{3}{8\pi} \frac{K'}{\nu x} \frac{1}{(1 + \frac{1}{4} \S^2)^2} \tag{20}$$

$$v = \frac{1}{4} \sqrt{\frac{3}{\pi}} \frac{\sqrt{K'}}{x} \frac{\S - \frac{1}{4} \S^3}{(1 + \frac{1}{4} \S^2)^2} \tag{21}$$

$$\S = \sqrt{\frac{3}{16\pi}} \frac{\sqrt{K'}}{} \frac{y}{x} \tag{22}$$

$$K' = J/\rho \tag{23}$$

$$Q = 2\pi \int_0^\infty uy\,dy = 8\pi\nu x \tag{24}$$

In equations (20) through (24), J is kinematic momentum, ρ is fluid density, ν is kinematic viscosity of the fluid, u is jet velocity in x-direction, v is jet velocity in y-direction and Q is volume flow rate in x-direction.

B. Application of Schlichting's Solution for Laminar, Circular Jets to Jet Flow in Turbulance Amplifiers - Flow in a Finite Field

It can be predicted from eq.(24) that the volume flow at a given distance from the orifice, x, is independent of the jet pressure at the orifice. A jet leaving the orifice under a high pressure remains narrower than one which leaves the orifice with a lower pressure.

However the latter carries with it a larger amount of stationary - ambient - fluid, so that the volume flow at a given distance from the orifice is equal to that in a faster jet, provided that the kinematic viscosity, ν, is the same in both cases.(12)

Regardless of the jet pressure at the orifice, volume flow, Q, increases with increasing distance from the orifice, according to eq.(24). Since,

$$\overline{V} \equiv \frac{2\pi\int_0^y uy\,dy}{A} \tag{25}$$

where $\overline{V}$ is the average velocity at x, A is the area over which the velocity is averaged, and y is the radial distance from the centerline of the jet, the average velocity over a finite area also increases with increasing x, on the condition that such an area can be defined.

However in the case of jet flow in finite fields - i.e. trubulance amplifiers,

(a) the condition of continuity is satisfied by constant discharge at successive sections in the direction of flow, instead of satisfying the condition of continuity by lateral flow from or to infinity as in the case of flow in infinite fields.[8]

(b) the change in momentum flux at successive sections in the direction of flow requires an accompanying pressure gradient in the same direction, thus the assumption of constant pressure in the flow direction for infinite fields is not valid for finite fields.[8]

(c) owing to the above discussion the average velocity over a finite area in the direction of flow is a function of the jet pressure at the orifice and the distance from the orifice, and is directly and inversely proportional to each respectively.

Therefore, in order to apply Schlichting's solution for infinite fields to a finite field, relevant assumptions and approximations have to be made. The assumptions and approximations made for the solution of the problem - fluid flow in turbulance amplifiers - are discussed in detail both for the cases of with-no-control-flow and with-control-flow.

1. With-No-Control-Flow Case

The objective of this part of the analysis is to use Schlichting's solutions to estimate the output pressure (useful output) as a function of supply pressure when the distance between supply and output tubes is kept constant and when there is no control flow.

It was discussed above that Schlichting's solutions apply to jet flow in an infinite boundary, where there is lateral flow to increase flow rate in flow direction, and where there is no pressure gradient in the same direction so that momentum at successive distances from the supply tube is constant. However in jet flow in a finite field, due to the abscence of lateral flow and the presence of a pressure gradient, velocity and pressure decrease in flow direction. Still from the above discussion another difference between infinite and finite fields is that in the former, pressure at successive distances from the input orifice is independent of the pressure at the orifice, while in the latter it is dependent on the pressure at the orifice.

In a solution given by Landau and Lifshitz[13], pressure decrease in jet direction in jet flow in infinite fields is given by

$$P \sim \frac{1}{x^2} \qquad (26)$$

and since pressure is related to velocity square,

$$u \sim \frac{1}{x} \qquad (27)$$

From Schlichting's solution, the expression for the centerline or maximum velocity, from eq.(20) is

$$u_{max} = \frac{3}{8\pi} \frac{K'}{\nu x} \tag{28}$$

where

$$K' = J/\rho \tag{29}$$

However if we assume J to be momentum input at the exit of the supply tube, of V_s is the supply velocity, then

$$K' = A_s V_s^2/\rho = A_s V_s^2 \tag{30}$$

since

$$P_s \sim V_s^2 \tag{31}$$

$$K' \sim P_s \tag{32}$$

Thus eq.(32) takes a form to satisfy the conditions for jet flow in a finite field, that is, u is inversely proportional to distance, x, and directly proportional to pressure input (supply pressure), P_s

$$u_{max}^2 \sim \frac{P_s}{x} \tag{33}$$

Thus the estimation of output pressures at successive distances from the supply tube will be related to the centerline velocity at that distance. If this pressure is related to the pressure drop between any two sections, since

$$P \sim u_{max}^2 \tag{34}$$

then

$$\Delta P_{1-2} \sim (u_{max_1})^2 - (u_{max_2})^2 \tag{35}$$

Applying Bernoulli's equation,

$$\Delta P_{12} = \frac{\gamma}{2g} (u_{max_1})^2 - (u_{max_2})^2 \tag{36}$$

However it is possible to average the maximum velocity at each section. If the velocity distribution is considered to be a cone with its height equal to u_{max}, it may be equated to a cylinder with its height equal to $\bar{u}_{max}$ (fig.7)

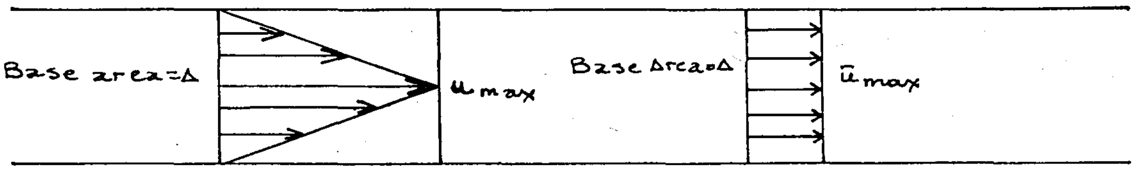

Fig. 7 - Approximate average of centerline velocity.

From fig.(7), since the base areas, A, are equal

$$\frac{1}{3} (u_{max}) \times (A) = (\bar{u}_{max}) \times (A)$$
$$\bar{u}_{max} = \frac{1}{3} u_{max} \tag{37}$$

Thus substituting the above expression into eq.(34)

$$\Delta P_{1-2} = \frac{\gamma}{2g} \{(\bar{u}_{max_1})^2 - (\bar{u}_{max_2})^2\} \tag{38}$$

In a turbulance amplifier pressure drop is considered to occur between supply and output tubes; therefore $(\bar{u}_{max_1})$ in eq.(38) refers to the average maximum velocity at the exit of the supply tube. Thus in order to make use of equation (38) it is necessary to estimate a fictitious maximum velocity at the exit of the supply tube. When u_{max} is plotted against x, distance in flow direction, at a constant supply pressure, it is observed that the curve approaches u_{max}-axis assymptotically (fig.8).

In fig.(8), $x = 0$ corresponds to the exit of the supply tube. In order to obtain a finite maximum velocity at the exit of the supply tube, the curve has to be linearly approximated at a selected distance from the supply tube. The distance is selected in accordance with experimental results given by Andrade and Tsien.[14] According to these results Schlichting's solution, which is for a point source, is valid for a finite source except in the immediate vicinity of the supply tube. Andrade and Tsien have performed their experiments on a cylindrical nozzle of 0.91 mm. and have found the "immediate vicinity" to be within less than 0.8 cm. from the supply tube. Thus maintaining the same (d/x) ratio, diameter over jet length ratio, for the problem under consideration

$$\frac{0.91}{8} = \frac{0.079}{x} \qquad \text{and} \qquad x = 0.696'' \tag{39}$$

Thus for any distance greater than 0.696 inches the solution is valid for a supply tube of diameter 0.079". Since in the analysis pertaining to the problem considered, the least distance was selected to be 0.788 inches by conditions of operation, a linear approximation for u_{max} at $x = 0$ is done by drawing a tangent to the curve at $x = 0.788$ inches. (fig. 8a).

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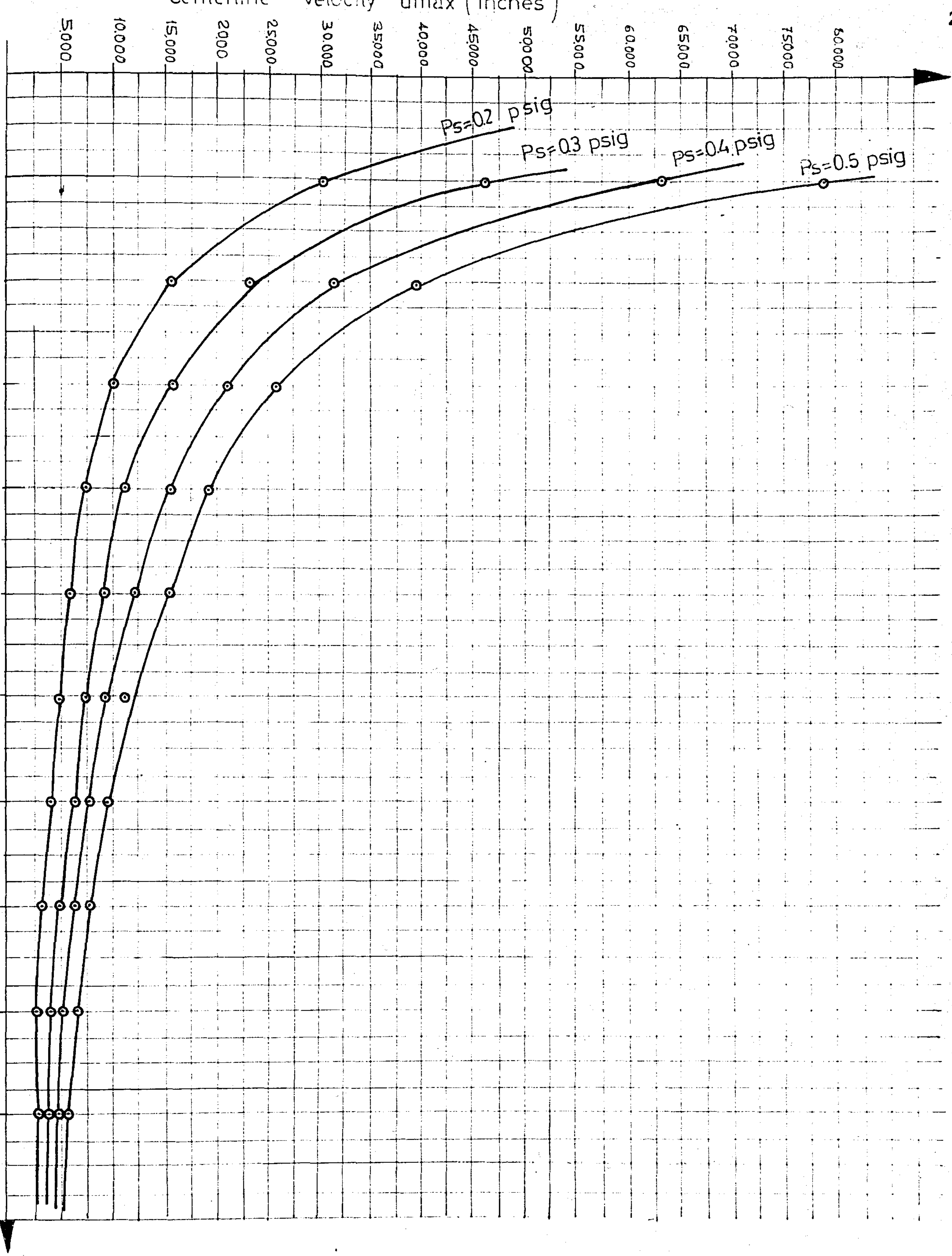

Fig.8 - Variation of u_{max} as a function of distance, at constant supply pressure.

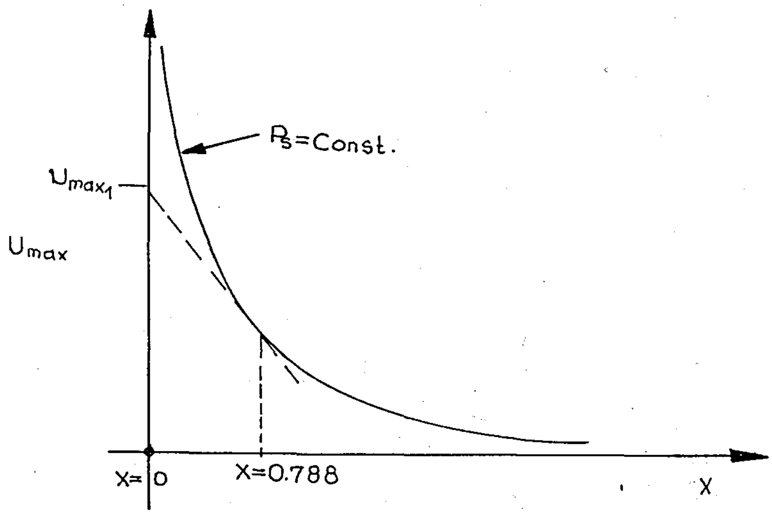

Fig.8a- Estimation of maximum supply velocity at a constant supply pressure for a turbulance amplifier with a supply tube diameter of 0.079 inches.

In order to use this method of estimation in numerical computations for a range of supply pressures it is necessary to find a general expression for u_{max_1}. An inspection of u_{max_1} values found by the method described above reveals that there is a relation between u_{max_1}, supply pressure and average velocity at the exit of the supply tube at that supply pressure, given by the expression

$$(u_{max_1}) = (U_{av.supp}) \times (P_s)^{1/2} \times 131.1 \qquad (40)$$

where P_s is in mm.w.c., and the expression is applicable only to a pressure range between 0.02 and 0.04 psi.

It is now possible to make use of eq.(38), so that ΔP_F, fictitious pressure drop between supply and output tubes, related to centerline velocity occuring at each section respectively, can be evaluated. However the real pressure drop is related to the average velocity at the exit of the supply tube, $U_{av.supp}$, and is calculated on the basis that

$$\Delta P \sim (U_{av.supp})^2 - (U_{av.out})^2 \tag{41}$$

therefore, the real pressure drop, ΔP_R, is given by

$$\Delta P_R = \{(U_{av.supp})^2/(\bar{u}_{max_1})^2\}\Delta P_F \tag{42}$$

and finally the output pressure is found from

$$P_o = P_s - \Delta P_R \tag{43}$$

The characteristic curve for P_o vs. P_s of a turbulance amplifier with no control pressure has a trend shown in fig.(9).

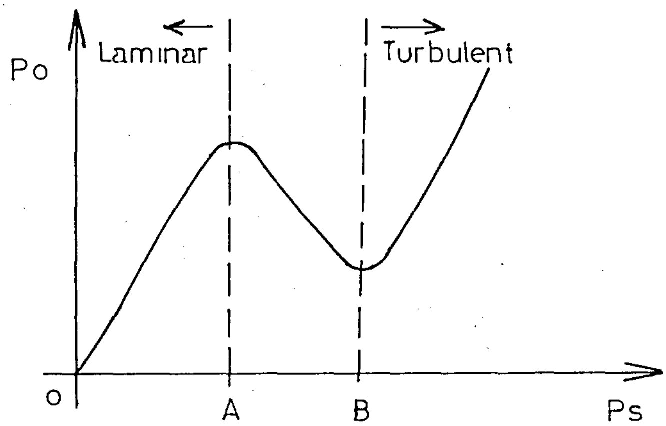

Fig.9 - Characteristic curve of a turbulance amplifier with no control pressure.(4,5,6)

From fig.(9), for values of P_s between zero and A output pressure increases almost linearly and the jet is laminar at the inlet of the output tube. However an increase in supply pressure after point A causes a decrease in the output pressure due to turbulance occurring between the two tubes. At point B supply jet becomes turbulent at the exit of the supply tube and output pressure begins to increase rapidly with further increase in supply pressure. The working pressure range of turbulance amplifiers is up to point A.[4,5,6]

Since the solutions pertaining to the problem so far discussed are for laminar flow only, numerical evaluation of output pressure is deficient in indicating point A. However experiments performed by Andrade and Tsien[14] have shown that up to a Reynolds number of approximately 500 and a (d/x) ratio of 0.91/33, the jet stays perfectly laminar. Considering this for our problem, the upper limit for supply pressure is determined to be 0.0025 psi by eq.(13) and for distance between supply and output tubes to be 3.0 inches. The maximum value of the distance between supply and output tubes is approximately in the range given in section III, according to operating conditions; whereas maximum value of P_s (0.0025 psi) is quite impractical. Thus in calculating output pressures for the model, pressure ranges given in section III are considered.

Therefore output pressures for the model have been evaluated for the ranges given below:

(a) distance between supply and output tubes, h, between 0.788 and 3.0 inches

(b) supply pressure, P_s between 2.13×10^{-2} and 4×10^{-2} psi.

Numerical calculations were done by a computer program and results are presented in table form in Appendix A. These are compared with experimental results, which will be discussed in the next section, section V.

However experiments performed were successful only for a narrow range of distance between supply and output tubes, and only for the case of no-control-flow. Therefore in order to have basis of comparison for the rest of the analytical results, the same method of analytical calculation has been performed for "the ideal amplifier" whose characteristic dimensions were given in section III. The defining expressions and limiting values for a supply tube diameter of 0.03 inches take the following form by a similar method of analysis

(a) maintaining the (d/x) ratio of 0.91/8 for the determination of the "immediate vicinity", h_{min} is found to be 0.2"

(b) the general equation for the evaluation of (u_{max_1}), eq.(40) takes the following form

$$u_{max_1} = (U_{av.supp}) \times (P_s)^{1/2} \times 94 \qquad (44)$$

where P_s is in psi.

(c) maintaining the (d/x) ratio of 0.91/33 for the determination of the maximum length between supply and output tubes, h_{max} is determined to be 1.5".

(d) for perfect laminarity maximum supply pressure at Re = 500 is found to be 0.4 psi by eq.(12).

Output pressures have been evaluated for the ranges given below:

(a) distance between supply and output tubes, h, between 0.2 and 2 inches.

(b) supply pressure, P_s, between 0.1 and 0.5 psi.

Numerical calculations were done by a computer program and results are presented in table form in Appendix A. These are compared with empirical results found in literature, in section VI.

2. With-control-flow Case[x]

In this part of the analysis output pressure is estimated when control pressure is applied. The procedure is similar to the one described in the previous part with an additional assumption of conservation of momentum at the point of impinge of the control and main jets. This analysis is done only for the "ideal amplifier", with a supply tube diameter of 0.03 inches, and a control tube diameter of 0.015 inches.

In order to consider the two flows from the supply and control tubes simultaneously on a single frame of reference, the following procedure is followed in accordance with fig.(10).

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[x] In the following analysis velocities denoted by u will refer to centerline velocities.

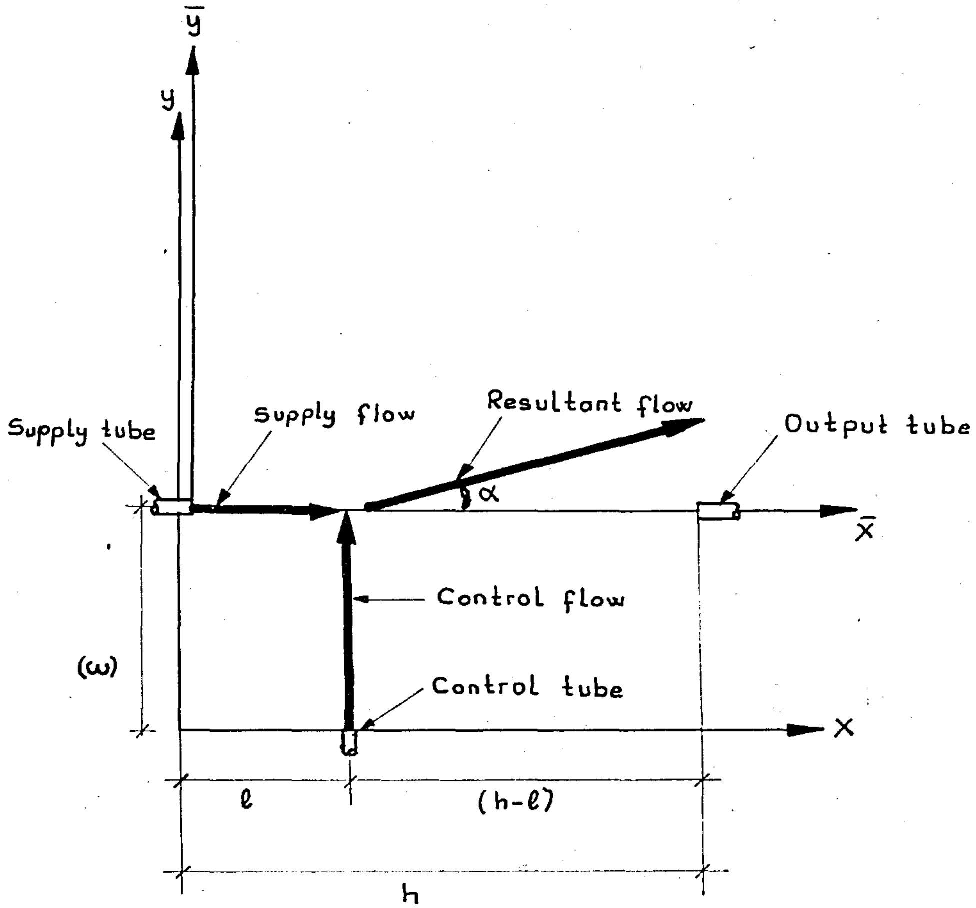

Fig. 10 - Geometric representation of with-control-flow case. Point A is the point of impinge of the supply and control jets.

According to the above figure, the centerline velocities for supply flow in $\bar{x} - \bar{y}$ frame and control flow in x - y frame are given by

$$u_{supp} = f(\bar{x})$$
$$u_{cont.} = f(y) \tag{45}$$

Since at the point of impinge (point A), in reference to x - y frame, $\bar{x} = \ell$, $y = \omega$, then

$$u_{supp} = f(\ell)$$
$$u_{cont.} = f(\omega) \tag{46}$$

Momentum of the control and supply jets, at point A can be written in terms of volume flow rates, respectively as

$$M_{supp} = Q_s u_{supp} = A_s (u_{supp})^2$$
$$M_{cont.} = Q_c u_{cont.} = A_c (u_{cont.})^2 \tag{47}$$

where A_s is the area of the supply jet and A_c is the area of the control jet at point A.

Since at small distances from the tubes the jet spread is negligible (in reference to the velocity profiles given in App. B), A_s and A_c are taken as the initial diameters of supply and control jets respectively.

Thus assuming conservation of momentum at point A,

$$M_R = M_{supp} + M_{cont} \tag{48}$$

and this total momentum is carried by the resultant flow, indicated in fig.(10).

Applying equation of continuity, volume flow rate of the resultant flow can also be found in terms of volume flow rates of supply and control jets as

$$Q_s = A_s (u_{supp})$$
$$Q_c = A_c (u_{cont.}) \tag{49}$$
$$Q_R = Q_s + Q_c$$

Thus the centerline velocity of resultant flow is

$$u_R = M_R / Q_R \tag{50}$$

The area of the resultant flow, A_R, at point A is given by

$$A_R = Q_R/u_R \tag{51}$$

Also the angle between the resultant flow and supply flow, α, is

$$\alpha = \tan^{-1}(M_c/M_s) \tag{52}$$

It is now possible to estimate a fictitious nozzle from which the resultant flow will be assumed to originate. (fig.11)

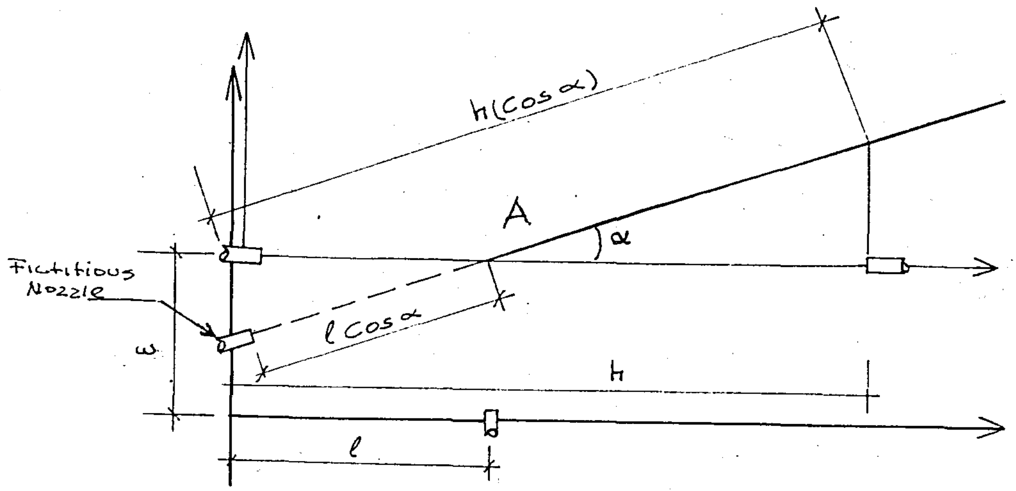

Fig. 11 - Geometric representation of the fictitious nozzle.

The fictitious nozzle, from geometry of fig.(11) is located at a distance $\ell/\cos\alpha$ from point A, and its diameter is equal to A_R. The location of the nozzle was seen to be somewhat arbitrary, since the flow properties depend on only the effective origin of the jet. However, such a selection of the location of the fictitious nozzle is necessary in order to set a reference point in the direction of the resultant flow to calculate the output pressure.

From Schlichting's expression for centerline velocity, u_R will be given by

$$u_R = \frac{3}{8\pi} \frac{K'}{(\ell/\cos\alpha)} \tag{53}$$

Thus, K', which is the input momentum divided by density of fluid can be evaluated. From this, the average input velocity at the exit of the fictitious nozzle is found as

$$U_{res.av} = \frac{\sqrt{K'}}{A_R} \tag{54}$$

Using Bernoulli's equation the input pressure at the fictitious nozzle is

$$P_R = \frac{\gamma}{g} (U_{res.av})^2 \tag{55}$$

At this point all the characteristics of the fictitious nozzle are known. Therefore, it is possible to evaluate a velocity output at the output tube in reference to a $X_1 - Y_1$ frame, fig.(12).

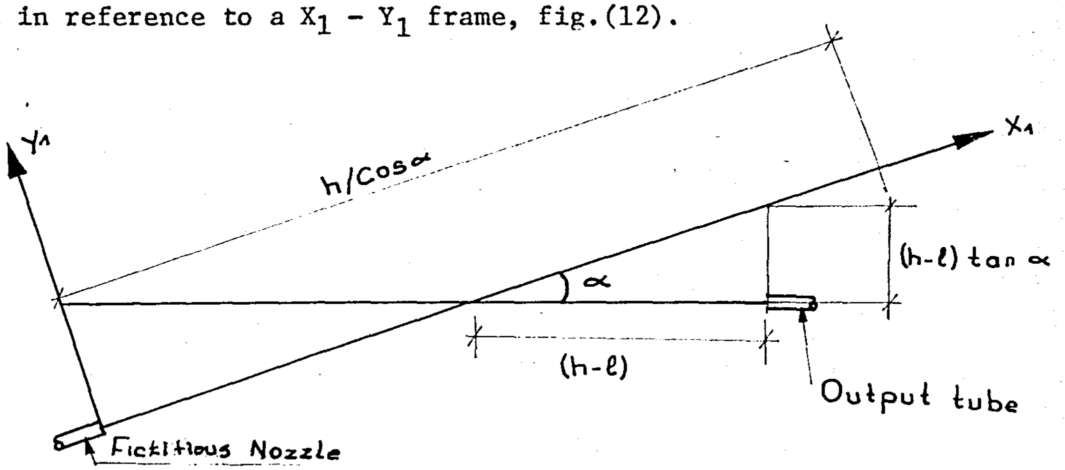

Fig. 12 - Geometric representation of the fictitious nozzle and the output tube on the reference frame $X_1 - Y_1$.

Considering $X_1 - Y_1$ frame, location of the output tube is at $X_1 = h/\cos\alpha$ and $Y_1 = (h - \ell)\tan\alpha$.

From equations (20) and (22) the centerline velocity of the portion of the resultant flow that is captured by the output tube is given by,

$$u_{out} = \frac{A}{X_1} \frac{1}{(1 + BY_1^2)^2} \tag{56}$$

where

$$A = (3/8\pi)(K'/\nu)$$

$$B = (3/16\pi)(K'/\nu)(1/X_1^2)$$

Since u_o enters the output tube at an angle of α, the effective centerline velocity will be taken as

$$(u_o)' = u_o \cos(\alpha) \tag{57}$$

Since this output pressure is also based on the centerline velocity assumption, fictitious pressure drop is given by

$$\Delta P_F = \frac{\gamma}{2g} \{(u_R')^2 - (u_o')^2\} \tag{58}$$

where u_R' is the maximum velocity at the exit of the fictitious nozzle, given by equation (44); and the real pressure drop is given by

$$\Delta P_T = \{(U_{res.av})^2/(u_R')^2\}\Delta P_F \tag{59}$$

Therefore the actual pressure at the output tube is

$$P_o = P_R - \Delta P_T \tag{60}$$

Output pressures for this case have been evaluated at constant values of ℓ and ω in order to predict the variation of P_o with P_c at constant P_s for a number of distances between the output and supply tubes. P_s, P_c and h ranges are as follows in reference to fig. (10).

(a) distance between supply and output tubes, h, between 0.2 and 2 inches.

(b) supply pressure, P_s, between 0.1 and 0.5 psi.

(c) control pressure, P_c, between 0.01 and 0.02 psi.

(d) constant values for ℓ and ω are 0.05 and 0.005 inches respectively.

Numerical calculations were done by a computer program and results are presented in table form in App.A. These results are compared with empirical results from literature in section VI.

The above analysis was an investigation of the output pressure as a function of P_s and P_c

$$(P_o/P_s) = f(P_c/P_s)_{h,\omega,\ell} = \text{const.}$$

A general approach, where ω and ℓ are also treated as variables, is presented in section VI.

V. EXPERIMENTS

Experiments have been performed at the automatic control laboratory of the Technical University of İstanbul. The experimental set-up had been used for a similar set of experiments performed on a bistable amplifier.

A. Experimental Set-up and the Model

Pressurized air from a compressor is admitted into the system through a pressure regulator, which decreases air pressure from 14.7 psi. to any desired value, and which is insensitive to pressure fluctuations. A three way valve directs low-pressure air from the regulator to three branches of plastic tubing. Flow rate, thus pressure, can be adjusted independently in each branch by control valves mounted on them. The three branches of plastic tubing direct air to supply and control tubes. Pressure in each tubing is measured by a U-tube manometer, the manometer connections being at halfway between control valve and the amplifier tubes. Output pressures are indicated by a special tube of 1/16" diameter, which is also connected to a U-tube manometer.

Plexiglass plates of 5 mm. and 10 mm. thickness, with dimensions of 10 cm. x 15 cm. were used in the construction of the models. Experimental set-up and the geometry of the models are illustrated in fig.(13a) and (b) respectively.

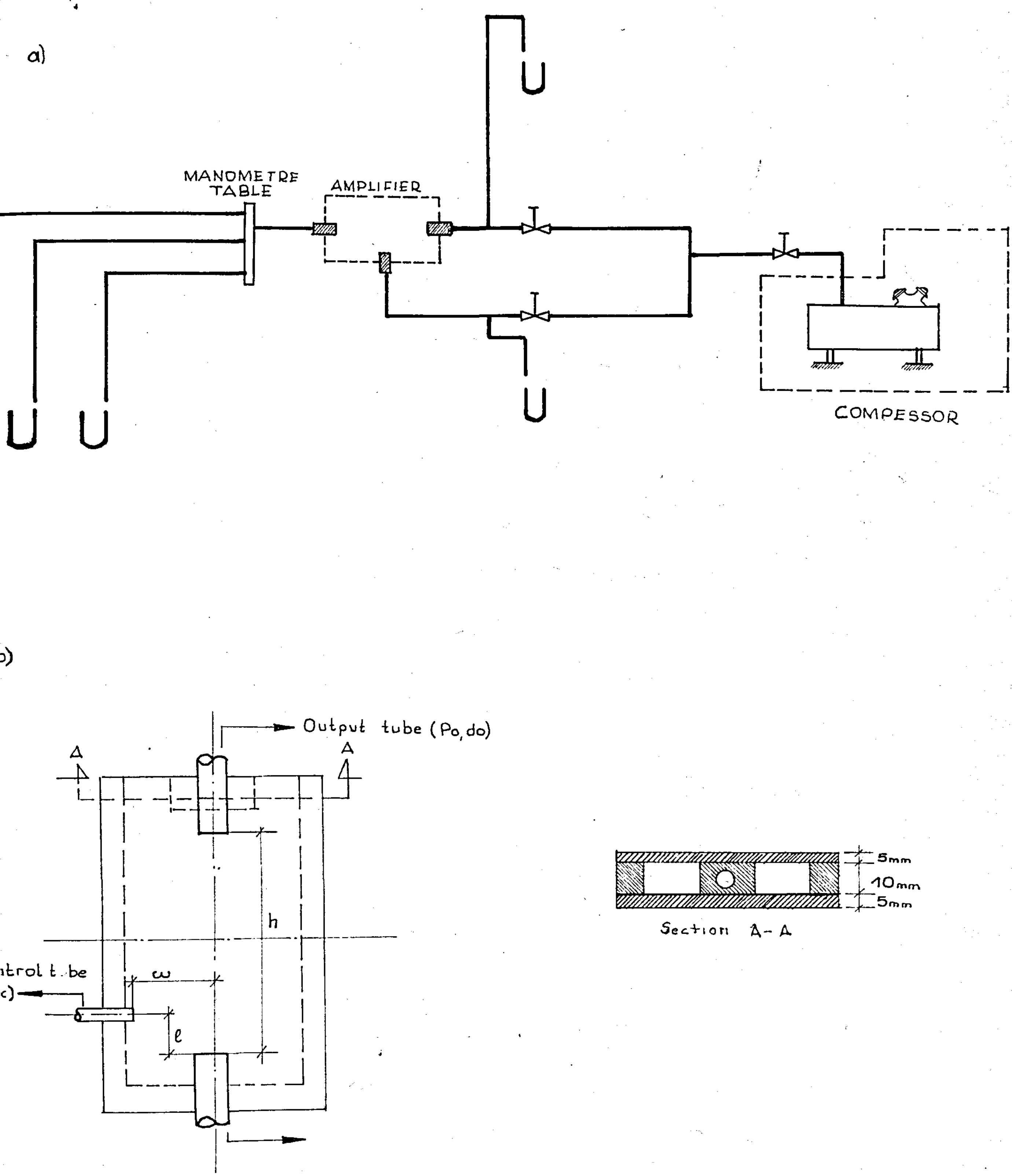

Fig.13 - (a) Experimental set-up

(b) Geometry of the model

B. Measurements and Results

Since both the plastic tubing and control and supply tubes have internal resistances, manometer readings of supply and control flow do not represent a true measurement of the pressures at the exit of the tubes. From section III, eq.(10),

$$P'_s = P_s + \Delta P$$

where P'_s, the pressure indicated by the manometer reading, is the supply pressure at the manometer junction, ΔP is total pressure loss in plastic tubing and supply tube, and P_s is supply pressure at the exit of the supply tube.

Total pressure loss in the plastic tubing and the supply tube was estimated by calibration, so that supply pressure at the exit of the supply tube was controlled by the manometer readings, taken at the junction (fig.14).

A series of experiments have been performed on two models, but satisfactory results could be obtained only for small distances between supply and output tubes, when supply pressure was in the turbulent region and for no-control-flow case. When control flow was introduced, practically no indication of output pressure was observed in the manometer connected to the output pressure indicator. Also for distances,greater than 0.788 inches between output and supply tubes, in no-control-flow case, experiments were unsuccessful.

Therefore experiments have been performed for the case of no-control-flow, at a distance of 0.788 inches between control and supply tubes.

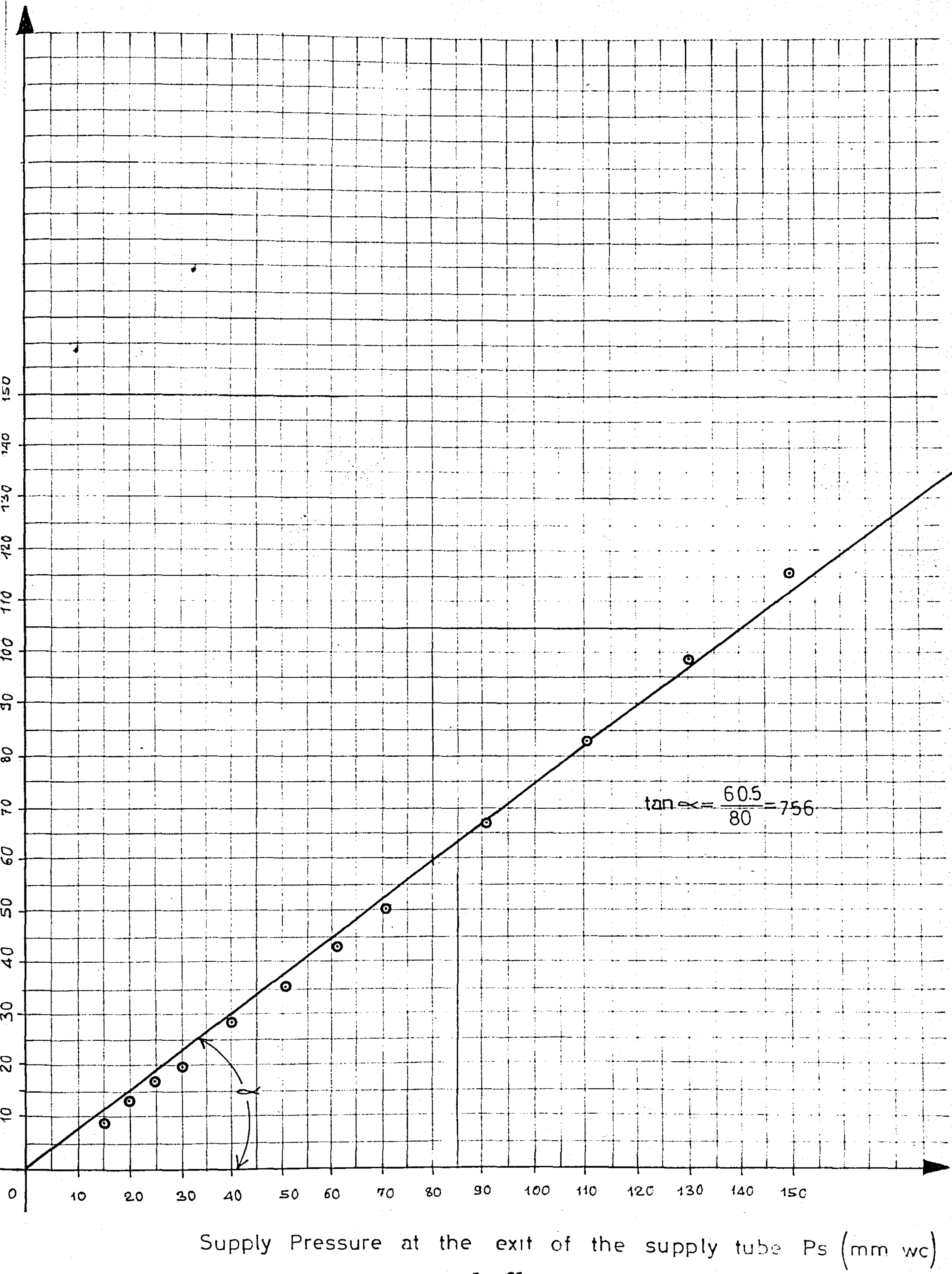

Fig.14 - Calibration curve for supply flow.

Readings were replicated two times and the average results are presented in table form.

Since these results are used to compare analytical results only in trend not magnitude, an error estimate analysis is unnecessary.

TABLE I: EXPERIMENTAL RESULTS FOR OUTPUT PRESSURE, WHEN THE DISTANCE BETWEEN SUPPLY AND OUTPUT TUBES IS 0.788 inches (20 mm) FOR NO-CONTROL-FLOW CASE

Run No.	P'_s (psi)	P_s (psi)	P_o (psi
1	18	15	8,5
2	26,4	20	12,5
3	33,1	25	16,5
4	38,5	30	19
5	45	35	22,5
6	53	40	28,5
7	59,6	45	30,5
8	66,3	50	36
9	72,8	55	40,5
10	79,5	60	43,5
11	86	65	48
12	92,6	70	52
13	99,5	75	56
14	106	80	60,5
15	112,5	85	64
16	119	90	67,5
17	126	95	73,5
18	132	100	76,5
19	139	105	80,5
20	146	110	83,5
21	152	115	89
22	159	120	93,5
23	166	125	97,5
24	172	130	100,5
25	179	135	105
26	185	140	109,5
27	192	145	113
28	199	150	117

P'_s : supply pressure at manometer junction, psig.

P_s : supply pressure at supply tube exit, psig.

P_o : output pressure, psig.

VI. DISCUSSION OF RESULTS

In this section analytical and experimental results will be discussed and compared both for the model and the 0.03 inch supply-tube-diameter amplifier seperately. The discussion of the results so far obtained sets various limits in which the assumptions leading to the analytical results are valid. A final analysis of the parameters is done within these limits by using a linear regression method which is also discussed in this section.

A. Discussion of the Results for the Model

It was discussed in section IV, that the characteristic curve for a turbulance amplifier has a trend shown in fig.(9), with two critical points, A and B. However the analytical approach is based on laminar jet equations so that the solutions are deficient in indicating points A and B. Thus using these solutions if supply pressure is increased further than point A, output pressure, according to the above discussion, will continue to increase linearly (fig. 15).

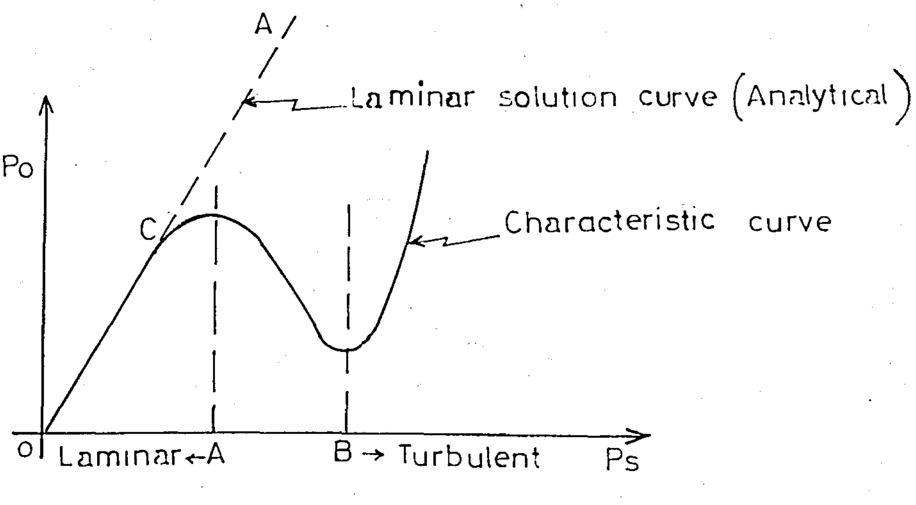

Fig.15 - Analytical curve for P_o vs. P_s for no-control-flow case, compared with the characteristic curve.

Therefore the solutions apply to supply pressure range limited by a maximum Re of 500, as was discussed in section IV, so that only the laminar region, which is the operating region of the turbulance amplifier is considered.

Maximum supply pressure at Re equal to 500, for the model of 0.079 inch supply tube diameter was found to be 0.0025 psig. Since this value is impractical for experiments, a pressure range of 0.02 to 0.04 psig has been taken as the supply pressure range. However this pressure range falls in the transition and turbulent regions, with Re around 2500. The expected outcome is that experimental results should indicate the portion of the curve after point B in fig.15, and analytical results should indicate the portion of the curve indicated by points C and D in the same figure.

Experimental and analytical results for the model at the same pressure range (0.02-0.04 psig) and the same distance between output and supply tubes (0.788 inches) are plotted in fig.16. It is observed that both are linear but have different slopes. This result is similar to the expected trend discussed above. Thus assumptions leading to analytical results are valid in trend; the magnitudewise verification is not possible.

B. Discussion of Results for the "Ideal Amplifier", (with a Supply Tube Diameter of 0.03 inches)

For this amplifier supply pressure is maintained in the laminar region, bounded by a maximum Re of 500. Thus, results obtained pertain to the portion O-A of fig.15, when no control flow is applied. P_o vs. P_s

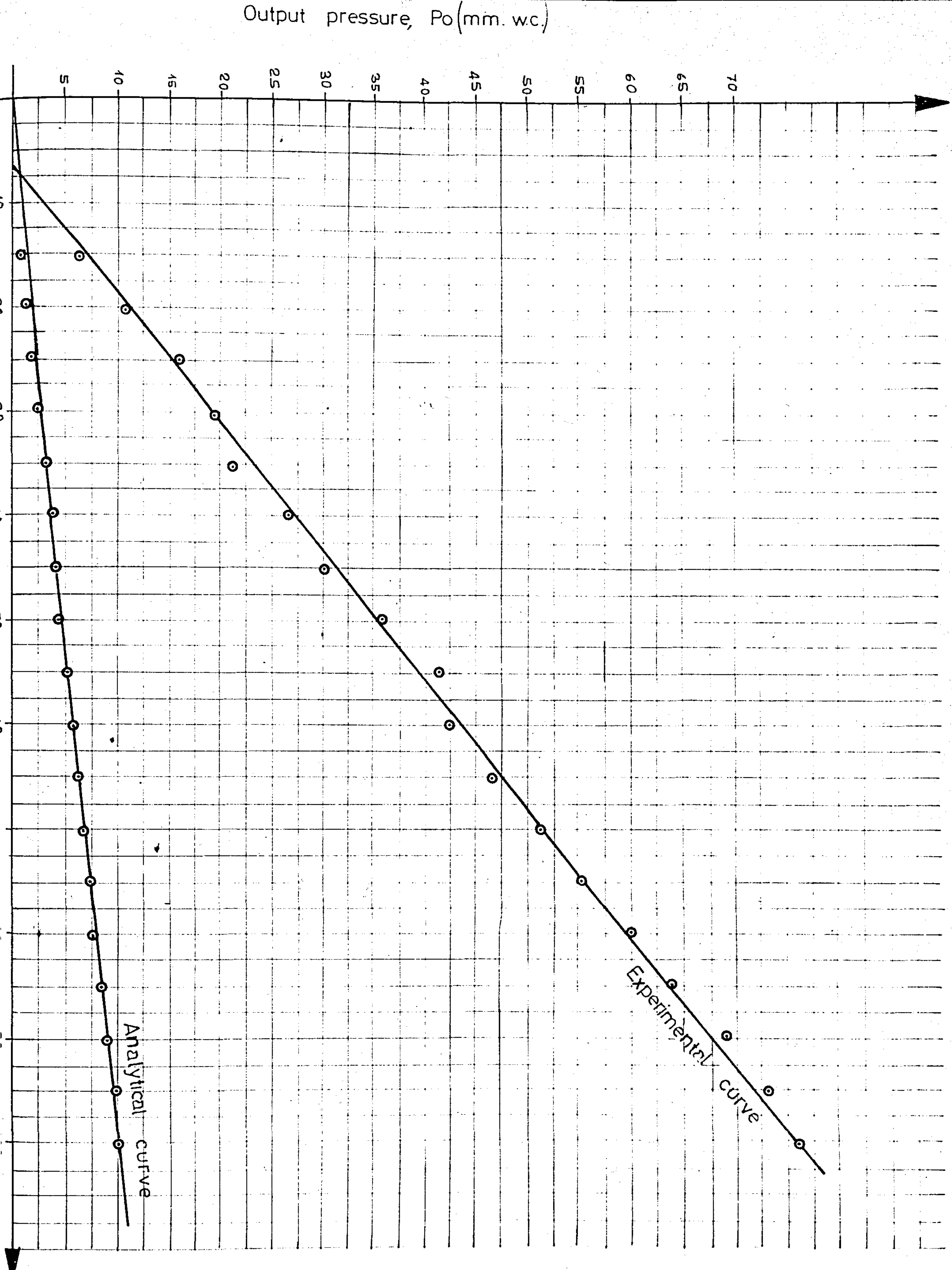

Fig.16 - Output pressure vs. supply pressure curve for a turbulance amplifier with supply tube diameter 0.079 inches for no-control-flow case.

curves for different lengths between supply and output tubes are presented in graphical form in fig.17. As the distance between the tubes increases the slope of the curves decreases, so that at a given supply pressure useful output also decreases with increasing distance between the tubes, which is an expected outcome.

In fig.18 and 18a, velocity profiles are plotted at successive distances from the supply tube for supply pressure 0.2 psig. It is observed that the jet spread is less in the latter case because of a more confined behaviour of the jet at higher input pressures.[9] Data is evaluated by a computer program and is presented in table form in App. A.

P_o vs. P_c curves for constant ℓ and ω (where $\ell = 0.05$ inches, $\omega = 0.005$ inches) are plotted in fig.19 through fig.22 for a control pressure range of 0.01 to 0.02 psig at constant supply pressures of 0.1, 0.2, 0.3, 0.4, 0.5 psig and at constant distances between supply and output tubes; the curves approach P_o-axis asymptotically. Experimental results obtained from ref. (5 and 6), for supply pressures of 0.2 and 0.5 psig at a distance between supply and output tubes of approximately 0.3 inches are also plotted on the corresponding analytical curves. P_o values at zero control pressure are observed to be very close in both cases, and the variation of the curves are similar. Thus assumptions leading to analytical results are verified both in trend and magnitude partially. Also, according to fig.23, the assumption of $P \sim 1/x^2$ is verified since the curves approach P_o-axis asymptotically.

A study of P_o vs. P_c curves reveals that, at supply pressure equal to 0.5 psig, when control pressure is equal to 0.01 psig. output pressure

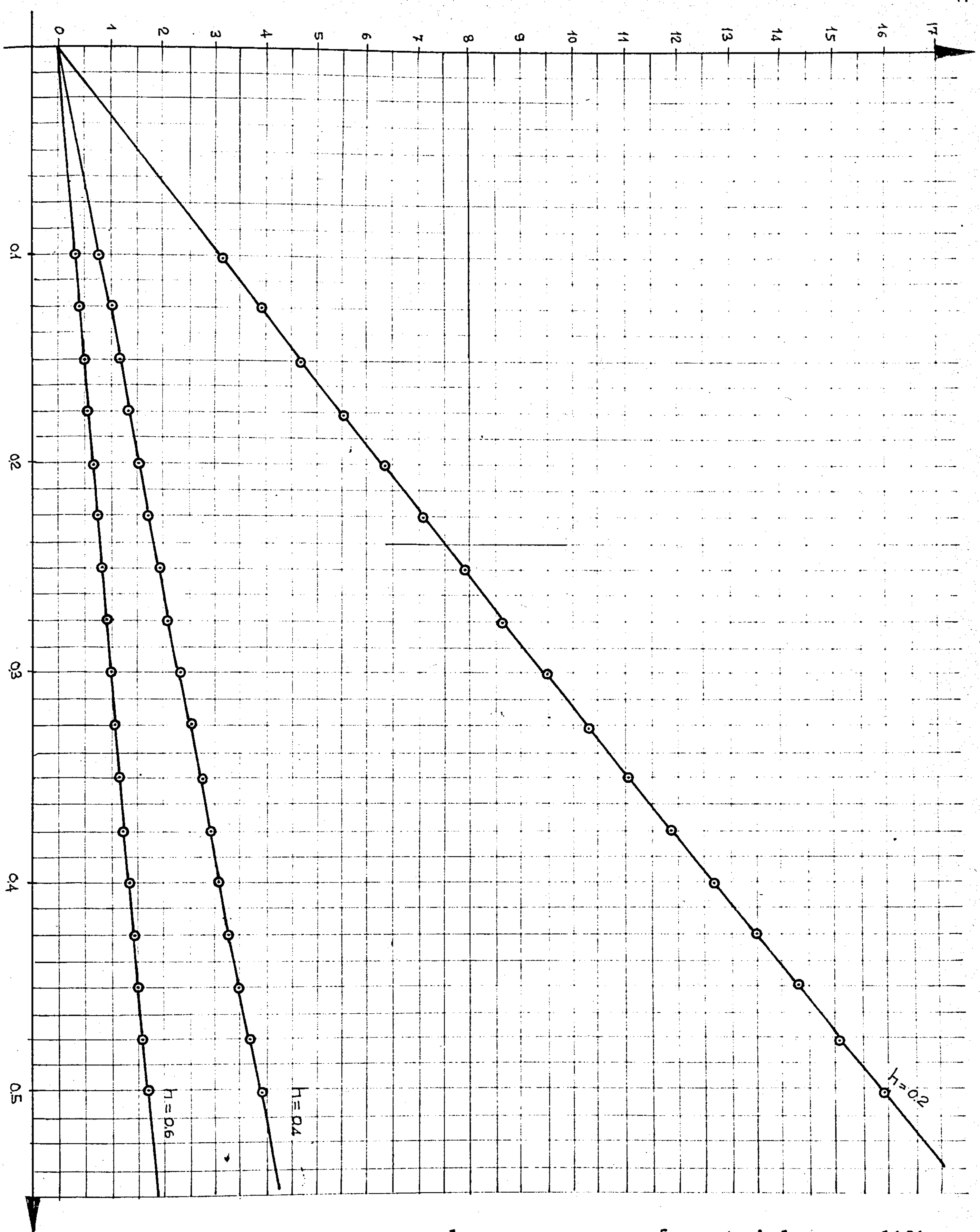

Fig.17 - Output pressure vs. supply pressure curves for a turbulance amplifier with 0.03 inches supply tube diameter, for no-control-flow case.

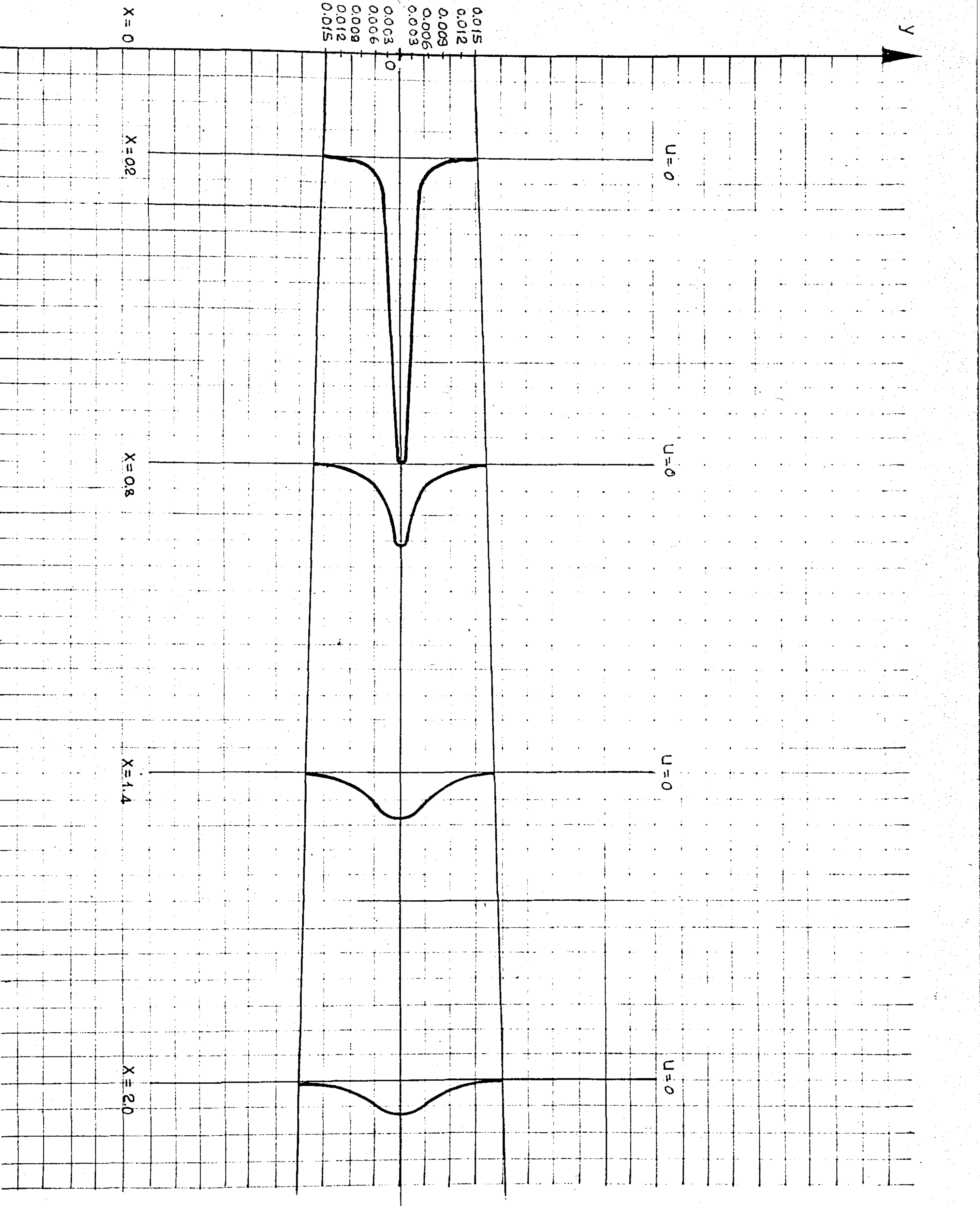

Fig.18 and 18a - Velocity profiles for a jet with initial diameter equal to 0.03 inches.
(18) When supply pressure is 0.4 psig (for this case velocity scale is 1 cm. = 20.000 in/sec.)
(18a) When supply pressure is 0.2 psig (for this case velocity scale is 1 cm. = 10.000 in/sec.)

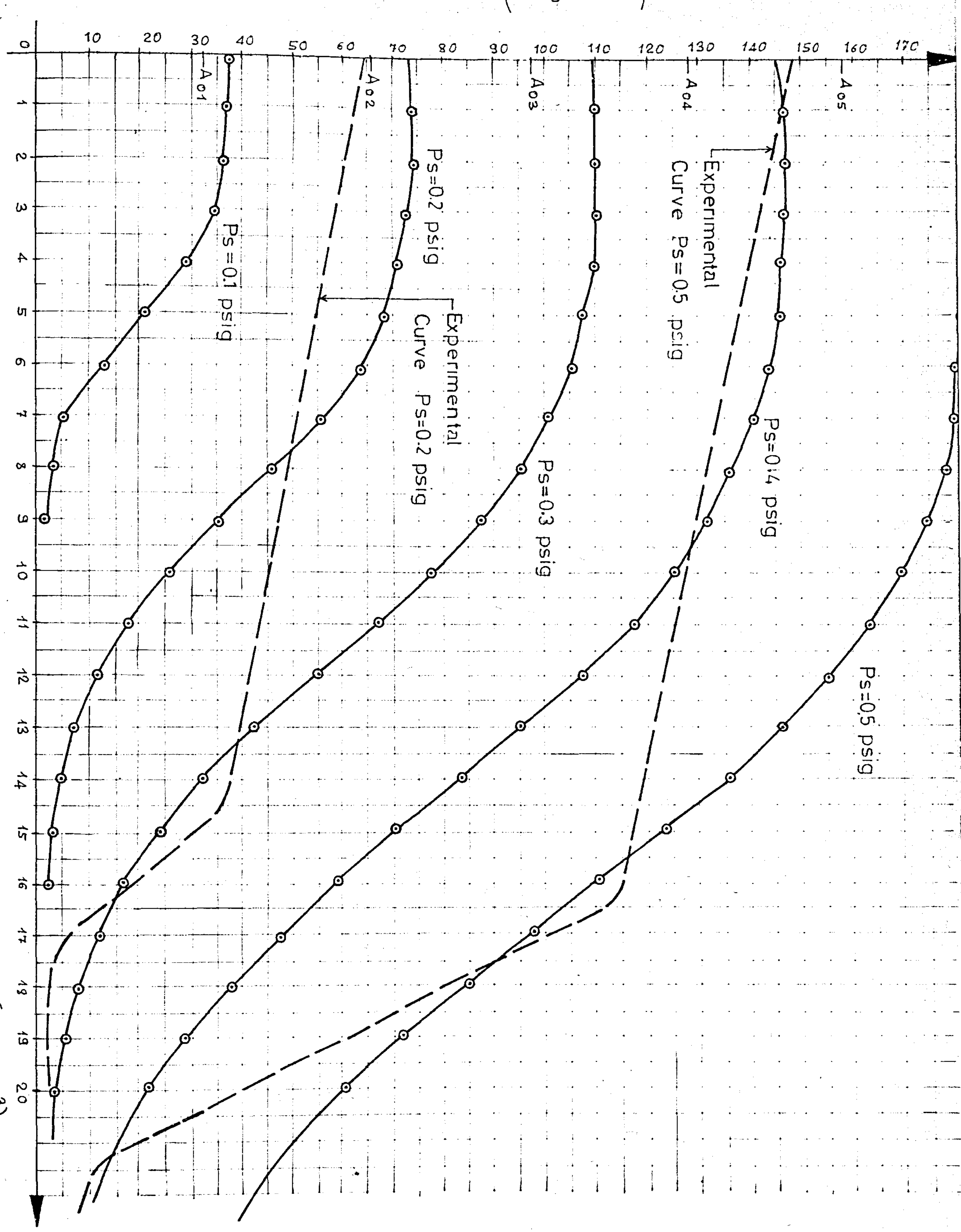

Fig.19 - Output pressure vs. control pressure for constant values of supply pressu when the distance between supply and output tubes is 0.2 inches. Dotted lines are corresponding experimental curves.[5] Points indicated by A on the abcissa refer to P_o values from no-control-flow analysis, subsrip indicating respective supply pressures.

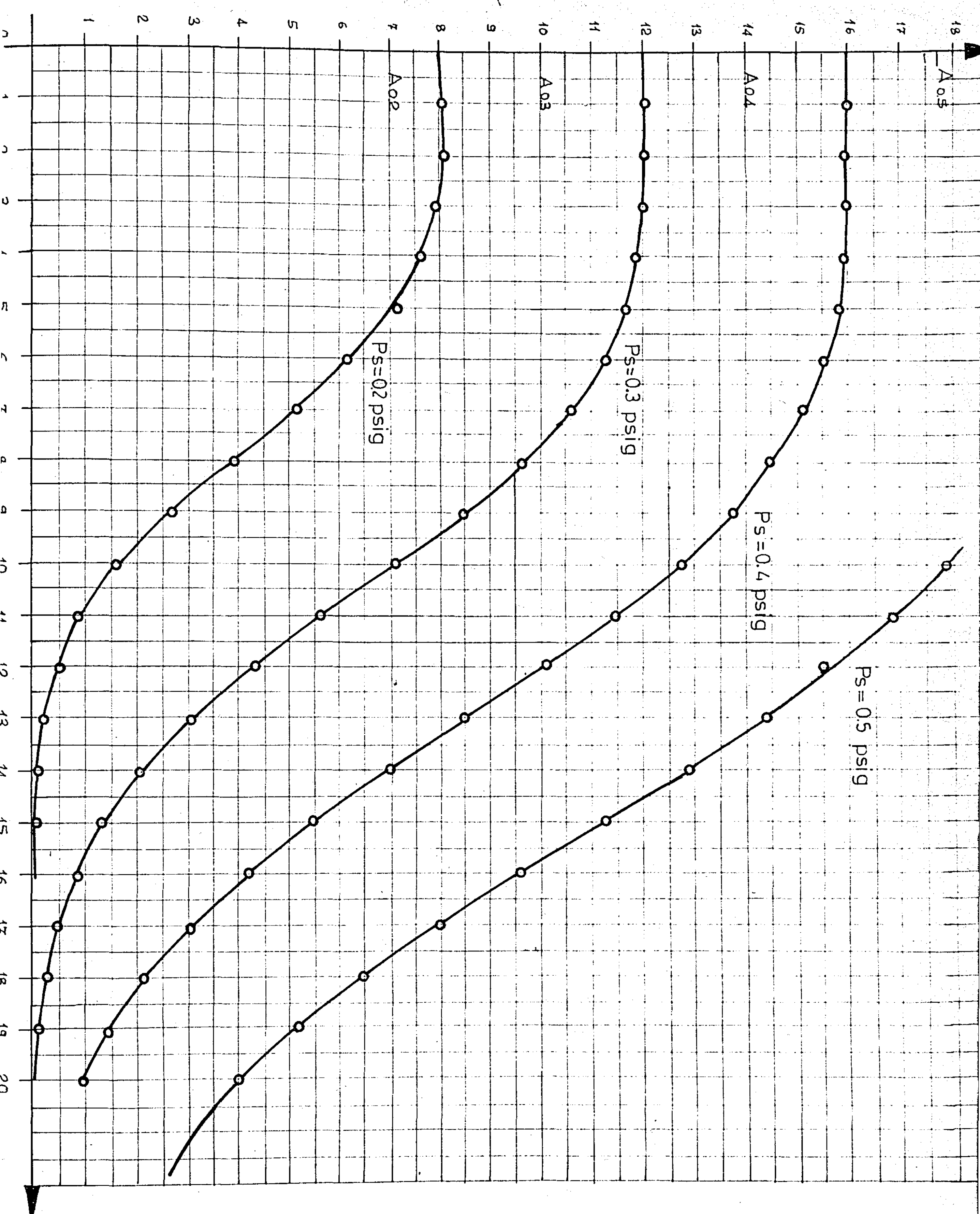

Fig.20 - Output pressure vs. control pressure for constant values of supply pressure when the distance between supply and output tubes is 0.6 inches. Points indicated by A on the abcissa refer to P_o values from no-control-flow analysis, subscripts indicating respective supply pressures.

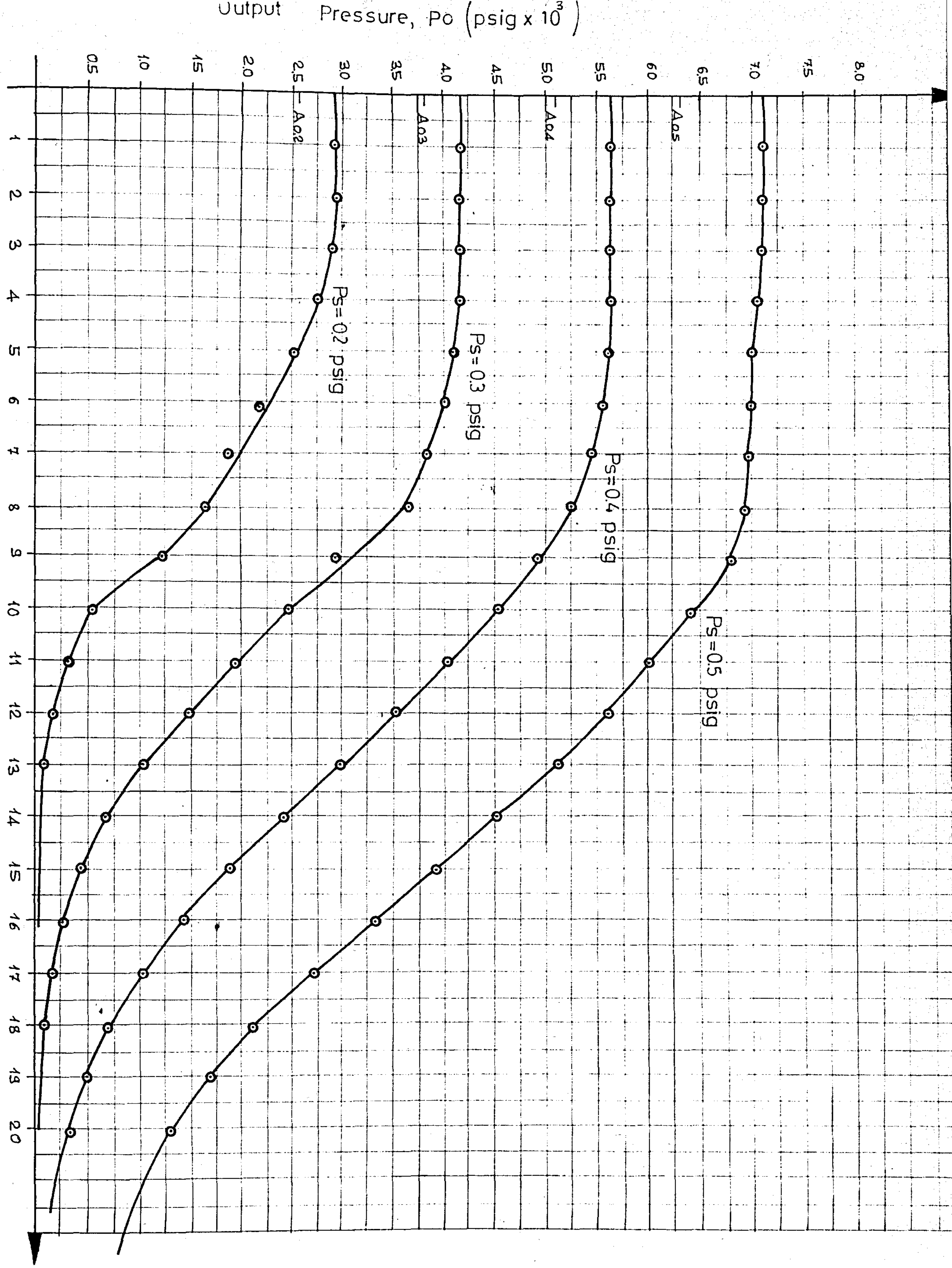

Fig.21 - Output pressure vs. control pressure for constant values of supply pressure when the distance between supply and output tubes is 1.0 inches. Points indicated by A on the abcissa refer to P_o values from no-control-flow analysis, subscripts indicating respective supply pressures.

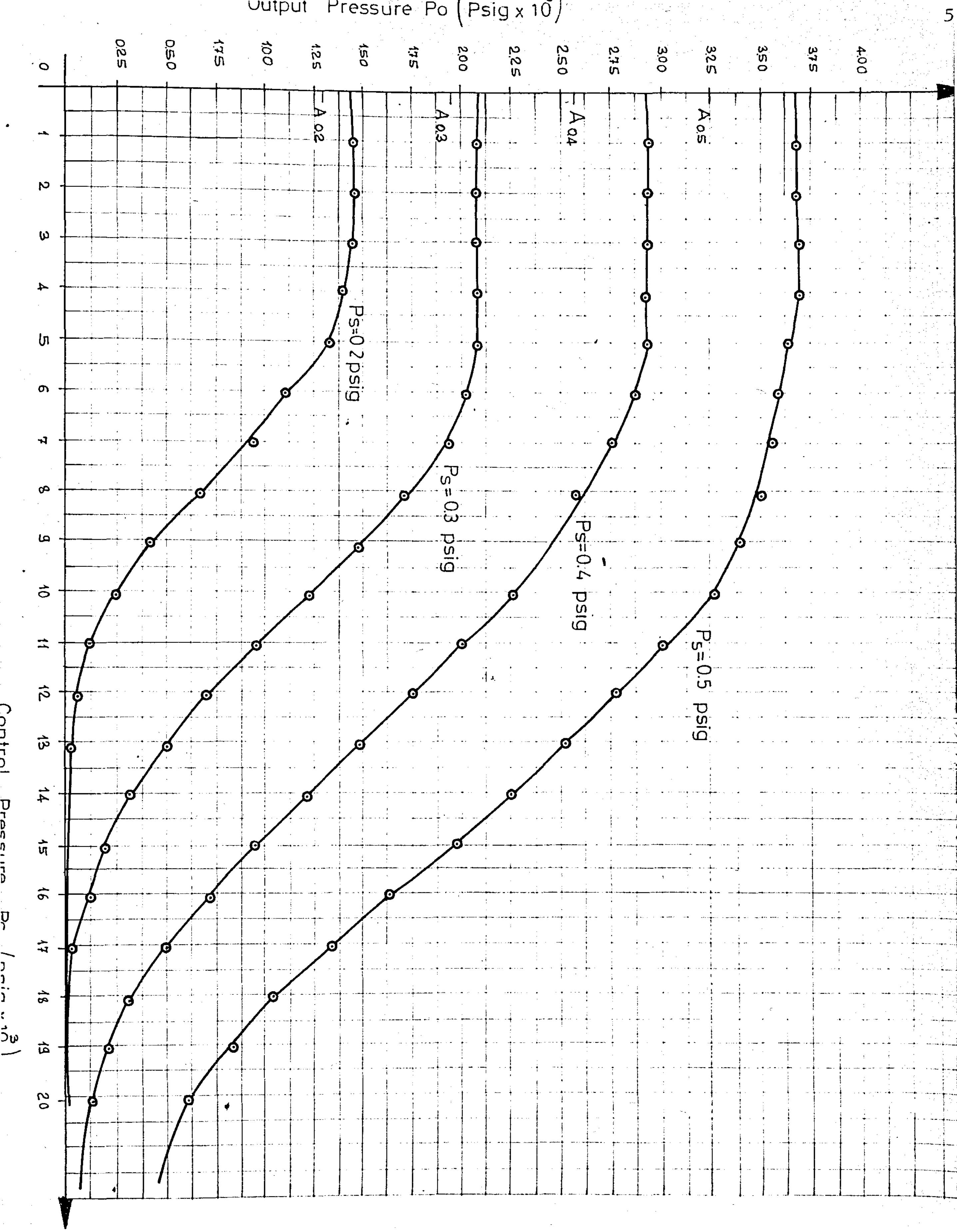

Fig.22 - Output pressure vs. control pressure for constant values of supply pressure when the distance between supply and output tubes is 1.4 inches. Points indicated by A on the abcissa refer to P_o values from no-control-flow analysis, subscripts indicating respective supply pressures.

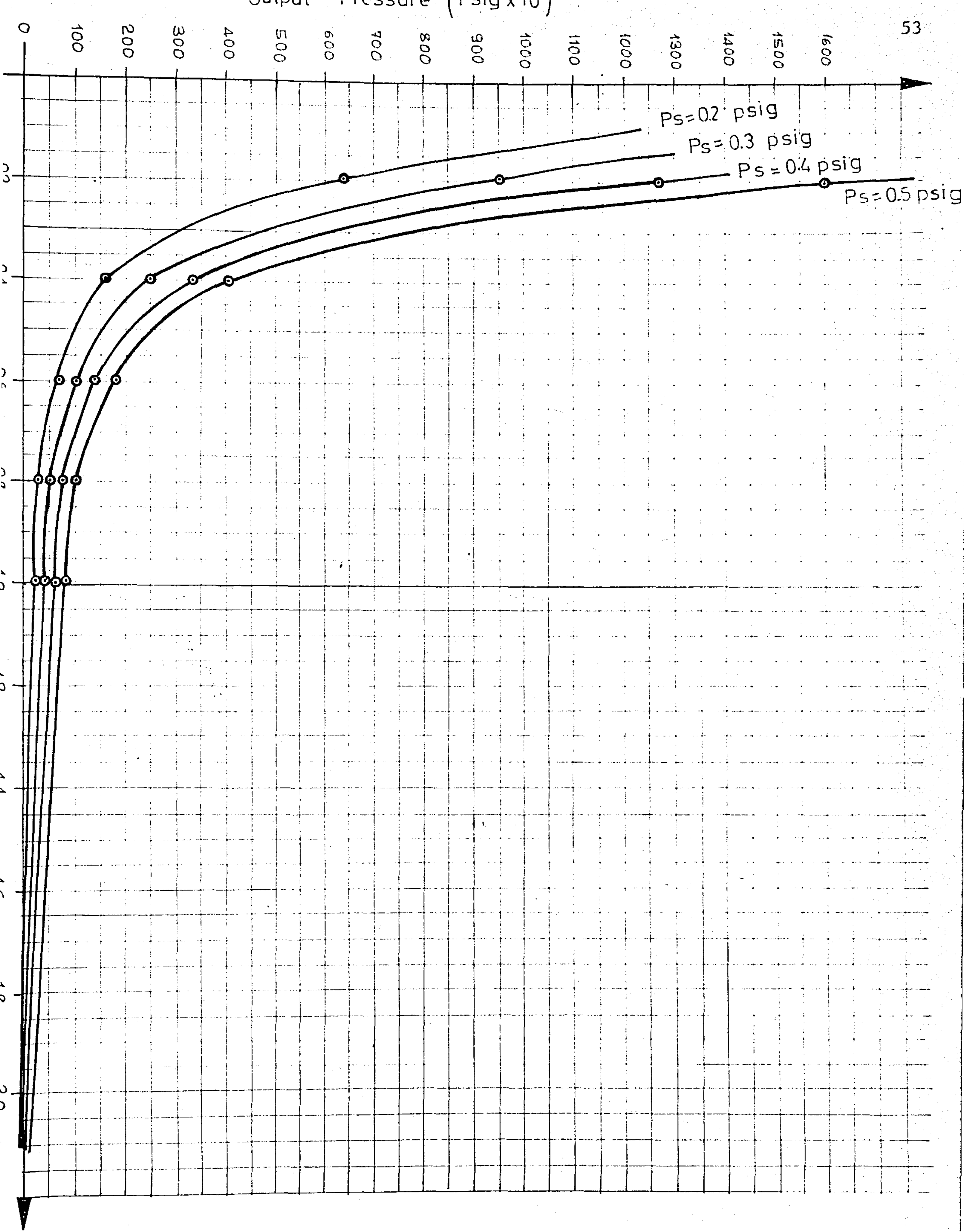

Fig.23 - Output pressure vs. distance between supply and output tubes at constant supply pressure for no-control-flow case.

is higher than output pressure at no control flow. This must be an outcome of the assumption of momentum conservation at the point of impinge, so that at supply pressures greater than 0.4 psig, the deflection angle, α, imposed on the supply jet by the control jet is practically zero, so that the result becomes an increase in momentum of the supply jet. The same discussion is also applicable to control pressures less than 0.01 psig at supply pressures greater than 0.2 psig. Therefore the validity of the assumption of momentum conservation is confined to a supply pressure range of 0.1 to 0.4 psig and a control pressure range of 0.01 to 0.02 psig.

C. Analysis of $\eta = P_o/P_s = \phi\,\{((P_c/P_s)^a\ \ell/h),((P_c/P_s)^b\ \omega/h)\}$ for the "Ideal Amplifier"

Estimation of output pressure, up to this point, has been done by considering ℓ and ω as constants. This analysis has given a general idea of the nature of variation of the dependent variable, P_o, as a function of independent variables P_s, P_c and h as well as of P_o/P_s as a function of P_c/P_s. It was predicted that P_o is a linear function of P_s in laminar region, up to Re number 500; whereas P_o/P_s is a logarithmic function of P_c/P_s. In this part of the analysis ℓ and ω are also treated as variables, operating ranges pertaining to each is estimated on the basis of the validity of assumptions made; and the function η is analysed by linear regression.

1. Operating Ranges of Geometric Variables ω and ℓ

Various values have been assigned to ℓ and ω and output pressures calculated by the procedure presented in section IV. Calculations indicated that for values of ℓ between 0.01 and 0.05 inches, and ω between 0.003 and 0.006 inches the variation of P_o and P_o/P_s are in an expected trend. Therefore when ℓ and ω are treated as variables, they are made to vary within their respective limits stated above.

2. Linear Regression

The regression program[x] that has been used is a linear program. However the function η is a nonlinear function. Therefore in order to use this program the powers a and b of the variable (P_c/P_s) have to be determined before. Previous analysis has shown that

$$P_o/P_s = A(P_c/P_s)^a \tag{61}$$

It is also known that

$$P \sim \frac{1}{x^2}$$

so that the powers of the geometric dimensionless variables must be two. Further, in order to compensate for the effect of distance between supply and output tubes when control pressure is zero, a new dimensionless variable, $(d/h)^2$, (diameter of supply tube divided by distance between supply and output tubes) is introduced, so that the final form of η is

$$\eta = P_o/P_s = \emptyset_2 \{ ((P_c/P_s)^a(\ell/h)^2) ,((P_c/P_s)^b(\omega/h)^2) (d/h)^2 \} \tag{62}$$

A linear regression will therefore yield

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x The program written by Asst. Prof. Mehmet Tümay is presented in App.B. This program is for 10 variables and a maximum of 75 data points.

$$P_o/P_s = A(P_c/P_s)^a(\ell/h)^2 + B\ (P_c/P_s)^b(\omega/h)^2 + C(d/h)^2 + D \qquad (63)$$

However since data must be given in linear form, the powers of P_c/P_s, a and b must be estimated before.

Maximum and minimum critical values were calculated for a and b on the following basis:

(a) setting $\ell = 0.05$ inches, $\omega = 0.001$ inches and $h = 0.20$ inches corresponding P_o values were evaluated for P_s between 0.1 and 0.4 psig and P_c between 0.01 and 0.02 psig by a computer program, results were correlated on a log-log basis and a maximum was found to be −0.04853

(b) setting $\ell = 0.01$ inches, $\omega = 0.003$ inches and $h = 2.0$ inches corresponding P_o values were evaluated for P_s between 0.1 and 0.4 psig and P_c between 0.01 and 0.02 psig by a computer program, results were correlated on a log-log basis and a minimum was found to be − 8.24867.

Various values in multiples of −8.24867 and −0.04853 were assigned to both a and b so that 10 variables to enter the final regression were obtained. Also 60 data points were selected, to cover the defined ranges of the parameters, and corresponding P_o evaluated for each data set by a computer program. The output of this program is used as the input of the regression program.[x]

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[x] The program and the results are presented in App.B.

Four of these variables were accepted by the regression program to be correlated at an entrance f-level of 2.5, so that the regression has yielded the following function, with an overall correlation coefficient of 0.95104, and a standard deviation of 0.0142[x],

$$\begin{aligned}(P_o/P_s) = & -2.48915\ (P_c/P_s)^{-0.04853}(\omega/h)^2 \\ & + 0.00903\ (P_c/P_s)^{-4.14860}\ (\ell/h)^2 \\ & - 0.0013\ (P_c/P_s)^{-5.53146}\ (\ell/h)^2 \\ & + 4.01687(d/h)^2 - 0.00168\end{aligned} \tag{64}$$

[x] The program and the results are presented in App.B.

VII. CONCLUSIONS

The analysis made for a turbulance amplifier of 0.03 inch supply tube diameter has been based on the following assumptions:

(a) application of Bernoulli's equation to a viscous flow

(b) application of Schlichting's solution for laminar, circular jets in an infinite field to jet flow in a finite field, by relating pressure decrease to centerline velocity.

(c) assumption of momentum conservation at the point of impinge of the supply and control jets.

Results obtained have been observed to be in close relation with the limited, available experimental results. Within the defined ranges of the parameters P_s, P_c, h, ω and ℓ, which are

(a) 0.1 psig $< P_s <$ 0.4 psig

(b) 0.01 psig $< P_c <$ 0.02 psig ; $1/40 < P_c/P_s < 1/5$

(c) 0.2 inches $< h <$ 2.00 inches

(d) 0.01 inches $< \ell <$ 0.05 inches

(e) 0.003 inches $< \omega <$ 0.006 inches

output pressure can be estimated by equation (64), which is outcome of the linear regression, with an overall correlation coefficient of 0.95104 and a standard deviation of 0.0142 at an f-level of 2.5. Thus 33 per cent of any number of P_o values calculated by using equation (64) will have a deviation of 0.0142 from the mean; and the probability of this to occur is 90 per cent.

The method presented may also be used generally for the design of a turbulance amplifier of a given supply tube diameter, by using the governing expressions developed.

It is also predicted from eq.(64) that the geometric parameter, ℓ, has a greater effect on the sensitivity of the device in comparison to the geometric parameter ω. Sensitivity increases, that is P_o/P_s decreases, when control tube is located close to the centerline. Sensitivity of the device increases also with decreasing distance between supply and control tubes, whereas it decreases with increasing h.

Useful output, output pressure at zero control pressure, is inversely proportional to the square of the distance between supply and output tubes and directly proportional to supply pressure. Therefore the effect of distance on useful output is more pronounced than the effect of supply pressure.

Results pertaining to the with-control-flow case have indicated that the assumption of momentum conservation can be applied for relatively larger values of control pressure. A possible way of increasing the range of application would be to find a mathematical expression for the physical situation at the point of impinge of the supply and control jets, so that the momentum loss may be defined and considered. However a more precise and elegant approach to the problem of jet flow in a finite field would be to assume a similarity parameter for the pressure gradient in the flow direction and then solve boundary layer equations, and obtain nonlinear differential equations characterizing the flow conditions, the solution of which may be possible by using numerical analysis techniques.

A P P E N D I X   A

TABLE I: OUTPUT PRESSURES FOR A TURBULANCE AMPLIFIER WITH

0.079 inch SUPPLY TUBE DIAMETER (NO-CONTROL-FLOW CASE)

h (inches)	P_s (psi)	$\bar{u}_{max_2}$ (in/sec)	$\bar{u}_{max_1}$ (in/sec)	P_o (psi)
.788	15.0	6085.81	19325.86	1.48748
.788	20.0	8114.42	25767.81	1.98331
.788	25.0	10143.03	32209.77	2.47913
.788	30.0	12171.63	38651.72	2.97496
.788	35.0	14200.24	45093.68	3.47079
.788	40.0	16228.85	51535.63	3.96662
.788	45.0	18257.45	57977.59	4.46244
.788	50.0	20286.06	64419.54	4.95827
.788	55.0	22314.67	70861.50	5.45410
.788	60.0	24343.27	77303.45	5.94993
.788	65.0	26371.88	83745.41	6.44575
.788	70.0	28400.49	90187.36	6.94158
.788	75.0	30429.09	96629.32	7.43740
.788	80.0	32457.70	103071.26	7.93325
.788	85.0	34486.31	109513.22	8.42907
.788	90.0	36514.91	115955.17	8.92490
.788	95.0	38543.52	122397.13	9.42072
.788	100.0	40572.12	128839.07	9.91657
1.970	15.0	2434.32	19325.86	.23799
1.970	20.0	3245.77	25767.81	.31733
1.970	25.0	4057.21	32209.77	.39666
1.970	30.0	4868.65	38651.72	.47599
1.970	35.0	5680.09	45093.68	.55532
1.970	40.0	6491.54	51535.63	.63466
1.970	45.0	7302.98	57977.59	.71399
1.970	50.0	8114.42	64419.54	.79332
1.970	55.0	8925.86	70861.50	.87265
1.970	60.0	9737.31	77303.45	.95199

(continued)

TABLE I (continued)

h (inches)	P_s (psi)	$\bar{u}_{max_2}$ (in/sec)	$\bar{u}_{max_1}$ (in/sec)	P_o (psi)
1.970	65.0	10548.75	83745.41	1.03132
1.970	70.0	11360.19	90187.36	1.11066
1.970	75.0	12171.63	96629.32	1.18998
1.970	80.0	12983.08	103071.26	1.26934
1.970	85.0	13794.52	109513.22	1.34866
1.970	90.0	14605.96	115955.17	1.42800
1.970	95.0	15417.41	122397.13	1.50732
1.970	100.0	16228.85	128839.07	1.58667

h : distance between supply and output tubes, inches.

P_s : supply pressure, psi.

$\bar{u}_{max_2}$: maximum average velocity at the entrance of the output tube, in/sec.

$\bar{u}_{max_1}$: maximum average velocity at the exit of the supply tube, in/sec.

P_o : output pressure, psi.

TABLE II: VELOCITY DISTRIBUTION OF A LAMINAR JET WITH AN INITIAL DIAMETER

(SUPPLY TUBE DIAMETER) OF 0.03 inches

h (inches)	P_s (psi)	y = 0	y = 0.003 inch.	y = 0.006 inch.	y = 0.009 inch.	y = 0.012 inch.	y = 0.015 inch
.20	.200000	31686.22500	424.97653	31.85429	6.51987	2.08906	.86070
.20	.225000	35647.00300	387.66958	28.51549	5.81396	1.86J30	.76595
.20	.250000	39607.78100	356.29510	25.80973	5.24595	1.67669	.69000
.20	.275000	43568.55900	329.56333	23.57267	4.77904	1.52607	.62775
.20	.300000	47529.33700	306.52687	21.69230	4.38845	1.40028	.57580
.20	.325000	51490.11500	286.47631	20.08963	4.05687	1.29364	.53179
.20	.350000	55450.89000	268.87110	18.70741	3.77187	1.20210	.49403
.20	.375000	59411.67000	253.29253	17.50308	3.52429	1.12266	.46128
.20	.400000	63372.45000	239.41178	16.44440	3.30720	1.05306	.43260
.20	.425000	67333.22500	226.96704	15.50646	3.11531	.99159	.40728
.20	.450000	71294.00500	215.74728	14.66971	2.94446	.93690	.38476
.20	.475000	75254.78000	205.58085	13.91863	2.79138	.88793	.36459
.20	.500000	79215.56000	196.32661	13.24070	2.65342	.84382	.34644
.40	.200000	15843.11200	1872.58650	212.48823	47.94384	15.92714	6.67527
.40	.225000	17823.50100	1799.36550	193.83475	43.14253	14.25774	5.96073
.40	.250000	19803.89000	1727.45940	178.14755	39.21318	12.90486	5.38433
.40	.275000	21784.27900	1658.26990	164.78166	35.93852	11.78633	4.90956
.40	.300000	23764.66800	1592.46640	153.26340	33.16779	10.84615	4.51171
.40	.325000	25745.05700	1530.30670	143.23813	30.79315	10.04481	4.17350
.40	.350000	27725.44500	1471.81470	134.43553	28.73544	9.35370	3.88245
.40	.375000	29705.83500	1416.88650	126.64626	26.93524	8.75154	3.62934
.40	.400000	31686.22500	1365.35020	119.70589	25.34710	8.22220	3.40721
.40	.425000	33666.61200	1317.00240	113.48351	23.93567	7.75323	3.21070
.40	.450000	35647.00200	1271.62730	107.87363	22.67303	7.33485	3.03562
.40	.475000	37627.39000	1229.01230	102.79042	21.53685	6.95931	2.87865
.40	.500000	39607.78000	1188.95250	98.16330	20.50904	6.62035	2.73711

(continued)

TABLE II (continued)

h (inches)	P_s (psi)	y = 0	y = 0.003 inch.	y = 0.006 inch.	y = 0.009 inch.	y = 0.012 inch.	y = 0.015 in
1.00	.200000	6337.24500	3718.93280	1284.04600	451.00166	182.90217	84.99529
1.00	.225000	7129.40060	3949.43310	1264.71960	425.75608	168.89574	77.53390
1.00	.250000	7921.55620	4149.13470	1240.54650	402.61791	156.79571	71.25902
1.00	.275000	8713.71180	4321.94080	1213.51270	381.49348	146.25890	65.91265
1.00	.300000	9505.86750	4471.19830	1184.94040	362.22406	137.01319	61.30536
1.00	.325000	10298.02300	4599.79230	1155.71400	344.63290	128.84247	57.29525
1.00	.350000	11090.17800	4710.21330	1126.42600	328.54629	121.57433	53.77421
1.00	.375000	11882.33400	4804.62230	1097.47070	313.80344	115.07017	50.65850
1.00	.400000	12674.49000	4884.89690	1069.10710	300.25910	109.21765	47.88235
1.00	.425000	13466.64500	4952.67470	1041.50120	287.78433	103.92494	45.39340
1.00	.450000	14258.80100	5009.38510	1014.75350	276.26543	99.11643	43.14945
1.00	.475000	15050.95600	5056.28240	988.92052	265.60249	94.72931	41.11616
1.00	.500000	15843.11200	5094.46900	964.02701	255.70796	90.71107	39.26531
1.20	.200000	5281.03750	3594.66260	1545.85440	624.19553	273.61987	132.97472
1.20	.225000	5941.16710	3872.73870	1555.48740	599.78846	256.00317	122.48063
1.20	.250000	6601.29680	4124.59480	1554.99950	575.81982	240.27465	113.46754
1.20	.275000	7261.42650	4352.72320	1547.15170	552.75648	226.21017	105.65586
1.20	.300000	7921.55620	4559.34660	1533.96270	530.82206	213.59640	98.82807
1.20	.325000	8581.68580	4746.45200	1516.92310	510.10221	202.24280	92.81397
1.20	.350000	9241.81500	4915.81910	1497.14200	490.60489	191.98415	87.47922
1.20	.375000	9901.94500	5069.04290	1475.45030	472.29551	182.67892	82.71681
1.20	.400000	10562.07500	5207.55750	1452.47350	455.11675	174.20667	78.44062
1.20	.425000	11222.20400	5332.65440	1428.68410	439.00070	166.46486	74.58068
1.20	.450000	11882.33400	5445.49700	1404.43970	423.87571	159.36614	71.07969
1.20	.475000	12542.46300	5547.13700	1380.01120	409.67077	152.83593	67.89025
1.20	.500000	13202.59300	5638.52660	1355.60360	396.31747	146.81027	64.97288

(continued)

TABLE II (continued)

h (inches)	P_s (psi)	y = 0	y = 0.003 inch.	y = 0.006 inch.	y = 0.009 inch.	y = 0.012 inch.	y = 0.015 inch.
1.80	.200000	3520.69160	2940.28510	1856.70410	1030.56960	559.67333	312.51770
1.80	.225000	3960.77810	3237.72280	1952.83400	1036.99160	544.67760	297.14100
1.80	.250000	4400.86450	3522.03280	2033.03420	1036.66640	528.69443	282.70118
1.80	.275000	4840.95100	3793.83900	2099.66910	1031.43440	512.41430	269.26646
1.80	.300000	5281.03750	4053.72890w	2154.71630	1022.64180	496.25757	256.82345
1.80	.325000	5721.12380	4302.26000	2199.83610	1011.28200	480.47634	245.32016
1.80	.350000	6161.21000	4539.95720	2236.43010	998.09474	465.21712	234.68850
1.80	.375000	6601.29660	4767.32080	2265.68430	983.63358	450.55907	224.85585
1.80	.400000	7041.38330	4984.82070	2288.60780	968.31573	436.53882	215.75130
1.80	.425000	7481.46940	5192.90390	2306.06130	952.45613	423.16487	207.30697
1.80	.450000	7921.55610	5391.99380	2318.78130	936.29315	410.42969	199.46206
1.80	.475000	8361.64220	5582.49110	2327.40050	920.00752	398.31467	192.16034
1.80	.500000	8801.72880	5764.77660	2332.46420	903.73573	386.79496	185.35154
2.00	.200000	3168.62250	2735.04840	1859.46640	1113.19670	642.02304	374.51729
2.00	.225000	3564.70030	3023.08320	1974.71650	1133.94890	632.35983	359.87306
2.00	.250000	3960.77810	3300.70890	2074.56730	1146.20140	620.27329	345.49185
2.00	.275000	4356.85590	3568.33370	2160.97040	1151.91330	606.75640	331.65389
2.00	.300000	4752.93370	3826.34730	2235.59910	1152.57840	592.47020	318.49323
2.00	.325000	5149.01150	4075.12160	2299.89610	1149.34370	577.85702	306.06131
2.00	.350000	5545.08900	4315.01090	2355.10660	1143.09810	563.21301	254.36292
2.00	.375000	5941.16700	4546.35450	2402.31110	1134.53440	548.73535	283.37730
2.00	.400000	6337.24500	4769.47720	2442.44840	1124.19520	534.55358	273.07004
2.00	.425000	6733.32350	4984.68830	2476.33730	1112.50920	520.75064	263.40041
2.00	.450000	7129.40050	5192.28470	2504.69250	1099.81440	507.37676	254.32541
2.00	.475000	7525.47800	5392.54860	2528.14120	1086.38000	494.46026	245.80245
2.00	.500000	7921.55600	5585.75200	2547.23450	1072.42060	482.01350	237.79048

h = Distance from the supply tube in axial direction, inches.

P_s = Pressure at the exit of the supply tube, psi.

y = Distance from the center of the supply tube in radial direction, inches.

TABLE III: OUTPUT PRESSURES FOR A TURBULANCE AMPLIFIER WITH 0.03 INCH SUPPLY TUBE DIAMETER (NO-CONTROL-FLOW CASE)

h(inches)	P_s (psi)	$\overline{u}_{max_2}$ (in/sec)	$\overline{u}_{max_1}$ (in/sec)	P_o (psi)	P_o/P_s
.20	.200000	31686.22500	56085.79000	.06383	.319179
.20	.225000	35647.00300	63096.51400	.07181w	.319179
.20	.250000	39607.78100	70107.23800	.07979	.319179
.20	.275000	43568.55900	77117.96200	.08777	.319179
.20	.300000	47529.33700	84128.68600	.09575	.319179
.20	.325000	51490.11500	91139.41000	.10373	.319179
.20	.350000	55450.89000	98150.12800	.11171	.319179
.20	.375000	59411.67000	105160.85000	.11969	.319179
.20	.400000	63372.45000	112171.58000	.12767	.319179
.20	.425000	67333.22500	119182.29000	.13565	.319179
.20	.450000	71294.00500	126193.02000	.14363	.319179
.20	.475000	75254.78000	133203.75000	.15161	.319179
.20	.500000	79215.56000	140214.47000	.15958	.319179
.40	.200000	15843.11200	56085.79000	.01595	.079795
.40	.225000	17823.50100	63096.51400	.01795	.079794
.40	.250000	19803.89000	70107.23800	.01994	.079794
.40	.275000	21784.27900	77117.96200	.02194	.079794
.40	.300000	23764.66800	84128.68600	.02393	.079794
.40	.325000	25745.05700	91139.41000	.02593	.079794
.40	.350000	27725.44500	98150.12800	.02792	.079794
.40	.375000	29705.83500	105160.85000	.02992	.079794
.40	.400000	31686.22500	112171.58000	.03191	.079794
.40	.425000	33666.61200	119182.29000	.03391	.079794
.40	.450000	35647.00200	126193.02000	.03590	.079794
.40	.475000	37627.39000	133203.75000	.03790	.079794
.40	.500000	39607.78000	140214.47000	.03989	.079794

(continued)

TABLE III (continued)

h (inches)	P_s (psi)	$\overline{u}_{max_2}$ (in/sec)	$\overline{u}_{max_1}$ (in/sec)	P_o (psi)	P_o/P_s
.60	.200000	10562.07500	56085.79000	.00709	.035464
.60	.225000	11882.33400	63096.51400	.00797	.035464
.60	.250000	13202.59300	70107.23800	.00886	.035464
.60	.275000	14522.85300	77117.96200	.00975	.035464
.60	.300000	15843.11200	84128.68600	.01063	.035464
.60	.325000	17163.37100	91139.41000	.01152	.035464
.60	.350000	18483.63000	98150.12800	.01241	.035464
.60	.375000	19803.89000	105160.85000	.01329	.035464
.60	.400000	21124.15000	112171.58000	.01418	.035464
.60	.425000	22444.40800	119182.29000	.01507	.035464
.60	.450000	23764.66800	126193.02000	.01595	.035464
.60	.475000	25084.92600	133203.75000	.01684	.035464
.60	.500000	26405.18600	140214.47000	.01773	.035464
1.00	.200000	6337.24500	56085.79000	.00255	.012767
1.00	.225000	7129.40060	63096.51400	.00287	.012767
1.00	.250000	7921.55620	70107.23800	.00319	.012767
1.00	.275000	8713.71180	77117.96200	.00351	.012767
1.00	.300000	9505.86750	84128.68600	.00383	.012767
1.00	.325000	10298.02300	91139.41000	.00414	.012767
1.00	.350000	11090.17800	98150.12800	.00446	.012767
1.00	.375000	11882.33400	105160.85000	.00478	.012767
1.00	.400000	12674.49000	112171.58000	.00510	.012767
1.00	.425000	13466.64500	119182.29000	.00542	.012767
1.00	.450000	14258.80100	126193.02000	.00574	.012767
1.00	.475000	15050.95600	133203.75000	.00606	.012767
1.00	.500000	15843.11200	140214.47000	.00638	.012767

(continued)

TABLE III (continued)

h (inches)	P_s (psi)	$\overline{u}_{max_2}$ (in/sec)	$\overline{u}_{max_1}$ (in/sec)	P_o (psi)	P_o/P_s
1.40	.200000	4526.60350	56085.79000	.00130	.006513
1.40	.225000	5092.42900	63096.51400	.00146	.006513
1.40	.250000	5658.25440	70107.23800	.00162	.006513
1.40	.275000	6224.07980	77117.96200	.00179	.006513
1.40	.300000	6789.90530	84128.63600	.00195	.006513
1.40	.325000	7355.73070	91139.41000	.00211	.006513
1.40	.350000	7921.55570	98150.12800	.00227	.006513
1.40	.375000	8487.38140	105160.85000	.00244	.006513
1.40	.400000	9053.20710	112171.58000	.00260	.006513
1.40	.425000	9619.03210	119182.29000	.00276	.006513
1.40	.450000	10184.85700	126193.02000	.00293	.006513
1.40	.475000	10750.68200	133203.75000	.00309	.006513
1.40	.500000	11316.50800	140214.47000	.00325	.006513
2.00	.200000	3168.62250	56085.79000	.00063	.003191
2.00	.225000	3564.70030	63096.51400	.00071	.003191
2.00	.250000	3960.77810	70107.23800	.00079	.003191
2.00	.275000	4356.85590	77117.96200	.00087	.003191
2.00	.300000	4752.93370	84128.68600	.00095	.003191
2.00	.325000	5149.01150	91139.41000	.00103	.003191
2.00	.350000	5545.08900	98150.12800	.00111	.003191
2.00	.375000	5941.16700	105160.85000	.00119	.003191
2.00	.400000	6337.24500	112171.58000	.00127	.003191
2.00	.425000	6733.32250	119182.29000	.00135	.003191
2.00	.450000	7129.40050	126193.02000	.00143	.003191
2.00	.475000	7525.47800	133203.75000	.00151	.003191
2.00	.500000	7921.55600	140214.47000	.00159	.003191

h : Distance between supply and output tubes, inches

P_s : Supply pressure, psi

$\overline{u}_{max_2}$: Maximum average velocity at the entrance of the output tube, in/sec.

$\overline{u}_{max_1}$: Maximum average velocity at the exit of the supply tube, in/sec.

P_o : Output pressure, psi.

TABLE IV: OUTPUT PRESSURES FOR THE CASE OF WITH-CONTROL-FLOW FOR A TURBULANCE AMPLIFIER WITH SUPPLY TUBE DIAMETER 0.030 inches AND CONTROL TUBE DIAMETER 0.015 inches[x]

h(inches)	P_s (psi)	P_c (psi)	P_o (psi)	P_o/P_s	P_c/P_s
.20000000	.10000000	.00001000	.03612496	.36124968	.00010000
.20000000	.10000000	.00301000	.03379793	.33797930	.03010000
.20000000	.10000000	.00601000	.01166642	.11666421	.06010000
.20000000	.10000000	.00901000	.00072541	.00725412	.09010000
.20000000	.10000000	.01201000	.00002461	.00024619	.12010000
.20000000	.10000000	.01501000	.00000107	.00001070	.15010000
.20000000	.10000000	.01801000	.00000007	.00000072	.18010000
.20000000	.20000000	.00001000	.07224761	.36123805	.00005000
.20000000	.20000000	.00301000	.07215243	.36076219	.01505000
.20000000	.20000000	.00601000	.06222494	.31112472	.03005000
.20000000	.20000000	.00901000	.03404529	.17022649	.04505000
.20000000	.20000000	.01201000	.00950931	.04754656	.06005000
.20000000	.20000000	.01501000	.00156020	.00780104	.07505000
.20000000	.20000000	.01801000	.00020754	.00103771	.09005000
.20000000	.30000000	.00001000	.10837024	.36123413	.00003333
.20000000	.30000000	.00301000	.10871273	.36237576	.01003333
.20000000	.30000000	.00601000	.10431194	.34770646	.02003333
.20000000	.30000000	.00901000	.08606709	.28689031	.03003333
.20000000	.30000000	.01201000	.05322212	.17740709	.04003333
.20000000	.30000000	.01501000	.02264167	.07547224	.05003333
.20000000	.30000000	.01801000	.00685595	.02285318	.06003333

(continued)

[x] For this set of calculations, the distances ω and ℓ are 0.005 inches and 0.09 inches respectively.

TABLE IV (continued)

h(inches)	P_s (psi)	P_c (psi)	P_o (psi)	P_o/P_s	P_c/P_s
.20000000	.40000000	.00001000	.14449291	.36123227	.00002500
.20000000	.40000000	.00301000	.14498964	.36247410	.00752500
.20000000	.40000000	.00601000	.14276322	.35690805	.01502500
.20000000	.40000000	.00901000	.13162719	.32906797	.02252500
.20000000	.40000000	.01201000	.10598855	.26497137	.03002500
.20000000	.40000000	.01501000	.06941308	.17353271	.03752500
.20000000	.40000000	.01801000	.03553238	.08883095	.04502500
.20000000	.50000000	.00001000	.18061559	.36123118	.00002000
.20000000	.50000000	.00301000	.18118386	.36236772	.00602000
.20000000	.50000000	.00601000	.17999645	.35999290	.01202000
.20000000	.50000000	.00901000	.17282270	.34564540	.01802000
.20000000	.50000000	.01201000	.15436163	.30872326	.02402000
.20000000	.50000000	.01501000	.12255335	.24510670	.03002000
.20000000	.50000000	.01801000	.08307393	.16614787	.03602000
.60000000	.10000000	.00001000	.00401388	.04013887	.00010000
.60000000	.10000000	.00301000	.00360220	.03602205	.03010000
.60000000	.10000000	.00601000	.00080910	.00809109	.06010000
.60000000	.10000000	.00901000	.00002733	.00027331	.09010000
.60000000	.10000000	.01201000	.00000068	.00000686	.12010000
.60000000	.10000000	.01501000	.00000002	.00000028	.15010000
.60000000	.10000000	.01801000	.00000000	.00000005	.18010000
.60000000	.20000000	.00001000	.00802751	.04013755	.00005000
.60000000	.20000000	.00301000	.00797399	.03986999	.01505000
.60000000	.20000000	.00601000	.00637836	.03189178	.03005000
.60000000	.20000000	.00901000	.00270380	.01351900	.04505000
.60000000	.20000000	.01201000	.00051094	.00255471	.06005000
.60000000	.20000000	.01501000	.00005946	.00029732	.07505000
.60000000	.20000000	.01801000	.00000633	.00003169	.09005000

(continued)

TABLE IV (continued)

h(inches)	P_s (psi)	P_c (psi)	P_o (psi)	P_o/P_s	P_c/P_s
.60000000	.30000000	.00001000	.01204113	.04013710	.00003333
.60000000	.30000000	.00301000	.01205987	.04019959	.01003333
.60000000	.30000000	.00601000	.01130508	.03768361	.02003333
.60000000	.30000000	.00901000	.00850120	.02833733	.03003333
.60000000	.30000000	.01201000	.00429810	.01432700	.04003333
.60000000	.30000000	.01501000	.00137711	.00459039	.05003333
.60000000	.30000000	.01801000	.00031353	.00104513	.06003333
.60000000	.40000000	.00001000	.01605476	.04013690	.00002500
.60000000	.40000000	.00301000	.01609908	.04024772	.00752500
.60000000	.40000000	.00601000	.01569477	.03923694	.01502500
.60000000	.40000000	.00901000	.01388300	.03470750	.02252500
.60000000	.40000000	.01201000	.01010588	.02526472	.03002500
.60000000	.40000000	.01501000	.00556234	.01390585	.03752500
.60000000	.40000000	.01801000	.00226881	.00567203	.04502500
.60000000	.50000000	.00001000	.02006841	.04013682	.00002000
.60000000	.50000000	.00301000	.02012455	.04024911	.00602000
.60000000	.50000000	.00601000	.01989045	.03978091	.01202000
.60000000	.50000000	.00901000	.01868782	.03737564	.01802000
.60000000	.50000000	.01201000	.01579388	.03158777	.02402000
.60000000	.50000000	.01501000	.01129876	.02259753	.03002000
.60000000	.50000000	.01801000	.00655200	.01310400	.03602000
1.00000000	.10000000	.00001000	.00144499	.01444999	.00010000
1.00000000	.10000000	.00301000	.00128483	.01284837	.03010000
1.00000000	.10000000	.00601000	.00026399	.00263993	.06010000
1.00000000	.10000000	.00901000	.00000800	.00008006	.09010000
1.00000000	.10000000	.01201000	.00000019	.00000195	.12010000
1.00000000	.10000000	.01501000	.00000000	.00000009	.15010000
1.00000000	.10000000	.01801000	.00000000	.00000004	.18010000

(continued)

TABLE IV (continued)

h(inches)	P_s (psi)	P_c (psi)	P_o (psi)	P_o/P_s	P_c/P_s
1.0000000	.20000000	.00001000	.00288990	.01444950	.00005000
1.0000000	.20000000	.00301000	.00286718	.01433594	.01505000
1.0000000	.20000000	.00601000	.00225561	.01127807	.03005000
1.0000000	.20000000	.00901000	.00090619	.00453095	.04505000
1.0000000	.20000000	.01201000	.00015893	.00079467	.06005000
1.0000000	.20000000	.01501000	.00001744	.00008724	.07505000
1.0000000	.20000000	.01801000	.00000180	.00000904	.09005000
1.0000000	.30000000	.00001000	.00433481	.01444936	.00003333
1.0000000	.30000000	.00301000	.00433999	.01446666	.01003333
1.0000000	.30000000	.00601000	.00404726	.01349089	.02003333
1.0000000	.30000000	.00901000	.00298220	.00994067	.03003333
1.0000000	.30000000	.01201000	.00144543	.00481810	.04003333
1.0000000	.30000000	.01501000	.00043822	.00146074	.05003333
1.0000000	.30000000	.01801000	.00009480	.00031602	.06003333
1.0000000	.40000000	.00001000	.00577971	.01444927	.00002500
1.0000000	.40000000	.00301000	.00579478	.01448697	.00752500
1.0000000	.40000000	.00601000	.00563669	.01409174	.01502500
1.0000000	.40000000	.00901000	.00494039	.01235099	.02252500
1.0000000	.40000000	.01201000	.00351831	.00879578	.03002500
1.0000000	.40000000	.01501000	.00186767	.00466917	.03752500
1.0000000	.40000000	.01801000	.00072861	.00182153	.04502500
1.0000000	.50000000	.00001000	.00722464	.01444928	.00002000
1.0000000	.50000000	.00301000	.00724429	.01448859	.00602000
1.0000000	.50000000	.00601000	.00715180	.01430361	.01202000
1.0000000	.50000000	.00901000	.00668696	.01337393	.01802000
1.0000000	.50000000	.01201000	.00558306	.01116613	.02402000
1.0000000	.50000000	.01501000	.00390557	.00781114	.03002000
1.0000000	.50000000	.01801000	.00219288	.00438576	.03602000

(continued)

TABLE IV (continued)

h(inches)	P_s (psi)	P_c (psi)	P_o (psi)	P_o/P_s	P_c/P_s
1.40000000	.10000000	.00001000	.00073724	.00737246	.00010000
1.40000000	.10000000	.00301000	.00065287	.00652871	.03010000
1.40000000	.10000000	.00601000	.00012909	.00129092	.06010000
1.40000000	.10000000	.00901000	.00000374	.00003745	.09010000
1.40000000	.10000000	.01201000	.00000009	.00000090	.12010000
1.40000000	.10000000	.01501000	.00000000	.00000005	.15010000
1.40000000	.10000000	0.1801000	.00000000	.00000004	.18010000
1.40000000	.20000000	.00001000	.00147444	.00737220	.00005000
1.40000000	.20000000	.00301000	.00146207	.00731039	.01505000
1.40000000	.20000000	.00601000	.00114186	.00570933	.03005000
1.40000000	.20000000	.00901000	.00044822	.00224112	.04505000
1.40000000	.20000000	.01201000	.00007616	.00038083	.06005000
1.40000000	.20000000	.01501000	.00000815	.00004079	.07505000
1.40000000	.20000000	.01801000	.00000082	.00000414	.09005000
1.40000000	.30000000	.00001000	.00221163	.00737210	.00003333
1.40000000	.30000000	.00301000	.00221393	.00737979	.01003333
1.40000000	.30000000	.00601000	.00205989	.00686633	.02003333
1.40000000	.30000000	.00901000	.00150439	.00501465	.03003333
1.40000000	.30000000	.01201000	.00071597	.00238658	.04003333
1.40000000	.30000000	.01501000	.00021203	.00070678	.05003333
1.40000000	.30000000	.01801000	.00004490	.00014969	.06003333
1.40000000	.40000000	.00001000	.00294884	.00737210	.00002500
1.40000000	.40000000	.00301000	.00295633	.00739084	.00752500
1.40000000	.40000000	.00601000	.00287285	.00718214	.01502500
1.40000000	.40000000	.00901000	.00250784	.00626962	.02252500
1.40000000	.40000000	.01201000	.00176899	.00442249	.03002500
1.40000000	.40000000	.01501000	.00092448	.00231121	.03752500
1.40000000	.40000000	.01801000	.00035388	.00088471	.04502500

(continued)

TABLE IV (continued)

h(inches)	P_s (psi)	P_c (psi)	P_o (psi)	P_o/P_s	P_c/P_s
1.40000000	.50000000	.00001000	.00368604	.00737208	.00002000
1.40000000	.50000000	.00301000	.00369594	.00739189	.00602000
1.40000000	.50000000	.00601000	.00364691	.00729383	.01202000
1.40000000	.50000000	.00901000	.00340264	.00680529	.01802000
1.40000000	.50000000	.01201000	.00282585	.00565171	.02402000
1.40000000	.50000000	.01501000	.00195760	.00391521	.03002000
1.40000000	.50000000	.01801000	.00108397	.00216795	.03602000

h : distance between supply and output tubes, inches.

P_s : supply pressure, psi.

P_c : control pressure, psi.

P_o : output pressure, psi.

A P P E N D I X B

```
C     EVALUATION OF DATA POINTS FOR REGRESSION,
C      NUMBER OF DATA POINTS IS SIXTY
      DS=0.03
      DC=0.015
      AS=3.1416*DS*DS/4.0
      AC=3.1416*DC*DC/4.0
      DO 36 I=1,60
      READ 441,PS,PC,XZ,YZ,X
  441 FORMAT(3F20.5/2F20.5)
C     CALCULATION OF SUPPLY FLOW
   15 VSQ=PS*8900000.0
      PRES=VSQ*AS
      VOMS=(5.05*PRES)/XZ
      VOAVS=VOMS/3.0
      SUPFL=VOAVS*AS
C     CALCULATION OF CONTROL FLOW
  120 VCQ=PC*8900000.0
      PREC=VCQ*AC
      VOMC=(5.05*PREC)/YZ
      VOAVC=VOMC/3.0
      CONFL=VOAVC*AC
C     CALCULATICN OF OUTPUT FLOW
      SMOM=SUPFL*VOAVS
      CMOM=CONFL*VOAVC
      TMOM=SMOM+CMOM
      TMASS=SUPFL+CONFL
      VOAVN=TMOM/TMASS
      VOMN=VOAVN*3.0
      AN2=TMASS/VOAVN
      THETA=ATANF(CMOM/SMOM)
      DIST=XZ/COSF(THETA)
   41 PREM=DIST*VOMN/5.05
      VMQ=PREM/AN2
      PM=VMQ/8900000.0
      DX=X+XZ
      UZUN=DX/COSF(THETA)
      VAR=X*CMOM/SMOM
      SI=SQRTF(PREM)*10.4*VAR/UZUN
      SISQ=SI*SI*0.25
      DIV1=SISQ+1.0
      DIV2=DIV1*DIV1
      VOM1=(5.05*PREM)/(UZUN*DIV2)
      VOAV1=VOM1/3.0
      VSM1=(SQRTF(VMQ*PM))*94.
      VSAV1=VSM1/3.0
      DEL1P=((VSAV1*VSAV1)-(VOAV1*VOAV1))/8900000.0
      DELP=(VMQ/(VSAV1*VSAV1))*DEL1P
      THET2=COSF(THETA)*COSF(THETA)
      PO=(PM-DELP)*THET2
      EFF2=PC/PS
      EFF3=(YZ/DX)*(YZ/DX)
      EFF4=(XZ/DX)*(XZ/DX)
      VAR1=(EFF2**(-8.24867))*EFF4
      VAR2=(EFF2**(-8.24867))*EFF3
      VAR3=(EFF2**(-0.04853))*EFF4
      VAR4=(EFF2**(-0.04853))*EFF3
      VAR5=(EFF2**(-4.14860))*EFF4
      VAR6=(EFF2**(-4.14860))*EFF3
      VAR7=(EFF2**(-5.53146))*EFF4
      VAR8=(EFF2**(-5.53146))*EFF3
      VAR9=(AS/DX)*(AS/DX)
      VAR10=(PO/PS)
      DATNO=I
```

```
      PUNCH 444,DATNO,VAR1,VAR2,VAR3,VAR4,VAR5,VAR6,
     1VAR7,VAR8,VAR9,VAR10
  444 FORMAT(2F25.5/2F25.5/2F25.5/2F25.5/2F25.5/F25.5)
   36 CONTINUE
  632 STOP
      END
```

```
0.25            0.0130          0.021
0.0050          0.21
0.29            0.0121          0.032
0.0031          0.73
0.36            0.0191          0.014
0.0053          1.22
0.18            0.0102          0.033
0.0032          1.74
0.25            0.0123          0.038
0.0044          1.95
0.19            0.0114          0.036
0.0036          1.67
0.17            0.0176          0.023
0.0038          1.56
0.35            0.0167          0.025
0.0047          1.09
0.27            0.0155          0.042
0.0039          0.60
0.23            0.0143          0.036
0.0053          0.33
0.34            0.0138          0.035
0.0038          0.42
0.11            0.0116          0.044
0.0035          .26
.24             .0104           0.031
0.0057          1.37
0.32            0.0172          0.037
0.0049          0.48
0.33            0.0161          0.026
0.0042          0.89
0.26            0.0111          0.019
0.0055          1.51
0.29            0.0129          0.028
0.0034          1.76
0.25            0.0138          0.037
0.0053          1.19
0.18            0.0147          0.036
0.0042          0.83
0.19            0.0156          0.034
0.0031          0.21
0.25            0.0198          0.033
0.0036          0.75
0.37            0.0183          0.042
0.0037          1.68
0.15            0.0175          0.031
0.0038          1.82
0.33            0.0165          0.050
0.0059          1.54
0.17            0.0141          0.043
0.0040          1.66
0.14            0.0132          0.034
0.0051          1.28
0.31            0.0123          0.025
0.0033          1.30
0.22            0.0111          0.036
0.0035          1.92
0.24            0.0155          0.037
```

0.0054	0.74	
0.13	0.0176	0.018
0.0048	0.36	
0.13	0.0115	0.021
0.0042	0.26	
0.24	0.0136	0.014
0.0036	1.61	
0.32	0.0127	0.050
0.0034	1.91	
0.11	0.0141	0.016
0.0033	1.42	
0.14	0.0163	0.030
0.0031	0.56	
0.17	0.0184	0.049
0.0037	.59	
0.33	0.0172	0.041
0.0048	1.55	
0.26	0.0196	0.038
0.0026	1.26	
0.29	0.0121	0.047
0.0055	0.81	
0.25	0.0151	0.039
0.0054	0.29	
0.38	0.0161	0.040
0.0037	1.32	
0.19	0.0133	0.026
0.0036	1.27	
0.25	0.0187	0.023
0.0038	1.65	
0.37	0.0178	0.027
0.0049	0.96	
0.15	0.0161	0.035
0.0035	0.23	
0.13	0.0127	0.031
0.0053	0.72	
0.22	0.0136	0.018
0.0046	0.23	
0.24	0.0198	0.022
0.0038	1.25	
0.11	0.0173	0.019
0.0049	1.77	
0.34	0.0191	0.033
0.0032	1.96	
0.30	0.0102	0.047
0.0041	0.78	
0.27	0.0139	0.056
0.0037	1.29	
0.15	0.0128	0.024
0.0042	1.70	
0.17	0.0187	0.050
0.0038	1.91	
0.19	0.0196	0.031
0.0039	0.23	
0.35	0.0115	0.035
0.0051	0.75	
0.38	0.0171	0.0301
0.0057	1.29	
0.26	0.0163	0.065
0.0038	0.26	
0.29	0.0152	0.050
0.0059	1.92	
0.35	0.0414	0.036
0.0036	1.70	

```
C     BASAMAKLI REGRESYON
C
C     **************************************************************
C     NOTE
C     DEGISKENLERIN MIKTARI BAGIMSIZ + BAGIMLI DEGISKENLERE ESITTIR.
C     BAGIMLI DEGISKEN EN SON DEGISKENDIR.
C     **************************************************************
C
      DIMENSION DATA(10,75), VECTOR(11,11), AVE(10), SIGMA(10), COEN(10
     1 , SIGMCO(10), INDEX(10) , RUN(75)
C
  100 READ 5,TOL, EFIN, EFOUT, NOPROB, INVAR, NODATA,
     1IFWT,IFSTFP,IFRAW,IFAVE,IFRESD,IFCOEN,IFPRED,IFCNST
C
C     **************************************************************
C     IFWT = 1, BUTUN NISBETLER = 1.0
C     IFSTEP = 1.0, HER BASAMAK YAZILMAYACAK
C     IFRAW =1.0, HAM KARELER TOPLAMI YAZILMAYACAK
C     IFAVE = 1.0, ORTALAMALAR YAZILMAYACAK
C     IFRESD = 1.0, ARTIK KARELER TOPLAMI YAZILMAYACAK
C     IFCOEN = 1.0, KISMI KORELASYON KATSAYILARI YAZILMAYACAK
C     IFPRED = 1.0, HESAPLANMIS TAHMINI DEGERLER YAZILMAYACAK
C     IFCNST = 1.0, DENKLEMDE SABIT BULUNMAYACAK
C
C     BASLANGIC PROSEDURU
C     **************************************************************
      NOIN = 0
      VAR  = 0
      K    = 0
      FLEVEL = 0
      NOENT = 0
      NOMIN = 0
      NOMAX = 0
      NOVAR = INVAR
      NVP1 = NOVAR + 1
      NIX = 1
    2 IF (INVAR- 10) 110,110,1800
  110 DO 120 I = 1, NVP1
  130 DO 120 J = 1, NVP1
  120 VECTOR(I,J) = 0.0
  140 IF(IFWT) 900, 500, 150
  900 TYPE 905
      GO TO 910
C     **************************************************************
C     ASAGIDAKI DEYIMLER DATAYI CORE HAFIZAYA OKUR
C     **************************************************************
  150 DO 170 N = 1, NODATA
  160 READ 10 , RUN(N) , (DATA(L,N),  L = 1 , NOVAR )
  180 DO 190 I = 1, NOVAR
  200 VECTOR(I, NOVAR + 1) = VECTOR (I, NOVAR + 1) + DATA(I,N)
  210 DO 220 J = I, NOVAR
  220 VECTOR (I,J) = VECTOR (I,J) + DATA(I,N)*DATA(J,N)
  190 CONTINUE
  170 VECTOR(NVP1, NVP1    )    = VECTOR(NVP1, NVP1)    + 1.0
  230 GO TO 565
C     **************************************************************
C     DEGISKENLER NISBETLI OLDUGU VAKIT TOPLAMLARIN HESABI
C     **************************************************************
  500 DO 510 N = 1, NODATA
  520 READ 10, RUN, (DATA(L,N), L=1,NOVAR), WHT
  530 DO 540 I = 1, NOVAR
  550 VECTOR (I,NOVAR + 1) = VECTOR (I, NOVAR + 1) + DATA (I,N)*WHT
  560 DO 540 J = I , NOVAR
```

```
  540 VECTOR (I, J) = VECTOR (I,J) + DATA(I,N)*DATA(J,N)*WHT
  510 VECTOR (NVP1, NVP1)          = VECTOR (NVP1, NVP1)       +WHT
C     ****************************************************************
C     KARELER TOPLAMI HESABI TAMAMLANDI. BU MALUMAT HAFIZADA
C     VECTOR (I,J) LOKASYONUNDA
C     ****************************************************************
  565 NOVMI = NOVAR - 1
  566 NOVPL = NOVAR + 1
  568 PUNCH90, NOPROB,NODATA,NOVAR, EFIN, EFOUT
  570 IF (IFRAW) 900, 580, 650
  580 PUNCH 15
  590 PUNCH 20,(I,VECTOR(I,NOVPL),I=1,NOVMI)
  600 PUNCH 25, VECTOR (NOVAR, NOVPL)
  610 PUNCH 30
  620 PUNCH 35,((I,J,VECTOR(I,J),J=I,NOVMI),I=1,NOVMI)
  630 PUNCH 40,(I,VECTOR(I,NOVAR),I=1,NOVMI)
  640 PUNCH 45, VECTOR(NOVAR,NOVAR)
      GO TO 650
C     ****************************************************************
C     ARTIK KARELER TOPLAMI HESABI
C     ****************************************************************
  650 IF(IFCNST) 900,651,735
  651 IF(VECTOR(NOVPL,NOVPL)) 652,652,655
  652 PUNCH654
      GO TO 910
  655 DO 660 I = 1, NOVAR
  670 DO 660 J = I, NOVAR
  660 VECTOR (I,J) = VECTOR (I,J) - (VECTOR (I,NOVPL) * VECTOR (J,NOVPL
     1 / VECTOR (NOVPL, NOVPL))
  680 DO 690 I = 1, NOVAR
  690 AVE(I) = VECTOR(I,NOVPL) / VECTOR(NOVPL,NOVPL)
  700 IF (IFAVE) 900, 710, 735
  710 PUNCH 50
  720 PUNCH 20, (I,AVE(I), I=1,NOVMI)
  730 PUNCH 25, AVE(NOVAR)
  735 IF (IFRESD) 900, 740, 780
  740 PUNCH 55
  750 PUNCH 35,((I,J,VECTOR(I,J),J=I,NOVMI),I=I,NOVMI)
  760 PUNCH 40, (I,VECTOR(I,NOVAR),I=1,NOVMI)
  770 PUNCH 45, VECTOR(NOVAR,NOVAR)
  780 NOSTEP = -1
  781 NUMBER = 1
  782 DEFR     = VECTOR(NOVPL,NOVPL) - 1.0
  790 DO 800 I = 1,NOVAR
  791 IF(VECTOR(I,I)) 792,794,810
  792 PUNCH793, I
      GO TO 910
  794 PUNCH 795,I
  796 SIGMA(I) =      1.0
  797 GO TO 800
  810 SIGMA (I) = SQRTF (VECTOR (I,I))
  800 VECTOR(I,I) = 1.0
  820 DO 830 I = 1,NOVMI
  840 IP1 = I + 1
  841 DO 830 J = IP1, NOVAR
  850 VECTOR(I,J) = VECTOR(I,J) /(SIGMA(I)*SIGMA(J))
  830 VECTOR(J,I) = VECTOR(I,J)
  860 IF (IFCOEN) 900, 870, 1000
  870 PUNCH 60
  874 NOVM2 = NOVMI - 1
  875 DO 885 I = 1, NOVM2
  880 IP1 = I + 1
  885 PUNCH 35,(I,J,VECTOR(I,J),J=IP1,NOVMI )
```

```
  890 PUNCH 40, (I,VECTOR(I,NOVAR),I=1,NOVMI)
 1000 NOSTEP = NOSTEP + 1
 1001 IF (VECTOR( NOVAR,NOVAR)) 1002,1002,1010
 1002 NSTPM1 = NOSTEP - 1
      PUNCH 1004, NSTPM1
      GO TO 1381
 1010 SIGY = SIGMA(NOVAR) * SQRTF (VECTOR(NOVAR,NOVAR)/ DEFR)
 1011 IF(1.0 - VECTOR(NOVAR, NOVAR)) 1013,1013,1012
 1012 R = SQRTF(1.0 - VECTOR(NOVAR, NOVAR) )
      GO TO 1015
 1013 R = 0.0
 1015 DEFR = DEFR-1.
 1016 IF (DEFR ) 1017,1017,1020
 1017 PUNCH 1019, NOSTEP
      GO TO 1381
 1020 VMIN = 0.0
 1030 VMAX = 0.0
 1035 NOIN = 0
 1040 DO 1050 I = 1,NOVMI
 1041 IF (VECTOR (I,I)) 1042,1050,1060
 1042 PUNCH 1044, I, NOSTEP
 1045 GO TO 1381
 1060 IF (VECTOR(I,I) - TOL) 1050,1080,1080
 1080 VAR = VECTOR(I,NOVAR) * VECTOR(NOVAR,I) / VECTOR(I,I)
 1090 IF(VAR)1100,1050,1110
 1100 NOIN = NOIN + 1
 1120 INDEX(NOIN) = I
 1130 COEN(NOIN) = VECTOR(I,NOVAR) * SIGMA(NOVAR) / SIGMA (I)
 1140 SIGMCO(NOIN) = (SIGY / SIGMA(I)) * SQRTF(VECTOR(I,I))
 1150 IF (VMIN) 1160,1170,904
  904 PUNCH 906
      GO TO 910
 1170 VMIN = VAR
 1180 NOMIN = I
 1190 GO TO 1050
 1160 IF(VAR - VMIN)1050,1050,1170
 1110 IF (VAR- VMAX)1050,1050,1210
 1210 VMAX = VAR
 1220 NOMAX = I
 1050 CONTINUE
 1230 IF (NOIN) 903,1240,1245
  903 PUNCH 907
      GO TO 910
 1240 PUNCH 65, SIGY
 1260 GO TO 1350
 1245 IF(IFCNST) 900,1250,1246
 1246 CNST = 0.0
 1247 GO TO 1300
 1250 CNST = AVE(NOVAR)
 1270 DO 1280 I = 1,NOIN
 1290 J = INDEX(I)
 1280 CNST = CNST - (COEN(I) * AVE(J))
 1300 IF(IFSTEP) 900,1310,1320
 1310 IF (NOENT) 1311,1311,1313
 1311 PUNCH 91,NOSTEP,K
 1312 GO TO 1314
 1313 PUNCH 92,NOSTEP,K
 1314 PUNCH 70, FLEVEL, SIGY, R, CNST,
     1 (INDEX(J),COEN(J),SIGMCO(J), J = 1, NOIN )
 1315  GO TO (1316,1580),NIX
 1316 GO TO (1320,1580), NUMBER
 1320 FLEVEL = VMIN * DEFR / VECTOR (NOVAR,NOVAR)
 1330 IF(EFOUT + FLEVEL) 1350, 1350, 1340
```

```
 1340 K = NOMIN
 1345 NOENT = 0
      GO TO 1391
 1350 DENOM = VECTOR(NOVAR,NOVAR) - VMAX
      IF(DENOM) 1351,1351,1352
 1351 NIX = 2
      GO TO 1370
 1352 FLEVEL = VMAX* DEFR / DENOM
 1360 IF (EFIN - FLEVEL) 1370,1361,1380
 1361 IF (EFIN) 1380,1380,1370
 1370 K = NOMAX
 1390 NOENT = K
 1391 IF(K) 1392,1392,1400
 1392 PUNCH 1395, NOSTEP
 1394 GO TO 910
 1400 DO 1410   I = 1,NOVAR
 1420 IF (I-K) 1430,1410,1430
 1430 DO 1440   J = 1, NOVAR
 1450 IF (J-K) 1460,1440,1460
 1460 VECTOR(I,J) = VECTOR(I,J) - (VECTOR(I,K) * VECTOR (K,J) / VECTOR
     1(K,K))
 1440 CONTINUE
 1410 CONTINUE
 1470 DO 1480   I = 1, NOVAR
 1490 IF (I-K) 1500,1480,1500
 1500 VECTOR (I,K) = - VECTOR (I,K) / VECTOR (K,K)
 1480 CONTINUE
 1510 DO 1520 J = 1, NOVAR
 1530 IF (J-K) 1540,1520,1540
 1540 VECTOR(K,J) =   VECTOR (K,J) / VECTOR (K,K)
 1520 CONTINUE
 1550 VECTOR(K,K) = 1.0 / VECTOR(K,K)
 1560 GO TO (1000,1561),NIX
 1561 PUNCH 1004, NOSTEP
      R = 1.00
      SIGY = 0.0
      IFSTEP = 0
      GO TO 1015
 1380 PUNCH 75, NOSTEP
 1381 IF (IFSTEP) 900, 1580,1570
 1570 NUMBER = 2
 1571 GO TO 1310
 1580 PUNCH 1586,(L,VECTOR(L,L),L=1,NOVMI )
 1581 IF( IFPRED) 900,1582,910
 1582 PUNCH 85
 1590 DO  1660   N = 1, NODATA
 1610 YPRED = CNST
 1620 DO 1630  I = 1,NOIN
 1640 K = INDEX(I)
 1630 YPRED = YPRED + COEN(I)*DATA(K,N)
 1650 DEV = DATA(NOVAR,N) - YPRED
 1660 PUNCH 80, RUN(N) , DATA ( NOVAR , N ) , YPRED , DEV
  910 CONTINUE
      STOP
 1800 PUNCH 93, INVAR
      GO TO 910
C
C     ********************************************************************
C     GIRIS/CIKIS DEYIMLERI
C
C     ********************************************************************
    5 FORMAT (3F10.5,3I5,1H 10I2)
   10 FORMAT (2F25.5)
```

```
   15 FORMAT( 21HDEGISKENLERIN TOPLAMI  //  )
   20 FORMAT(12H           X( I2,3H) = F30.4,   /     )
   25 FORMAT(17H                  Y  =F30.4)
   30 FORMAT( // 19HHAM KARELER TOPLAMI  ,/  )
   35 FORMAT (   7H     X(I2,7H) VS X(I2,3H) = F30.6,      /      )
   40 FORMAT (   7H     X(I2,12H) VS   Y   =  F30.6,  /  )
   45 FORMAT (   21H      Y      VS   Y   =F30.6)
   50 FORMAT( // 32HDEGISKENLERIN ORTALAMA DEGERLERI   //   )
   55 FORMAT(  // 21HARTIK KARELER TOPLAMI   // )
   60 FORMAT( // 28HKISMI KORELASYON KATSAYILARI  //  )
   65 FORMAT (31HY DEGERININ STANDART HATASI  = F20.6 )
   70 FORMAT (//16H   F SEVIYESI = F12.4 /34H   Y DEGERININ STANDART HA
     1 ASI  = F12.4 /36H   COK YONLU KORELASYON KATSAYISI = F12.5 /11H
     2 SABIT = F13.5 /60H              DEGISKEN        KATSAYI   KATSAYI S
     3NDRT. HATASI //  (16H                 X-I3,F15.5, F15.5 ))
   75 FORMAT (/42HTAMAMLANAN REGRESYON BASAMAKLARI SAYISI = I5 // )
   80 FORMAT (7X  F7.2        ,2H  F12.5,3H   F12.5,2H  F12.5)
   85 FORMAT (// 47HTAHMINI VE HAKIKI DEGERLERIN KARSILASTIRILMASI //55H
     1              OKUMA      HAKIKI          TAHMINI         FARK // )
   90 FORMAT (21H BASAMAKLI REGRESYON //12H PROBLEM NO.I10 //15H DATA SA
     1YISI = I5 //18H DEGISKEN SAYISI = I10 //44H DEGISKENIN REGRESYONA
     2GIRECEGI F SEVIYESI = F10.3 //50H DEGISKENIN REGRESYONDAN CIKARILA
     3CAGI F SEVIYESI = F9.3 ///)
   91 FORMAT (/ 11HBASAMAK NO.I5 /35H   REGRESYONDAN CIKARTILAN DEGISKEN
     1 I8 )
   92 FORMAT ( 11HBASAMAK NO.I5 /28H   REGRESYONA GIREN DEGISKEN I8 )
   93 FORMAT (48HDEGISKEN SAYISININ ONDAN BUYUK OLMAMASI LAZIMDIR )
  654 FORMAT (15HDATA VERILMEDI )
  793 FORMAT (39HARTIK KARELERDE YANLIS VAR.DEGISKEN NO.I4,30HNEGATIVDIR
     1.PROBLEM DURDURULDU.)
  795 FORMAT (// I5,24HNO.LU DEGISKEN SABITTIR )
  905 FORMAT (28HKONTROL KARTINDA YANLIS VAR.)
  906 FORMAT (21HVMIN POSITIV, YANLIS )
  907 FORMAT (21HNOIN NEGATIV, YANLIS )
 1004 FORMAT (// 26HY KARE NEGATIV.BASAMAK NO.I4,22HDA PROBLEM DURDURUL
     1U )
 1019 FORMAT (/35HSERBESTLIK DERECESI YOK.BASAMAK NO.I4 )
 1044 FORMAT (/ 12HDEGISKEN NO.I4,16H KARESI NEGATIV.20H BASAMAK HESAPL
     1NDI )
 1395 FORMAT (/ 17HK=0. BASAMAK NO. I4)
 1586 FORMAT (24HDIYAGONAL ELEMANLAR       /20H   DEG.NO.      DEGER//
     1(1H  I 7, F16.6))
C
C     ******************************************************************
C     GIRIS/CIKIS DEYIMLERININ SONU
C     ******************************************************************
      END
```

BASAMAKLI REGRESYON

PROBLEM NO. 10020

DATA SAYISI = 60

DEGISKEN SAYISI = 10

DEGISKENIN REGRESYONA GIRECEGI F SEVIYESI = 2.500

DEGISKENIN REGRESYONDAN CIKARILACAGI F SEVIYESI = 2.500

KISMI KORELASYON KATSAYILARI

X(1) VS X(2) =	.864113
X(1) VS X(3) =	.025938
X(1) VS X(4) =	-.040394
X(1) VS X(5) =	.764759
X(1) VS X(6) =	.484688
X(1) VS X(7) =	.932064
X(1) VS X(8) =	.703015
X(1) VS X(9) =	-.045299
X(2) VS X(3) =	.009366
X(2) VS X(4) =	.114633
X(2) VS X(5) =	.665579
X(2) VS X(6) =	.685731
X(2) VS X(7) =	.811110
X(2) VS X(8) =	.885492
X(2) VS X(9) =	.057791
X(3) VS X(4) =	.543202
X(3) VS X(5) =	.496673
X(3) VS X(6) =	.212946
X(3) VS X(7) =	.246638
X(3) VS X(8) =	.119181
X(3) VS X(9) =	.698105
X(4) VS X(5) =	.295477
X(4) VS X(6) =	.660226

```
X( 4) VS X( 7) =                              .141901
X( 4) VS X( 8) =                              .446132
X( 4) VS X( 9) =                              .922390
X( 5) VS X( 6) =                              .660199
X( 5) VS X( 7) =                              .939833
X( 5) VS X( 8) =                              .724001
X( 5) VS X( 9) =                              .267911
X( 6) VS X( 7) =                              .635292
X( 6) VS X( 8) =                              .942886
X( 6) VS X( 9) =                              .479563
X( 7) VS X( 8) =                              .778005
X( 7) VS X( 9) =                              .113651
X( 8) VS X( 9) =                              .305741
X( 1) VS   Y   =                              .004232
X( 2) VS   Y   =                              .197024
X( 3) VS   Y   =                              .125413
X( 4) VS   Y   =                              .826938
X( 5) VS   Y   =                              .212517
X( 6) VS   Y   =                              .749881
X( 7) VS   Y   =                              .141155
X( 8) VS   Y   =                              .550476
X( 9) VS   Y   =                              .639616
Y DEGERININ STANDART HATASI   =               .043359
BASAMAK NO.     1
  REGRESYONA GIREN DEGISKEN         4

  F SEVIYESI =      125.4436
  Y DEGERININ STANDART HAT ASI   =        .0245
  COK YONLU KORELASYON KATSAYISI =         .82693
  SABIT =         -.00517
          DEGISKEN          KATSAYI    KATSAYI STNDRT. HATASI

             X-  4       335.36550         29.94291
BASAMAK NO.     2
  REGRESYONA GIREN DEGISKEN         3

  F SEVIYESI =      50.6206
  Y DEGERININ STANDART HAT ASI   =        .0180
```

COK YONLU KORELASYON KATSAYISI = .91243
SABIT = -.00054

DEGISKEN	KATSAYI	KATS/YI STNDRT. HATASI
X- 3	-2.57653	.36213
X- 4	436.54963	26.18103

BASAMAK NO. 3
REGRESYONA GIREN DEGISKEN 6

F SEVIYESI = 14.8762
Y DEGERININ STANDART HAT ASI = .0161
COK YONLU KORELASYON KATSAYISI = .93149
SABIT = -.00243

DEGISKEN	KATSAYI	KATSAYI STNDRT. HATASI
X- 3	-2.27909	.33378
X- 4	356.17462	31.39280
X- 6	.00 66	.00017

BASAMAK NO. 4
REGRESYONA GIREN DEGISKEN 8

F SEVIYESI = 11.5310
Y DEGERININ STANDART HAT ASI = .0148
COK YONLU KORELASYON KATSAYISI = .94372
SABIT = -.00143

DEGISKEN	KATSAYI	KATSAYI STNDRT. HATASI
X- 3	-2.03391	.31462
X- 4	260.00994	40.39174
X- 6	.00266	.00060
X- 8	-.0 2	0.00000

BASAMAK NO. 5
REGRESYONA GIREN DEGISKEN 2

F SEVIYESI = 3.0861
Y DEGERININ STANDART HAT ASI = .0145
COK YONLU KORELASYON KATSAYISI = .94685
SABIT = -.00088

DEGISKEN	KATSAYI	KATS/YI STNDRT. HATASI
X- 2	0.0	.00000
X- 3	-2.02647	.30885
X- 4	211.73190	48.24017
X- 6	.00613	.00206
X- 8	-.0 8	.00003

BASAMAK NO. 6
REGRESYONA GIREN DEGISKEN 9

F SEVIYESI = 4.4104
Y DEGERININ STANDART HAT ASI = .0141
COK YONLU KORELASYON KATSAYISI = .95104
SABIT = -.00168

DEGISKEN	KATSAYI	KATSAYI STNDRT. HATASI
X- 2	0.0	.00000
X- 3	-2.48890	.37176
X- 4	.19625	111.06125
X- 6	.00903	.00243
X- 8	-.00013	.00004

X- 9	4.01381	1.91123

BASAMAK NO. 7

REGRESYONDAN CIKARTILAN DEGISKEN 4

F SEVIYESI = 0.0000

Y DEGERININ STANDART HAT ASI = .0142

COK YONLU KORELASYON KATSAYISI = .95104

SABIT = -.00168

DEGISKEN	KATSAYI	KATSAYI STNDRT. HATASI
X- 2	0.0	.00000
X- 3	-2.48915	.34663
X- 6	.00903	.00156
X- 8	-.00 13	.00003
X- 9	4.01687	.81282

TAMAMLANAN REGRESYON BASAMAKLARI SAYISI = 7

DIYAGONAL ELEMANLAR

DEG.NO.	DEGER
1	.207106
2	83.822240
3	2.078828
4	.024030
5	.176413
6	197.120730
7	.200401
8	437.852890
9	3.680545

TAHMINI VE HAKIKI DEGERLERIN KARSILASTIRILMASI

OKUMA	HAKIKI	TAHMINI	FARK
1.00	.00933	.00848	.00084
2.00	.00617	.00565	.00051
3.00	.25155	.25323	-.00168
4.00	.00034	-.00021	.00055
5.00	.00108	.00042	.00065
6.00	.00027	-.00012	.00039
7.00	.00026	-.00042	.00068
8.00	.00917	.00799	.00117
9.00	.00080	.00945	-.00865
10.00	.04165	.06877	-.02712
11.00	.02797	.02234	.00562
12.00	0.00000	-.01156	.01156
13.00	.00655	.00557	.00097
14.00	.01674	.03622	-.01948
15.00	.01109	.01[illegible]	.00103
16.00	.00609	.00460	.00148
17.00	.00197	.00031	.00165
18.00	.00413	.00594	-.00181
19.00	.00031	.00209	-.00178
20.00	.00034	.03020	-.02986
21.00	.00010	.00296	-.00286
22.00	.00010	-.00003	.00013
23.00	0.00000	-.00121	.00121

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