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THE PENNSYLVANIA STATE UNIVERSITY
COLLEGE OF ENGINEERING

SYSTEMS AND CONTROLS LABORATORY

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THE SYSTEMS AND CONTROLS LABORATORY

The Systems and Controls Laboratory was started in 1964 to encourage graduate research and development on engineering systems, with emphasis on improving the understanding of basic elements and devices and bridging the gap between theory and practice. The experimental equipment and facilities of this systems laboratory have been provided for carrying out experimental investigations on devices and systems involving many of the different engineering disciplines. Staff members, graduate fellows, and graduate assistants are now working on projects and thesis topics of vital interest to engineers concerned with the advanced design and development of new engineering systems.

Much of the work involves mathematical and computer modeling and analysis and the experimental investigation of breadboard and prototype systems or devices. A major goal of this work has been to accomplish a useful synthesis of analytical and experimental methods in research and development of advanced engineering systems for effective use by engineers and scientists working on future aerospace systems.

Financial support for this program is derived from the University, the National Aeronautics and Space Administration, and the Harry Diamond Laboratories. A major share of the projects in the Systems and Controls Laboratory are supervised by Dr. J. L. Shearer, Rockwell Professor of Engineering, assisted by other members of the graduate faculty.

CONTENTS

(NASA-CR-136530) [FLUIDICS RESEARCH, INCLUDING VORTEX AND JET PIPE VALVES] (Pennsylvania State Univ.) 14 p HC $3.00 CSCL 14B
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RESPONSE CHARACTERISTICS OF LAMINAR FLUIDIC AMPLIFIERS

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The development of the jet-deflection proportional amplifier has resulted in commercial units which operate entirely in the turbulent regime. Because of the inherent noise associated with turbulent flow, the dynamic range* of these devices is limited. Typical dynamic ranges of available commercial jet-deflection amplifiers vary from 100 to 500 at bandwidths of 0 to 500 Hz and 0 to 25 Hz respectively. Attempts to increase the dynamic range, increase the bandwidth, and lower the system power consumption would seem to indicate a necessity for jet-deflection proportional amplifiers which would operate in the laminar regime.

As early as 1962 Powell [16] investigated the characteristics of free laminar jets. Because of the nature of flow in the mixing region, an initially laminar jet eventually becomes turbulent sufficiently far downstream and may undergo transition earlier if a secondary jet is impinged on the primary laminar jet. Powell in his experiments showed that it is possible to obtain laminar jet deflection with a secondary jet without making it go turbulent.

Boyd and Barbin [17] also investigated the effect of a transverse secondary flow on a free axisymmetric laminar jet. Using pressure ratios (secondary to primary) of 0.00 to 0.10 they studied the conditions under which the primary jet would break up. For a pressure ratio of 0.00 the primary jet remained laminar for 16 diameters while for a pressure ratio of 0.10, transition occurred between 7 and 10 diameters downstream.

Beatty and Markland [18] further investigated the feasibility of obtaining laminar jet deflection. By discharging carbon dioxide jets into an air environment and observing the flow by Schlieren optics they determined that the maximum laminar length occurred in the vicinity of a Reynolds number of 600. They state that the length of the supply tube, which was varied from 5 diameters to 60 diameters, was not important in determining the laminar length of the jet. However, it is difficult to draw accurate conclusions because of the large amount of scatter in the data. Pressure recovery for the undeflected jet was found to be a maximum at a Reynolds number of 800. However they found that when the jet was deflected, the laminar length was strongly dependent on the supply tube length with transition occurring more easily for the shorter tubes. Angles between the supply tube and the control tube of 15° to 60° were studied.

These investigations are representative of a number of studies on the phenomena of free laminar jet breakdown and deflection. However, the problem of stability in a semi-confined laminar jet such as is encountered in fluidic devices is of primary importance for obtaining laminar jet deflection. Manion and Mon [19] state that a pressure field proportional amplifier developed by Griffin and Gebben [20] for operation in the turbulent regime was adapted by R. F. Hellbaum of NASA (Langley) for operation in the laminar regime. Blocked output pressure gains of 8 to 10 were achieved with a dynamic range of 500 to 1000 for a bandwidth of 0 to 20 Hz. However, it was found that the gain decreased as the d-c control level** was increased. He overcame this problem by a vent pressure level control and staged five amplifiers with an average gain per state of 4.74.

Manion and Mon [19] of Harry Diamond Laboratories continued the development and staging of laminar proportional amplifiers. Their work resulted in the design shown in Fig. 1. They state that this geometry effectively eliminates the pressure sensitivity to d-c level when properly staged supply pressures are used. The device exhibits good saturation characteristics with a single-stage pressure gain greater than 15 and a dynamic range in excess of 1200 for a bandwidth of 0 to 20 Hz. With a three-stage laminar gain block they have obtained a pressure gain greater than 1000, a dynamic range of about 500, and a bandwidth greater than 0 to 100 Hz.

Their experiments also include an estimate of a suitable operating Reynolds number range. Basing the Reynolds number on the element depth, which they justify as being the characteristic dimension for aspects ratios equal to or less than one, they concluded that the best operating Reynolds number range is 750 to 1500.

They present a proposed solution to the bias level sensitivity problem by a control volume technique that indicates the significant parameters involved. A control volume analysis was made to describe the dynamic response of this amplifier and good agreement with experimental data was found. Although the dynamic response depends upon the physical size of the element as well as the operating Reynolds number, typical elements responded well at frequencies up to 500 Hz with some elements responding at frequencies exceeding 1000 Hz.

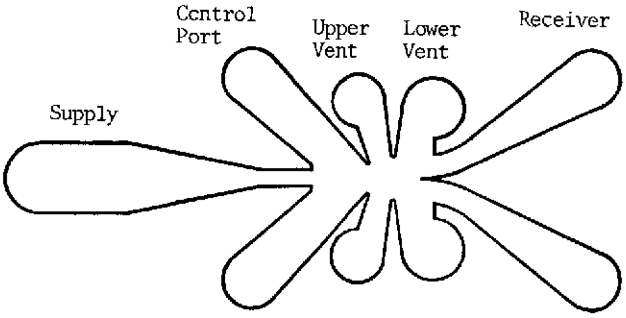

Fig. 1. Schematic of Laminar Proportional Amplifier

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* The term "dynamic range" is defined here as the input pressure required to cause saturation of the output divided by the minimum input signal causing an output that can be observed above the noise.

** The term "d-c control level" is used to denote the mean value around which both control pressures vary.

In order to further investigate the laminar proportional amplifier proposed by Manion and Mon [19] as shown in Fig. 1, a program of research has begun in the Systems and Controls Laboratory at The Pennsylvania State University. The first phase of this program was to qualitatively study the phenomena involved with laminar jet amplification by means of flow visualization of a large-scale working model of the proportional laminar-jet amplifier. The model, which was constructed of plexiglass, used water fed by constant head tanks as the working fluid. Dye injection was used as a means of flow visualization. Supply nozzle heights of 1/2 inch and 1/4 inch and a nozzle width of 1/2 inch were studied, resulting in aspect ratios of 1 and 1/2 respectively. A primary Reynolds number range of 600 to 2100, based on the supply nozzle height, as suggested by Manion and Mon, was investigated.

In an attempt to further understand the behavior of a semi-confined laminar jet and to investigate the effects of control ports, vents and receivers, models were constructed of the supply nozzle alone, the supply nozzle with control ports and also the supply nozzle with control ports, vents and receivers. Thus using dye injection with the aspect ratios under consideration, a qualitative study was made on the effect of some of the solid boundaries present in the amplifier geometry.

In order to closely relate the large-scale model to the proposed small-scale laminated model, all inputs and outputs to the amplifier were situated normal to the plan-view of the amplifier. It was determined during the early stages of the investigation that a secondary flow existing in the nozzle was induced by a sharp change in the flow direction as the fluid entered the plenum chamber at a right angle. Since it was desired that the jet exhibit laminar flow characteristics, various methods of eliminating this secondary flow were investigated. It was found that several layers of wire screen upstream in the supply nozzle were sufficient to break the secondary flow up into small scale turbulence that would decay before reaching the nozzle exit plane. This resulted in a laminar flow at the exit plane of the supply nozzle for all conditions investigated.

The laminar semi-confined jet emanating from the supply nozzle in the absence of control ports or receivers was studied for the two aspect ratios of 1 and 1/2.

For Reynolds numbers less than 600, the jet remained consistently quiet and laminar over the primary region of interest for both aspect ratios (up to 10 nozzle widths downstream of the nozzle exit plane). As the Reynolds number was increased it was observed that the aspect ratio of 1/2 produced a jet which was laminar over a greater distance downstream than when the jet was produced by an aspect ratio of 1 at the same Reynolds number. This trend was apparent over the entire Reynolds number range studied.

At a Reynolds number of about 800, both aspect ratios yielded laminar jets which remained laminar beyond 10 nozzle widths downstream (10W). The jet having an aspect ratio of 1/2 showed a slightly greater spreading than the jet with an aspect ratio of 1. As the Reynolds number was increased to 950 the two aspect ratios still yielded laminar jets over the region of interest although the jet at an aspect ratio of 1 began to undergo transition around 10W downstream.

Figures 2 and 3 present photographs of the semi-confined jets at aspect ratios of 1 and 1/2 and a Reynolds number of 1100 respectively. As indicated by Fig. 2 the jet remained essentially laminar up to around 7W where transition began in the outer region of the jet. The core of the jet was found to remain laminar to 11W or 12W. By contrast Fig. 3 indicates that the jet for an aspect ratio of 1/2 remains laminar well beyond 10W.

As the Reynolds number was increased the laminar length of the jets was decreased. For an aspect ratio of 1 it was noted that the jet was characterized by the symmetrical formation, growth, and coalescence of vortices. Although not always apparent at the lower Reynolds numbers (i.e. less

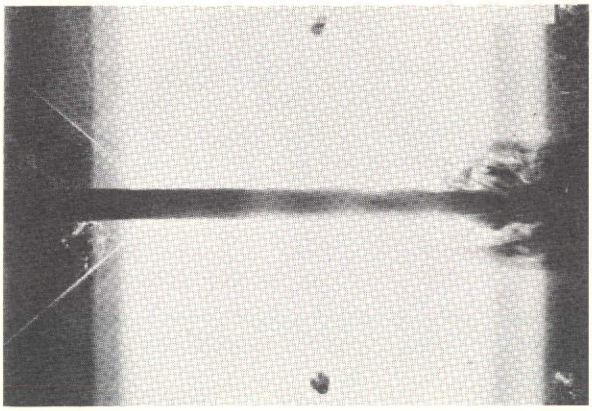

Fig. 2. Semi-confined jet for aspect ratio of 1 and Reynolds number of 1100

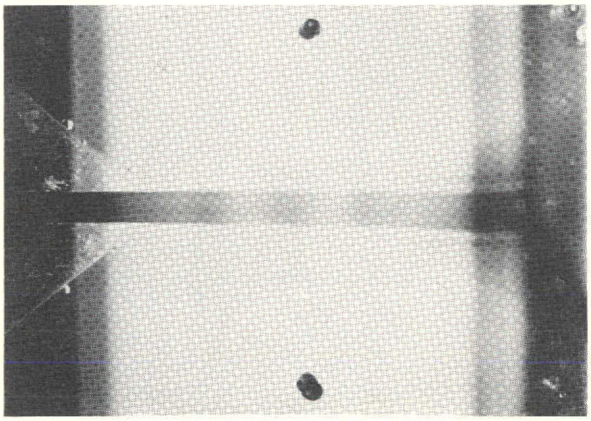

Fig. 3. Semi-confined jet for aspect ratio of 1/2 and Reynolds number of 1100

than 800), at higher Reynolds numbers (i.e. greater than 1300) the vortex formation was readily apparent. The distance from the nozzle exit that formation of the vortices would occur decreased with increasing Reynolds number. Fig. 4 shows the symmetrical vortex formation for a Reynolds number of 2100. Events preceding the vortex formation first became visible at about 2W, beyond which the jet underwent alternating transverse expansion and then contraction with the subsequent formation of vortex pairs. The vortices seemed to maintain their identity until about 7W where the core of the jet was no longer evident. By 10W the jet had become completely turbulent. This same type of formation, growth and coalescence was observed for all tests with aspect ratios of 1 with Reynolds number greater than 1300. For Reynolds numbers less than this, the process was much less well-defined.

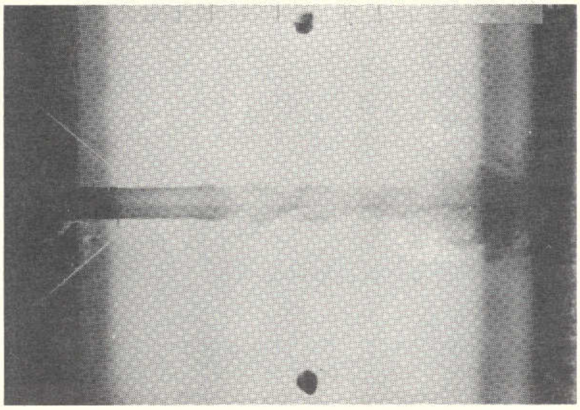

Fig. 4. Semi-confined jet for aspect ratio of 1 and Reynolds number of 2100

It should be noted that the laminar jet was extremely sensitive to any upstream or external disturbances. As previously mentioned, the wire screens in the supply plenum chamber helped damp out unwanted flow noise. Almost all of the observations made were performed during quiet periods in the laboratory when external disturbances could be kept to a minimum.

For an aspect ratio of 1/2 the jet maintained a laminar flow to at least 10W for Reynolds numbers up to 1300. For Reynolds numbers greater than this, slight asymmetrical instabilities began appearing although the jet would maintain its identity to at least 10W for Reynolds number up to 1400. Above this value the jet would experience asymmetrical vortex growth and transition to turbulence before 10W. The above ranges of Reynolds numbers are not precise since the vortex growth with increasing Reynolds number is a continuous process, and they are given only as reasonable estimates.

Figure 5 shows the jet for a Reynolds number of 2100 and an aspect ratio of 1/2. As is seen, the jet remains laminar out to 4W at which point

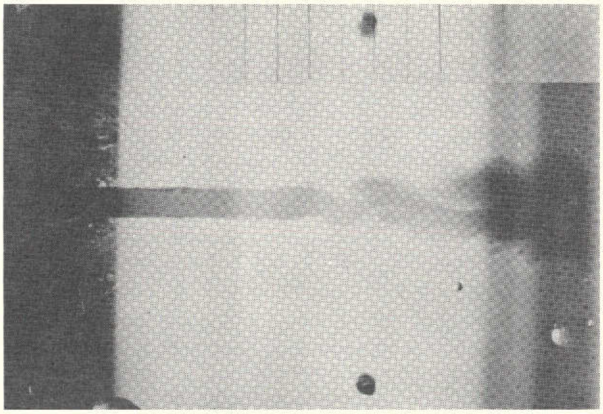

Fig. 5. Semi-confined jet for aspect ratio of 1/2 and Reynolds number of 2100

the first vortex becomes visible. The core flow up to this point has only been slightly disturbed. However, the growth of the out-of-phase vortices downstream causes the flow to undergo sinuous deformation until the jet undergoes a complete breakdown by 10W. This type of sinuous breakdown was characteristic of all instabilities which occurred for an aspect ratio of 1/2 in the region of interest. It should be noted that the jet produced by an aspect ratio of 1/2 was less sensitive to upstream and external disturbances than was the jet having an aspect ratio of 1. Rockwell and Niccolls [21] have investigated the breakdown of planar jets for a Reynolds number range based on the nozzle width of 1860 to 10,800 for an aspect ratio of 3. Both symmetrical and asymmetrical modes of vortex growth and coalescence were observed for this Reynolds number range.

The hydrogen bubble generation technique was applied at the mid-height of the supply nozzle exit with an aspect ratio of 1. Information obtained from this technique indicated that at the lower Reynolds numbers investigated, the laminar flow was fairly well developed at the nozzle exit. The exit plane flow became less developed as the Reynolds number was increased until at the higher range the flow at the mid-plane was relatively uniform. In his work on the flow fields of jets, Sato [22] reported that for undeveloped nozzle exit velocity profiles the symmetrical mode dominated while for highly developed exit velocity profiles the asymmetrical mode dominated.

The flow field established by the semi-confined laminar jet in the presence of the control ports was also investigated for the same aspect ratios and Reynolds number range as for the previous case. However, it was found that the flow field established in the region of the control knife edges was essentially unaffected by the addition of vent knife edges and receivers. This agrees with the quantitative data of Manion and Mon [19] in which they show that the input characteristics are essentially uncoupled from the output loading for positive control pressures. A qualitative analysis of the flow field for the laminar amplifier shown in Fig. 1 was conducted for the previously stated range of Reynolds numbers and aspect ratios. For very low Reynolds numbers (i.e. below the primary range investigated) it was found for blocked inputs that the spreading of the jet was sufficient to cause flow to spill back into the control ports.

However, for the primary Reynolds number range under consideration it was found that for blocked inputs a feedback flow was established from the vent region into the control ports due to the pressure gradient caused by the entrainment of the jet. As the feedback flow enters the control ports it forms a vortex with its center located close to the leading edge of the control knife edge. The jet begins to undergo a slight expansion immediately upon passing the control knife edges due to an increase in static pressure. This widening of the jet is more apparent for the aspect ratio of 1 and for Reynolds numbers less than 1300, since above this value instabilities begin to occur in the flow which obscure this effect.

Figures 6 and 7 show the flow field in the amplifiers at a Reynolds number of 1100 and aspect ratios of 1 and 1/2 respectively. In both of these figures the vortex generated by the feedback flow is apparent.

The design of the receivers is such that the portion of the jet not entering the receiver is spilled off into the lower vents. However a portion of this spill-off is fed back into the upper vents and eventually into the control port region. As indicated by Figs. 6 and 7 two additional vortices are produced in the lower vents adjacent to the jet for blocked inputs.

As the control inputs are increased above the blocked conditions the amount of feedback flow into the control ports is decreased until eventually it ceases at which point no pressure gradient exists between the control ports and vents. At this point the jet was observed to essentially behave as the semi-confined jet in the absence of control ports and vents. The breakdown of the jet for an aspect ratio of 1 occurred at approximately the same distance downstream as the planar jet previously discussed and was characterized by the formation of symmetrical vortices. The jet for an aspect ratio of 1/2 still exhibited an asymmetrical sinuous breakdown.

As the control pressure was increased above that of the vents, the breakdown of the supply jet appeared to be slightly retarded. Eventually it was evident that as the control pressure was increased, the jet began to undergo a reduction in width immediately upon leaving the control port region due to the reduction in pressure.

The Reynolds number range in which the device should operate is limited by excessive jet spreading on the one hand and transition to turbulence on the other. At lower Reynolds numbers the jet seems to spread as an unseparated flow from a small passage into a large one, rapidly losing center line velocity. At higher Reynolds numbers instabilities indicating the onset of turbulence occur, creating undesirable signal noise conditions.

For an aspect ratio of 1 the maximum Reynolds number appears to be approximately 1300. Above this value symmetrical vortices are formed and grow in a manner likely to induce undesirable noise in the output signal. From qualitative analysis it is difficult to determine the lower Reynolds number at which the reduced signal gain becomes unacceptable although it would appear to be in the vicinity of a Reynolds number of 650.

For an aspect ratio of 1/2 the maximum Reynolds number appears to be approximately 1400 in order to maintain quiet operation. Above this value asymmetrical instabilities become pronounced which are likely to result in increased noise. Because of the slightly greater jet spreading than for an aspect ratio of 1, the lower Reynolds number appears to be in the vicinity of 750.

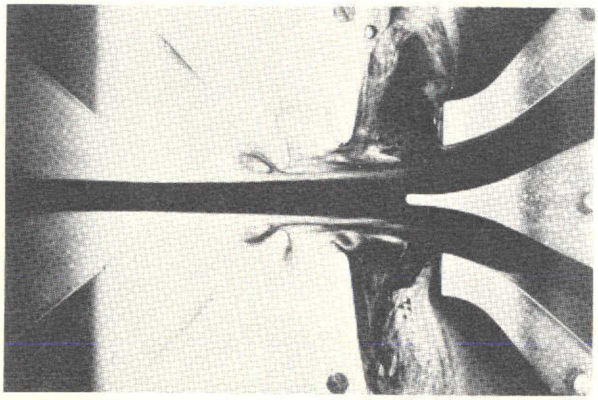

Fig. 6. Flow in amplifier for aspect ratio of 1 and Reynolds number of 1100

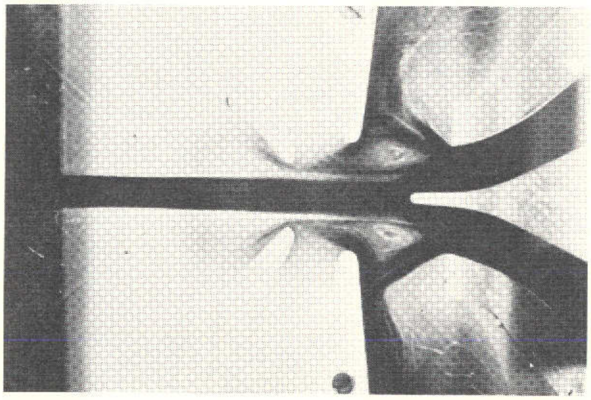

Fig. 7. Flow in amplifier for aspect ratio of 1/2 and Reynolds number of 1100

If the supply jet could be suddenly deflected at the nozzle exit plane so that it followed a straight path in the control port region, the setback of the control knife edges would be just sufficient to allow the jet to impinge with maximum effect at the receiver. However, as indicated by Fig. 8 (Reynolds number of 1100 and aspect ratio of 1/2) when the jet is fully deflected, it does not deflect in a straight line but instead is deflected with a noticeable curvature in the control port region. If the supply jet were to continue in a straight line tangent to the jet at the exit of the control port region the deflection would be too great to achieve maximum effect at the receivers. However, it is noticed that the jet does not continue in a straight line but instead undergoes a reversal of curvature because of the increase in the vent pressure. Because of this it appears that the original setback of the control knife edges (1/2W) can be reduced and still allow the jet to undergo maximum deflection.

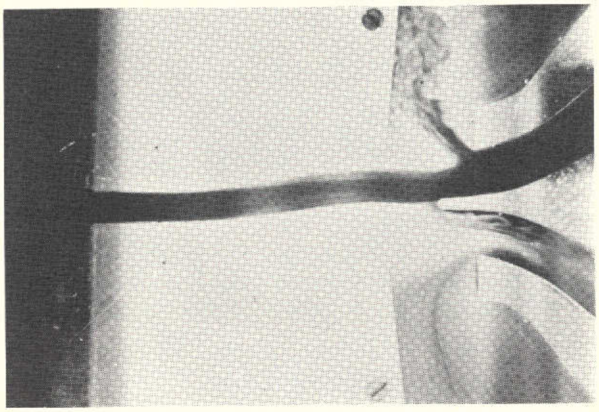

Fig. 8. Jet deflection in amplifier for aspect ratio of 1/2, Reynolds number of 1100 and setback of 0.5W.

In order to more fully investigate the qualitative effects of the setback, a new model with an aspect ratio of 1/2 was constructed. This model had a lateral spacing of the control knife edges of 1.6W resulting in a setback of 0.3W. Flow visualization of this model indicated that for blocked control ports the pressure in the control port region was negative for Reynolds numbers from 750 to 2100 resulting in a feedback flow from the vent region into the control port region. For Reynolds numbers below this range the spreading of the jet was sufficient to cause a portion of it to be peeled off at the control knife edges and returned to the control port region. Even though the reduced setback may be advantageous from an input impedance and d-c level sensitivity standpoint, it is undesirable in not allowing the jet to undergo full deflection as indicated by Fig. 9 for a Reynolds number of 1100.

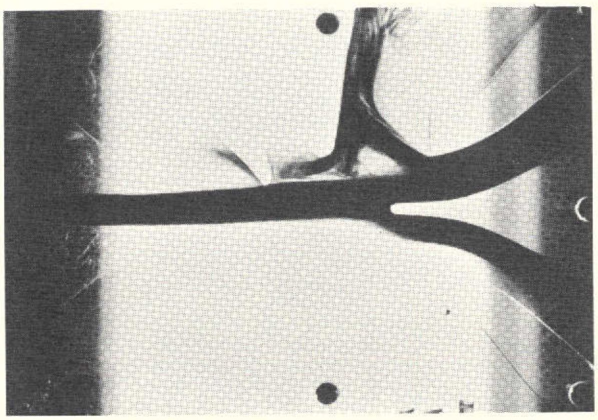

Fig. 9. Jet deflection in amplifier for aspect ratio of 1/2, Reynolds number of 1100 and setback of 0.3W

Another model with an aspect ratio of 1/2 was constructed with a control knife edge width of 1.8W which resulted in a setback of 0.4W. This device exhibited operating characteristics similar to the model with a setback of 0.5W. However, the jet was still not able to undergo full deflection, as indicated by Fig. 10 for a Reynolds number of 1100.

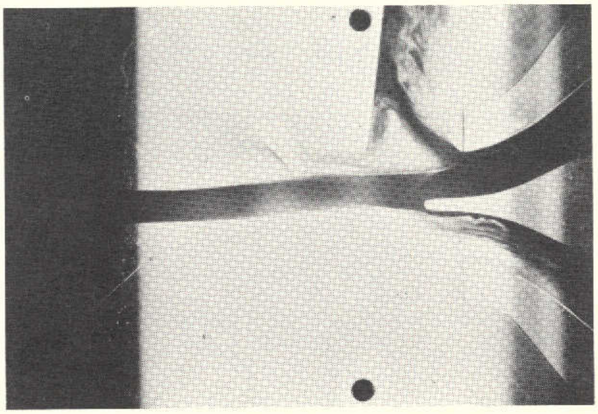

Fig. 10. Jet deflection in amplifier for aspect ratio of 1/2, Reynolds number of 1100 and setback of 0.4W.

It appears that increasing the distance between control knife edges from 1.8W to 1.9W would allow full deflection of the jet as well as still achieving a higher input impedance and smaller d-c level sensitivity factor [19] (as compared to the 2W case). In addition it may be possible to improve the design of the lower vent region so as to reduce the reversal of jet curvature, thus allowing full jet deflection at the receivers even when the setback is as small as 0.4W.

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POWER AMPLIFICATION WITH A VORTEX VALVE

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Preliminary testing has been completed of a vortex valve (obtained on a loan basis from Bendix Research Laboratories) used as a pressure amplifier. Currently a vortex amplifier stage is being designed to drive an actuator consisting of a pneumatic ram with a mass load.

Investigations such as the one presented by Taplin and McFall [23] provide the effects of: (1) loading, (2) total back pressure and (3) vent back pressure on a vortex pressure amplifier. There is also some mention made about staging amplifiers, but not enough information is included to provide a thorough understanding of the major factors involved. Other works, by Mayer [24] and Foster and Parker [25] provide information concerning parametric analysis of a vortex pressure amplifier and a vortex valve respectively. Finally there are articles such as those by Kwok [26] and Savino and Keshock [27], which study, theoretically and experimentally, the pressure and velocity profiles inside vortex valves in order to enhance knowledge about the complicated vortex flow field for future valve design. The above examples are only given to indicate the types of literature available; there being many other similar works.

Consequently, it was necessary to determine pressure-flow characteristics of specific devices, which would be needed in designing a flow amplifier rather than a pressure amplifier. Specifically needed were pressure-flow characteristics for a vortex valve with fixed downstream pressure and varying upstream pressure.

This report describes the experimental work done to date, and indicates the future goals of one of the research projects currently being developed--a vortex flow amplifier driven positioning servosystem. Figure 11 is a block diagram representation of the basic servosystem.

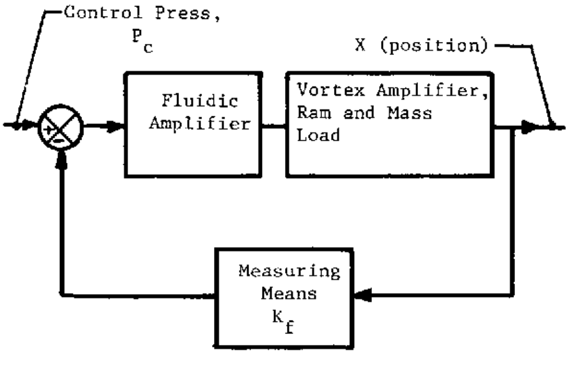


Fig. 11. Block Diagram of Basic Servosystem

From Fig.11, the servosystem can be divided into three main subsystems. Currently, the vortex amplifier-ram-mass load subsystem is under study. A schematic representation of the subsystem can be seen in Fig. 12. In this case, the motion of the mass is controlled by varying the control signal, P_c, to the vortex valve.

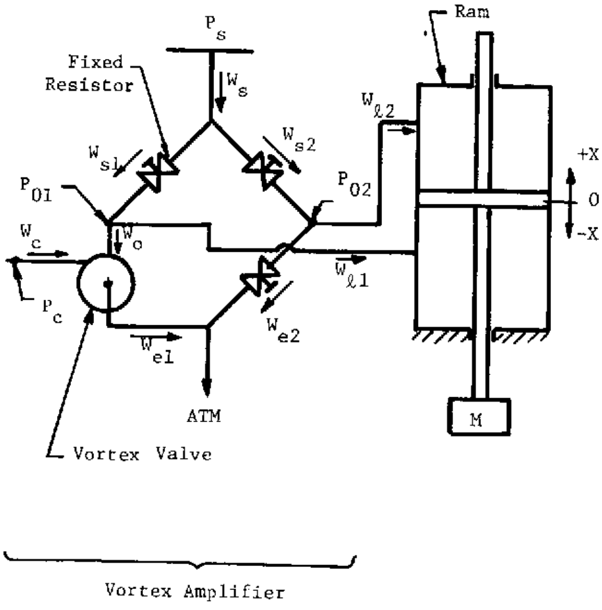


Fig. 12. Vortex Amplifier - Ram - Mass Load System

In order to evolve a rational procedure for designing the vortex amplifier stage, it was necessary to measure the pressure-flow characteristics for the vortex valve and the fixed upstream resistor comprising two arms of the four-arm bridge in Fig. 12. Accordingly, test setups were provided as shown in Fig. 13, to measure the necessary pressure-flow curves as shown in Fig.14 .

These curves graphically illustrate the variation of effective impedances for the vortex valve and for the upstream resistor when large variations in pressure and flow occur. The slope at any point on a P_c = constant curve is the inverse of the impedance, seen at the upstream point during normal operation. The upper limit, of the curves labeled (A) shows the upper bound of normal operation when the operating impedance is a minimum for each control pressure. At this upper bound, the control flow becomes zero and the control pressure is determined only by the internal flow conditions in the valve. When the control flow is zero there is no swirl in the vortex chamber and the impedance is the same as that of the exit holes. The lower limit of curves (A), represented by the abscissa, results when sufficient swirl is induced to completely block inflow at the upstream port. The operating impedances for each P_c = constant are greatest near this lower bound.

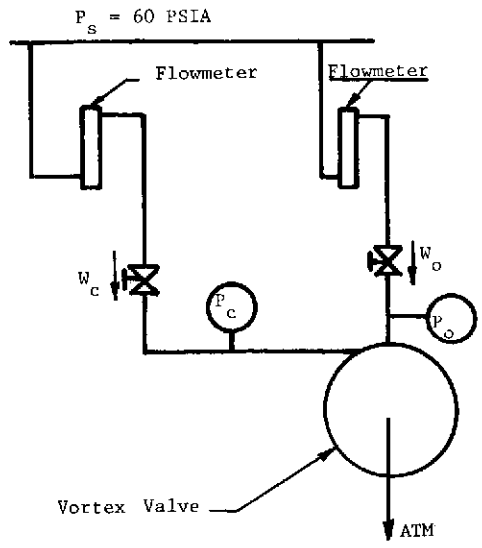


Fig. 13a Set-up Used to Obtain Pressure-Flow Characteristics of Vortex Valve

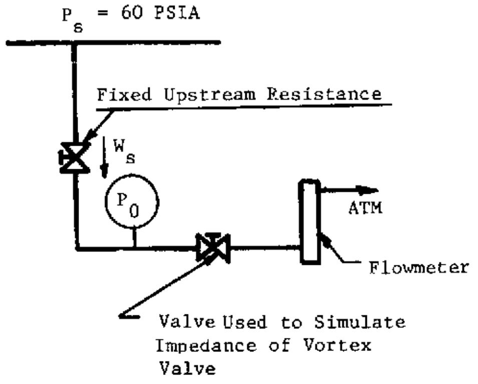
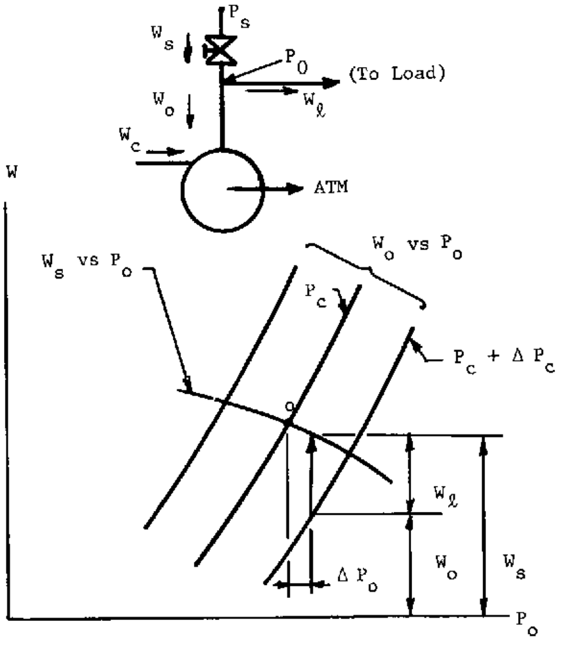


Fig. 13b. Set-up Used to Obtain Pressure-Flow Characteristics of a Fixed Upstream Resistance

Figure 15 illustrates how reasonably linear operation (and linearized analysis) is achieved when small perturbations of pressure and flow occur. A typical operating point, Point 0 shown in Fig. 14, occurs at the intersection of curve (B) with a curve for P_c = constant. Variations of W_s, W_o, W_ℓ, P_c and P_o are then represented as shown in Fig. 15.

After obtaining these characteristics, the circuit in Fig. 12 was constructed and tested at some chosen operating point. Preliminary qualitative tests, with a smaller vortex valve, had indicated that this valve did not have the flow capability to provide fast enough ram response. Hence, a vortex valve having characteristics shown in Fig. 14 was tested and found to have a flow capability of twice that of the first. The adequacy of this new amplifier has yet to be determined. If this provides the desired ram response, it will be possible to proceed to the next phase of development.



$$\Delta W_\ell = (\partial W_\ell/\partial P_c)\,\Delta P_c \Big|_{\Delta P_o=0} + (\partial W_\ell/\partial P_o)\,\Delta P_o \Big|_{\Delta P_c=0}$$

Fig. 15. Linearized Analysis Applied to Fig. 14

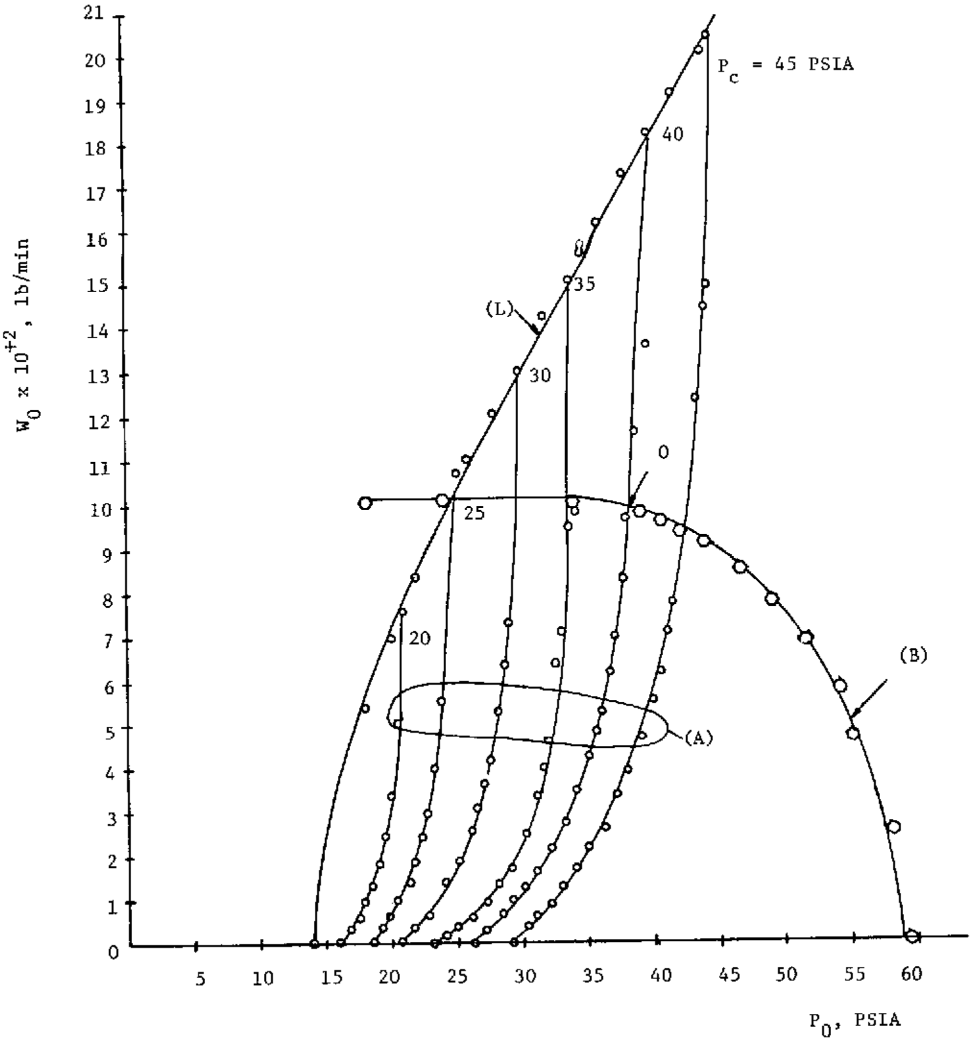


Fig. 14. Pressure-Flow Characteristics of Bendix Vortex Valve S/N3, X-15

This next phase consists of choosing a fluidic amplifier to be used to drive the vortex flow amplifier. Making this choice will probably require a load line analysis with input impedance characteristics of the vortex value, similar to that done in Fig. 15. Once in operation, the primary purpose of this device is to provide the capability of varying control pressure and flow in a manner suitable to drive a ram. One method being explored is the use of a flip-flop with an automatic switching circuit, although other possibilities are to be considered before a final choice is made. Completion of this section leads to the final phase.

This last phase will consist of performance tests on a closed loop system of Fig. 11. This will include: (1) dynamic response measurements, (2) investigation of stability variation with parameters yet to be chosen, and (3) use of phase plane displays of actual performance.

This work has been supported by NASA Grant 39-009-023.

PULSED-SUPPLY-MODE FLUIDICS

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The operation of fluidic elements and control systems employing a pulsed source of power is proposed. Operation in this fashion could reduce the total energy expenditure required to achieve the desired control action in fluidic systems. Thus the effectiveness of fluidic control components would be increased. Pulsed supply fluidic systems will still possess the potential advantages of high reliability; no moving parts to wear out; safety in explosive environments; and insensitivity to vibration, and acceleration and high radiation. In addition the range of application of fluidics as a control technology should be increased. The use of pulse-width-modulation, sampled-data and other discrete interval control by other types of control devices (electronics, hydraulics) supports this idea. It is anticipated that the effectiveness of fluidic systems can be increased in this manner.

Fluidic devices, like any other class of control devices, have both good and bad characteristics. The relative advantages and disadvantages normally determine the type of components employed in a particular control application. A basically poor characteristic of fluidic devices, which is detrimental to wider application of fluidic systems, is a relatively high flow or energy consumption. This problem is especially acute in large systems containing many elements.

Two approaches have been followed in the past to diminish or remove this restriction. One approach is the partial use of moving parts devices (pistons, diaphragms, ball valves). This technique sacrifices several major advantages of fluidics. These include potentially high reliability, no moving parts to wear out, insensitivity to vibration and acceleration. Glaettli [28] compared moving part versus non-moving part fluidic devices on the basis of reliability, speed of response, size and power consumption. He concluded that no single attribute was sufficient to determine the "better" device, but that a consideration of the specific application plus a combination of several of the above attributes was necessary to determine the more appropriate type of device. Clark [29] describes three hybrid fluidic systems, which were composed of mixed moving part and non-moving part elements. The moving part devices were used to overcome inherent disadvantages of pure fluid devices, which include high air consumption.

The second approach has been one of optimization. Many studies have been directed towards increasing the efficiency of various fluidic devices. Most of these studies have been concerned with changing the internal geometry of fluidic devices. Sarpkaya and Kirshner [30] performed a comprehensive study of the performance characteristics of vented and unvented bistable amplifiers having either straight, concave, or convex-Coanda walls. For blocked load conditions their data shows pressure recovery for convex-Coanda walls 29% higher than for straight walls. The maximum efficiency (recovered pressure times flow divided by supply pressure times flow) attained was 45% unvented and 25% vented. Boothe [31] employed a cusped splitter to obtain a bistable amplifier with somewhat higher pressure recovery. A blocked load pressure recovery of 78% and a maximum efficiency of 30% were achieved. Rupert [32] investigated the output pressure-flow characteristics of a jet-receiver-diffuser-load system as a function of jet parameters and the geometry of the receiver. Moses and Comparin [33] studied the effects of geometric parameters on flow and pressure recovery in wall-attachment fluid amplifiers. Table I of their paper lists the effects of ten geometric parameters on pressure recovery and approximate optimum values of the parameters. Beeken [34] obtained the output pressure recovery of a curved wall-attachment device as a function of certain key geometric parameters. His conclusions contain values of four geometric parameters for optimized pressure recovery. Kallevig [35] investigated the effect of receiver geometry on gain and pressure recovery in a proportional fluid amplifier. He found that geometric changes had conflicting effects on gain and efficiency. These are just a few of the many studies done on improving amplifier performance by varying internal geometry.

Small [36] gives a method of optimizing the size of wall-attachment-type elements in order to achieve a given frequency response with minimum power consumption. Griffin's doctoral thesis [37] consisted of the optimization of a pneumatic rate gyroscope. Greber, Koerper and Taft [38] optimized a vortex amplifier for a maximum flow shut-off capability. Syred, Royle and Tippetts [39] optimized turn down ratio in a high gain vortex device without an increase in noise amplitude. Watton [40] formulated static and dynamic models of a proportional fluidic amplifier. The equations predicted the geometry for optimum performance. Unfortunately the mathematical models did not agree with experimental data.

Neither of these approaches, the partial use of moving parts devices or optimization of some sort, appear to attack the problem at its source, which is the continuous consumption of power by an element irrespective of the need for control action or logic function.

To the best of our knowledge no one has investigated the basic idea of operating in an intermittent mode employing a pulsed power supply. This idea can be applied to sampled-data, pulse-width-modulated, and other discrete interval modes of control. We envision a system using a nominal ten-percent-on, ninety-percent-off cycle to take fullest advantage of this mode of operation, which is a form of amplitude modulation. A cycle like this could reduce energy consumption by as much as eighty percent of that when the same system is run continuously. This cycle is somewhat similar to pulse modulation (PWM or PAM) except that the pulses do not ride on a DC level. Another way to use pulsed supplies is in a pulse rate modulation scheme, which would have fixed amplitude and fixed on-period and a variable off-period. Warren [41] described the idea of using digital amplifiers in PWM (supplied continuously) to obtain proportional output. Campagnuolo and coworkers [42] and Campagnuolo and Holmes [43] studied the gain stages of a reaction jet control system for missile guidance. The PWM gain stages were based on continuous operation of bistable elements. Byrd [44] described a similar type of PWM digital amplifier system which was flight tested. Lloyd [45] studied a linear proportional op-amp made of two bistable stages, which were pulse-width-modulated by means of a linear resistance feedback network. Booth and Woodson [46] describe the general idea of "AC" fluidic systems. The advantages of AC over DC are:

1. Comparison of signals is made on a frequency basis. Hence null shift problems are minimized.
2. Signal-to-noise ratio can be improved, since "clipping" can be applied. AC operation minimizes low frequency noise effects.
3. Transmission of signals in frequency form is not as critical of line attentuation and leakage as compared to DC signal transmission.

Pulsed supply mode fluidics may not have all the advantages of "AC" fluidics, but a higher signal-to-noise ratio seems very promising with the use of a pulsed supply. All of the pulse-width-modulation techniques that are being used in fluidic systems today require continuous supplies. Also their signals contain DC levels that often cause bias problems and that are wasteful of supply energy.

Besides the straightforward reduction of energy expenditure due to the on-off mode of operation, we also expect to find some characteristics of fluidic devices improved by operating in this fashion. The supply or power jet of many fluidic devices should develop (spread) slower for the case of a developing jet due to decreased entrainment. Thus a greater proportion of supply energy can be captured by the receivers, which should increase the gain. Wall attachment devices using a pulsed power jet may be switched with much lower control levels than those needed by conventionally operated devices. A very low level control signal applied continuously or during the start up period of a power pulse can very easily move the initially low momentum power jet towards one wall causing the power jet to attach to that wall. Once attached, the power jet will remain attached by the Coanda effect while the power jet energy increases to its fully-on value. Chadwick [47] explored this idea using a regularly pulsed (unity on-to-off time ratio) supply. He found much greater gain and input sensitivity in a wall-attachment device using the regularly-pulsed supply in place of a continuous supply. He also found several other applications including a sensitive pulse detector, a "latching AND" gate, a shift register stage, and a pulse divider. Another area where the pulsed mode may prove advantageous is in reducing coupling and loading effects. During the short on-time in the pulsed mode, coupling and loading effects may not have sufficient time to build up to the level where they cause unwanted switching. Only experiments can determine if this desirable effect will be realized. Perhaps the vents can be done away with entirely, or perhaps a modified venting region will be required.

There is a need to carry out a systematic investigation to determine if these desirable effects can be realized when a pulsed-supply-mode of operation is used. Knowledge is needed about the characteristics of a pulsed jet such as its spreading rate, decay of centerline velocity, beam deflection characteristics, wall attachment capability, etc. It is also important to learn how much pressure recovery can be achieved when the supply jet is pulsed and to discover the salient features needed in the receivers and vent regions.

An exploratory investigation is being started to test the feasibility of this intermittent mode of operation. The first stage of this investigation is being directed towards instrumentation of off-the-shelf proportional and bistable fluidic amplifiers* in order to obtain initial operating data. Average or mean measurements of supply, control and receiver pressures, flows and powers are to be made in each case. This testing is well suited for small scale, commerically-available devices. Here the feasibility of the basic idea of the pulsed-mode of operation will be tested.

Long-range goals of this work will be to achieve: (1) increased efficiency of fluidic amplifiers and fluidic control systems by operating with pulsed supplies, (2) better understanding of the external factors influencing operation in pulsed supply mode, (3) a description of how the operating characteristics of bistable and proportional fluid amplifiers are affected by pulsed supplies and (4) hopefully, a simple demonstration-type fluidic control system using a pulsed supply.

At the present time sources of support are being sought for this research.

SPEED CONTROL SYSTEM EMPLOYING A JET PIPE VALVE

Huan C. Tran, Graduate Student in M. E.

Over the past 50 years various types of speed control systems have been developed for prime movers. In most cases some sort of fluid control is involved; in some cases the system is completely hydraulic or pneumatic. In other cases the system may be mostly electrical or electronic with fluid power being used only for high power level actuation.

For controlling the speed of small steam turbines, which to now have usually been controlled with hydraulic governors, it would be advantageous in certain ways to employ electronic controls, using a steam-powered actuator to drive the turbine throttle valve.

Based on current state-of-the-art in the use of compressible fluids for actuation and control, it is apparent that it should be possible to employ steam as the working fluid in such a system. Special means will probably be required to eliminate accumulation of condensate where it could cause difficulty. Also, if a jet pipe valve is used to control the flow of steam to the actuator, the problem with accumulation of condensate should be greatly minimized.

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* General Electric, Corning, or other manufacturers.

Therefore, it was decided to undertake an experimental investigation and preliminary design of a steam-powered fluid amplification system using the jet-pipe valve. Some equipment for initial experimentation, including a force-motor driven jet valve, has been provided by the Terry Steam Corporation, Windsor, Connecticut.

Figure 16 illustrates the overall control system that would be employed to control turbine speed, with a small electric motor and tachometer used to simulate the throttle valve and turbine dynamics. Initial experiments will determine the pressure flow characteristics of the jet pipe valve with compressed air and modifications will be made as needed to adequately drive a ram actuator.

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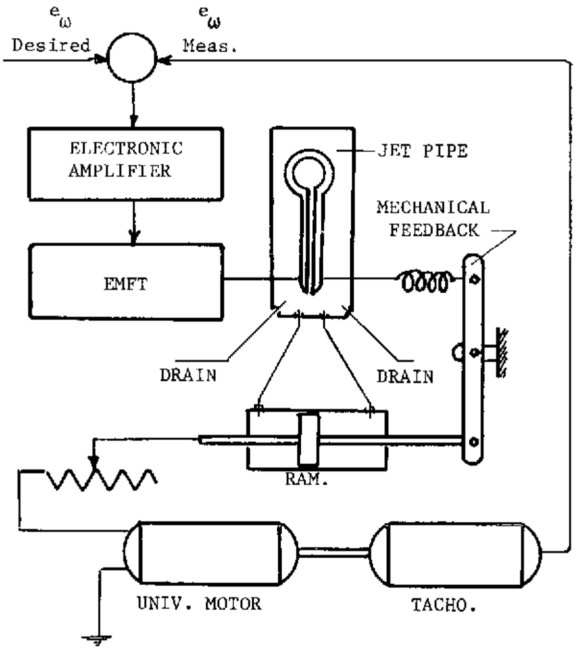

Fig. 16. Jet Pipe in the Simulated Speed Control System

FLUIDICS REFERENCE CENTER

R. Yaros, Graduate Fellow in M. E.

The Fluidics Reference Center (FRC) is an information bank containing available publications in fluidics and fluidics-related fields. Publications from approximately 1960 to date are included. The Fluidics Reference Center has been described in previous Systems and Controls Laboratory (SCL) Research Reports [9, 10, 11, 13, 15]. Research Report No. 10 [10] describes the area coding system being used by the FRC and lists the major areas. The search routines used in the computerized information retrieval are covered in Research Report No. 11 [11].

In the last SCL Report [15] the difficulties that have been encountered in constructing the manual search and retrieval system were discussed. The major problem is the large quantity of secretarial work involved and lack of financial support for this work.

The previously proposed manual author file (principal author only) has been constructed. This file contains all index information and the abstract of the paper. At the present time work is underway on the construction of the manual area code files. Cross-referencing by major areas will be included in these manual files.

As they are constructed the manual files are being printed on 5 x 8 index cards. In the near future we hope to have copies of the manual files on 5 x 8 cards available for purchase by individuals and organizations who desire a manual system of their own. At present the information contained in the FRC is available on magnetic tape. Further information concerning the services available from the Fluidics Reference Center can be obtained by writing to the Director of the Systems and Controls Laboratory, whose address is given at the end of this SCL Report.

Currently the Fluidics Reference Center contains approximately 1200 entries. Three-hundred additional papers have been culled from the literature and are awaiting key punching before being added to the library. A systematic search is underway to continue to add new papers as they are published and to find pertinent papers previously overlooked.

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For further information about the projects mentioned in this report of the activities of the Systems and Controls Laboratory, inquiries should be addressed to: Director, Systems and Controls Laboratory, 214 Mechanical Engineering Building, University Park, Pennsylvania 16802.

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