Design and Development of a Fluidic Chamber Pressure Control Subsystem for the NERVA Engine

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A design concept for a nuclear-rocket engine fluidic chamber pressure control subsystem is presented, together with the development approach used for the major components. Nuclear-rocket engine system performance requirements dictate a different design philosophy than is used in commercial fluidic systems. Static and dynamic fluidic subsystem requirements for the nuclear-rocket engine are examined in terms of experimental and theoretical performance. As a part of this program, an investigation has been conducted of a vortex valve to control the turbine inlet conditions for the NERVA engine. A full-scale prototype valve and several second-generation subscale valves were tested with a variety of gases, temperatures, pressures, and geometries. A scaling law has been shown to adequately take into account these various conditions. A computer model was developed to predict vortex valve performance, and calculated results have correlated well with experimental data. The results of this investigation indicate the feasibility of replacing the current chamber-pressure control loop with a more reliable fluidic subsystem.

Nomenclature

A = flow area
C_D = discharge coefficient
$F(s)$ = transfer function
$\dot{m}$ = flow rate
m = moment
M = Mach number
P, P_t = static and total pressures, respectively
r = radius
T, T_t = static and total temperatures, respectively
u = velocity
ρ = density

Subscripts

c,s = control and supply flows
ch = engine chamber conditions
e = at valve exit
nc = outlet flow at no-control flow conditions
o = at valve periphery
out = outlet flow
p = pump
t = turbine
z = axial component

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The Nuclear Engine for Rocket Vehicle Application (NERVA) program is administered by the Space Nuclear Systems Office, a joint office of the U.S. Atomic Energy Commission and NASA. Aerojet Nuclear Systems Company is the prime contractor for the engine system. Westinghouse Electric Company is the principal subcontractor for the nuclear subsystem.

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Introduction

A FLUIDIC-CHAMBER pressure-control subsystem for a nuclear-rocket engine will improve control system reliability, since it will have fewer moving parts, more nuclear and solar radiation immunity, and be self-cooling during operation. A fluidic system will require less component redundancy and less electrical wiring; in addition, the hydrogen propellant can be used for the fluid power supply source.

The engine has two primary control loops: the chamber-pressure loop, and the chamber-temperature loop. Although there is some dynamic interaction, chamber pressure is primarily controlled by regulating turbine power; and chamber temperature is controlled by adjusting the power level of the reactor. Both of these loops are amenable to fluidic implementation.

The chamber-pressure control loop offers the more immediate potential for a possible fluidics application because all control functions of the basic loop that require moving parts or electronic devices may be performed by fluidic devices. A demonstration of an acceptable fluidic chamber-pressure control loop will suggest possible means of converting other control functions of the engine from electromechanical to fluidic technology.

Preliminary studies of this concept, initiated at Aerojet in 1966, were confined to subscale designs and devices employing ambient nitrogen as a working fluid.

The working fluid for the full-scale system is hydrogen, since it is available at various engine stations in gaseous or liquid conditions at high pressures. Engine performance requirements dictate that the fluidic control system shall not degrade the engine specific impulse; i.e., the maximum amount of propellant is to be used for thrust generation at the engine operational temperature of 4250°R. This requirement resulted in the preliminary design concept shown in Fig. 1.

Subsystem Design Concept

A basic flow schematic of the proposed fluidic chamber pressure (P_c) control subsystem is presented in Fig. 1, which identifies the basic flow paths for the energy sources and sinks necessary to maintain fluidic control of the subsystem. Engine-chamber pressure (Pch) is related to the hot-bleed measured chamber pressure $[(Pch)_m]$ by a calibrated tap-off line. $(Pch)_m$ is one input to the first-stage fluid-amplifier, the other being chamber-pressure demand $[(Pch)d]$ generated by the electric-to-fluidic converter. This device accepts an electrical signal from the engine programmer proportional to $(Pch)d$, uses the gas from the nozzle outlet torus (reflector inlet) as a fluid-energy source, and reduces its pressure (with a pressure regulator) to produce the required chamber-pressure demand from the engine programmer. The energy source for all fluidic-amplifier stages is drawn from the nozzle exit torus (700 psia and 203°R at engine design point).

The output of the first-stage proportional-beam amplifier is adjusted by the appropriate fluidic compensation to become the input control pressures (P_{CA1} and P_{CA2}) for the second-stage beam amplifier which is the driver amplifier. The proportional-beam-driver amplifier outputs become the control input to the vortex valve (P_c), or are vented back to the pressure vessel at a pressure of 635 psia.

The ejector pump on the outlet leg of the final (driver) amplifier stage uses pump discharge fluid at 900 psi and 50°R to recirculate the unused control fluid back to the reactor inlet, providing a matched impedance load to the final-stage driver amplifier.

The vortex valve accepts the flow from the hot-bleed port at its supply port (pressure supply). The control input then regulates the vortex-valve outlet pressure (turbine-inlet pressure) to regulate, in turn, turbopump-assembly torque output and, hence, turbopump output pressure and flow rate. Because the vortex valve is not a shutoff device, positive shutoff for engine shutdown is provided by a mechanical turbine-block valve.

The engine could use a topping cycle, in which power is obtained by passing the bulk of the propellant through a turbine after it has been used to cool some of the structural components of the engine. In this cycle all flow would continue through the reactor after passing through the turbine, resulting in no loss in specific impulse.

Use of the hot-bleed concept and the specific engine design state points (pressure and temperature) provided criteria for design and testing. The goal of utilizing the fluid at the maximum temperature leads to the basic fluidic amplifier requirements of optimizing flow gain between the amplifier stages without atmospheric venting for impedance isolation, and provides maximum recirculation of unused vortex-valve control fluid through the engine.

Vortex Valve Design Requirements

A key component in the chamber pressure control subsystem design is the vortex valve which has received considerable interest in recent years as a device for fluidically varying the effective restriction to flow in a line.[1–8] This valve may be used to control the flow in either the hot-bleed or topping cycle. For the hot-bleed cycle, the valve is used in series with the turbine to increase pressure drop between the hot-bleed port and the turbine inlet. In the case of the topping cycle, the valve is more likely to be used in parallel with the turbine, minimizing pump discharge pressure, to bypass a fraction of the flow around the turbine. The two types of valves would be quite different. The valve requirements for the hot-bleed cycle are considered here because this is the cycle used on the most recently tested engine, and the cycle for which full-scale vortex valve data have been obtained. However, the engineering approach and the fluidic component parametric data presented are generally applicable to the development of fluidic controls for either cycle. This is noted since the topping cycle is currently favored for flight engine application.

For a 75,000-lb thrust engine, the turbine power control valve (TPCV) for the hot-bleed cycle must have a flow

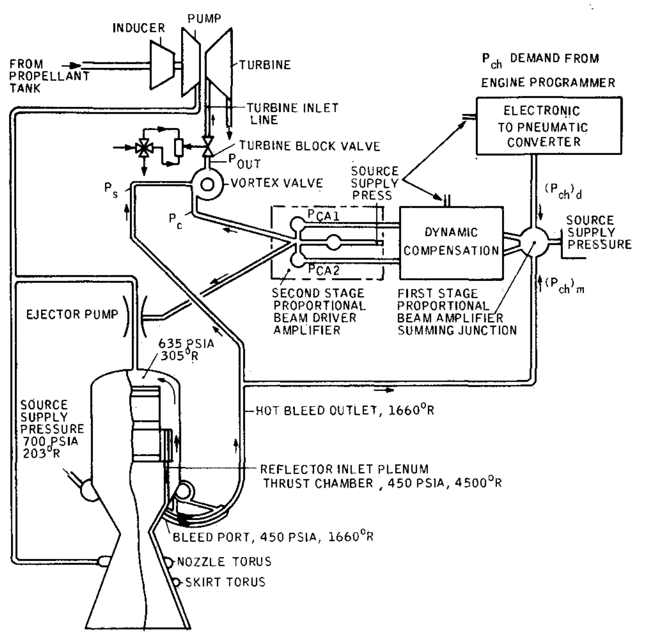


Fig. 1 Hot-bleed-cycle nuclear rocket engine; fluidic chamber pressure control subsystem flow schematic and design-point operating conditions.

capacity of approximately 5 lb/sec of hydrogen at 1660°R and 450 psia. The desired operating range of the engine can be encompassed by a valve that can be throttled to vary power to the turbine from maximum to 60% of maximum. A separate mechanical valve must be provided for complete shutoff.

Since any loss in turbine efficiency results in a loss of engine specific impulse, it is important that the amount of pressure recovery across the valve in the fully open position be as large as possible. The mechanical valve has a pressure recovery of about 95%; the fluidic valve must have at least 90% recovery. The valve should also weigh less than 100 lb, the approximate weight of the current mechanical TPCV.

The standard vortex valve must be controlled by high-pressure flow. The only sources within the hot-bleed engine for control pressures in excess of chamber pressure are at low temperatures. The prime source is at 700 psia and 200°R (Fig. 1). If the control flow to the vortex valve is to be controlled mechanically, most of the 700 psia will be available to drive the vortex, but since the major interest is in a complete fluidic subsystem, allowances must be made for pressure losses in the fluidic amplifiers upstream of the vortex control port. Allowing a 70% pressure recovery for the amplifiers reduces the available vortex control pressure to approximately 500 psia. A small control flow is desired to ease the demand on upstream fluidic components, and to reduce the effect of enthalpy dilution caused by the cold control flow. A control flow requirement of 1 lb/sec appears to be an upper bound.

Description of Theoretical Model

A detailed analytical model of a vortex valve has been formulated: 1) to investigate parametric variations other than those available in the literature; 2) to help evaluate experimental results; and 3) to provide a design tool for future matching of a vortex valve to the complete chamber pressure control system. Correlation between calculated results and experimental data has in general been good over a wide range of valve parameters.

The analytic approach is similar to that of Bauer[6] and Bichara and Orner.[7] The valve is divided into an inlet region, the valve main chamber, and an outlet region (Fig. 2). In the inlet region there is a transition from separate supply

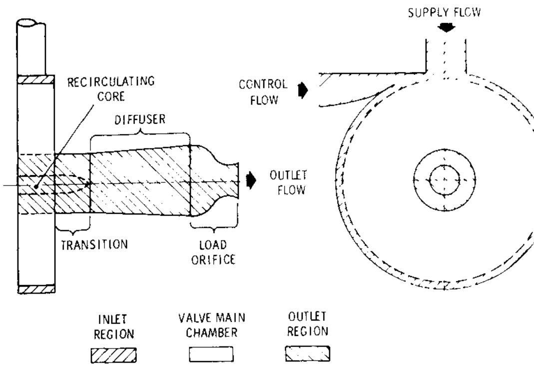


Fig. 2 Basic regimes in analytical model.

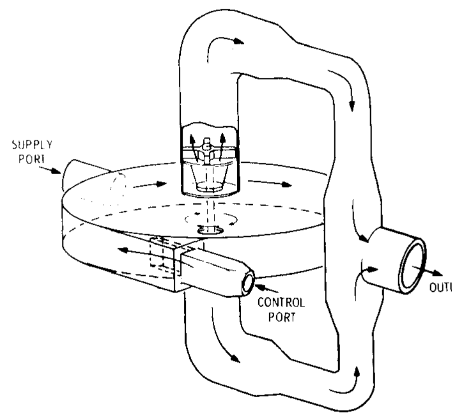


Fig. 4 30-in. vortex valve.

and control flows, which enter at the valve periphery, to a mixed uniform swirling flow. The tangential velocities of this mixed flow are then amplified in the main chamber of the valve as the fluid flows radially inward towards the valve exit. The transition from radial to axial flow takes place in the outlet region, the amount of flow passing through the valve exit being controlled by the degree of swirl developed at that point.

The current analysis differs from previous theoretical models in the treatment of the outlet region and by giving consideration to heat-transfer effects throughout the valve. Either a constant back pressure at the valve exit, or a particular weight flow/pressure relationship (which might exist for such applications as a sonic or subsonic orifice or a length of pipe with significant pressure loss downstream of the valve exit) can be specified. The flow through the valve exit may be either choked or unchoked. In the latter case, the presence of a recirculation core along the valve axis is included in the calculations.

In keeping the analytical model as general as possible, for application to a broad range of valve conditions, flow was considered to be compressible. A heat-transfer analysis was included to handle the case of supply and control flows at different temperatures, resulting in different fluid and valve wall temperatures.[8]

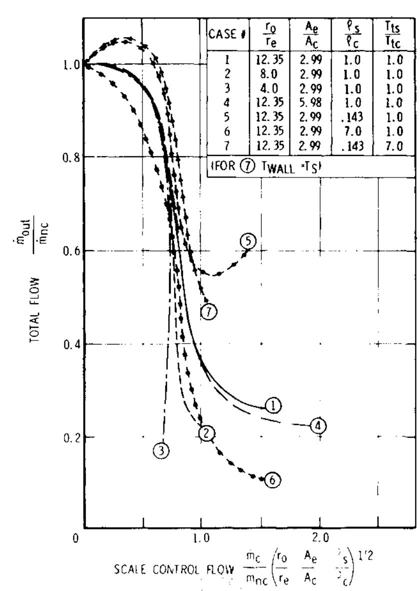
Correlation of Theoretical and Experimental Results

To evaluate the vortex-valve computer model, experimental data representing a varied range of valve geometries and operating conditions were gathered, and the corresponding theoretical results were calculated. The data included: 1) A valve with a number of small, radial supply ports and tangential control ports operating in the incompressible regime and exhausting to a fixed back pressure.[9] 2) A button-type valve with the supply flow entering axially through an annular passage and with flow choked at the outlet.[6] 3) An Aerojet subscale valve with two opposed supply ports and a choked-load orifice.

As reported in Ref. 8, there is good correlation with the data of Wormley and of Bauer, and the prediction of bistable output obtained with Bauer's low-radius-ratio valve is of particular interest. Data from one of the opposed-supply subscale vortex valve models of a possible TPCV correlated well with theoretical results in the upper portion of the curve, but less well in the viscous region. A possible explanation for the discrepancy in the high-swirl region is the presence of some swirl upstream of the load orifice, contrary to the no-swirl assumption made in the analysis. Further investigation is planned to check this possibility.

Although the computer model is a useful design tool, a scaling law is desirable for narrowing the range of design parameters for a specific application. Wormley[9] found a successful scaling parameter to account for geometric effects and Lewellen et al.,[10] found a similar one to include temperature effects. This scaling is accomplished by multiplying the normalized control-weight flow by

$$(r_0 A_e \rho_s / r_e A_c \rho_c)^{1/2} \quad (1)$$



CASE #	r_0/r_e	A_e/A_c	ρ_s/ρ_c	T_{ts}/T_{tc}
1	12.35	2.99	1.0	1.0
2	8.0	2.99	1.0	1.0
3	4.0	2.99	1.0	1.0
4	12.35	5.98	1.0	1.0
5	12.35	2.99	.143	1.0
6	12.35	2.99	7.0	1.0
7	12.35	2.99	.143	7.0

Fig. 3 Analytical scaling parameter considering the effects of valve geometry and gas density.

and is illustrated in Fig. 3 with theoretical results from the computer model. For a wide range of geometric parameters and gas densities, the scaling parameter is successful in grouping the results into a "universal" curve in the region where the assumptions of inviscid flow and small changes in outlet flow density (used in deriving the scaling parameter) are valid. In the high-swirl region approaching cut-off, viscous effects become significant; hence, the "tails" of the curves do not scale. Also, at low control flows with greatly differing supply and control flow densities, significant deviations in outlet flow density occur before swirl effects begin to dominate.

The main conclusions drawn from the correlation studies are that the computer model is effective in predicting vortex-valve performance, and that the theoretical performance can be scaled to a universal curve over a significant region for a wide range of valve geometries and operating conditions.

Full-Scale Tests

To demonstrate the basic feasibility of the fluidic TPCV concept, a full-scale prototype vortex valve was designed

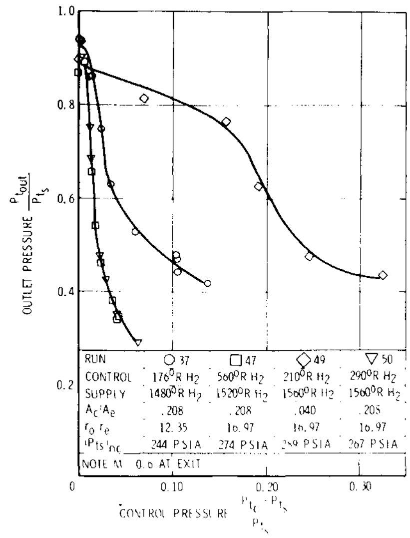


Fig. 5 Pressure performance for the prototype 30-in. vortex valve.

using preliminary theoretical results and subscale test data. A large radius ratio (r_o/r_e) was chosen to accomplish such control (Fig. 3). For the hot-bleed engine cycle considered, valve outlet flow chokes at the turbine nozzle entrance. Thus, the valve-exit Mach number at the full-flow condition must be a compromise between the desire to maintain it sufficiently low for good pressure recovery, and the desire to choke the valve exit for maximum effectiveness and minimum size. A valve exhaust Mach number of 0.6 at no-control flow, followed by a diffuser to improve pressure recovery, was chosen for these tests.

The prototype valve (Fig. 4), constructed of nickel steel with a vortex chamber 30-in. diam and 2-in. thick, is the largest gas vortex valve known. The valve was tested primarily with hot hydrogen supply ($\approx$1600°R) and cold control (200°R) gases. Pressure performances for typical tests are shown in Fig. 5.

These observations were made for the prototype vortex valve: 1) Valve characteristics, when properly normalized, appear to be insensitive to changes in supply pressure; 2) No-control pressure recovery is approximately 90%; 3) Other valve parameters being equal, the control pressure requirements are independent of control or supply temperature (Figure 5); 4) For $\dot{m}_{out}/\dot{m}_{nc} \geq 0.6$ (the area of interest for a hot-bleed cycle engine) a universal curve results when $\dot{m}_{out}/\dot{m}_{nc}$ is plotted against

$$(\dot{m}_c/\dot{m}_{nc})\ (\dot{m}_c/\dot{m}_{nc})(\rho_S A_e r_0/\rho_c A_c r_e)^{1/2} \qquad (2)$$

The verification of this curve has been extended to include

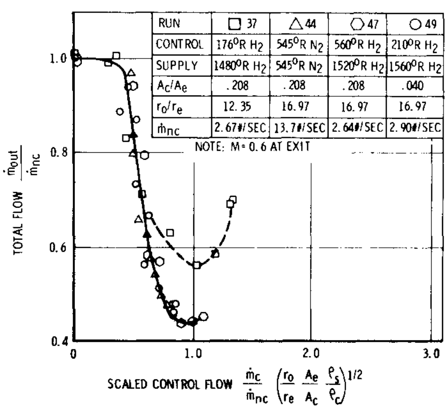


Fig. 6 Experimental universal curves for the prototype 30-in. vortex valve.

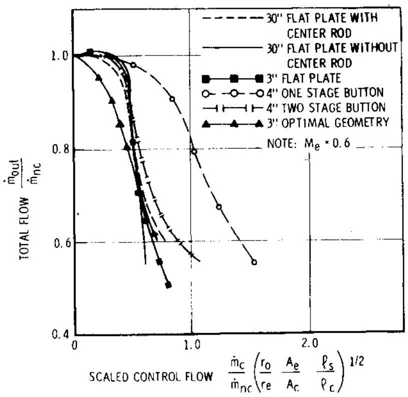


Fig. 7 Experimental vortex-valve comparison.

variation in radius ratio, gas types, and density ratios (Fig. 6); 5) Comparison of the data with the analytical data in Fig. 3 indicates that the full-scale valve has better performance than was predicted; and 6) A pressure noise, which can have a large amplitude, exists during full-flow conditions.

A few additional subscale flat-plate vortex valve tests with a single supply were conducted concurrently with the prototype program. For a 3-in. valve with a radius ratio of 12.85 and $M = 0.6$ at the exit, the scaled performance was the same as that of the prototype (Fig. 7).

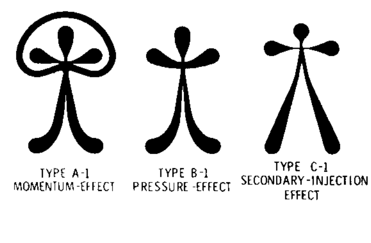
The prototype valve has adequate throttling capability but is larger than desirable for a flight-weight design. Valve weight may be reduced either by designing a more efficient structure to support the stresses of a given diameter valve, or by reducing the required radius ratio to permit a smaller valve. By optimizing the geometry of the vortex chamber to reduce stress at a given pressure, it should be possible to reduce the weight of the full-scale valve with a center support rod by approximately a factor of four. A subscale valve with such an optimal geometry has been found to have performance equal to that of a flat-plate valve but with some modification in the shape of the curve (Fig. 7).

Valve size may possibly be reduced in at least three ways: 1) by increasing the control-jet momentum without changing P_c or $\dot{m}_c$, by allowing for some heat transfer to the cold control fluid; 2) by introducing the supply flow into the valve with a slight swirl to give the valve a bias; and 3) by adding a passive second stage to the valve. Use of one or more of these concepts would reduce the weight of the valve to less than the allowed 100 lb. For these reasons, it appears possible for a fluidic vortex valve to meet the TPCV requirements.

Amplifier Design

Design of the amplifier stages necessary to complete the feedback loop (Fig. 1) required investigation of the relative performance of unvented amplifiers. Direct-beam deflection types of jet-interaction devices that employ either momentum, pressure, or secondary injection control were studied. Figure 8 shows the basic design silhouettes for which Table 1 presents a qualitative performance evaluation. Two subscale amplifier sizes were studied under various loading conditions, including the uneven output impedance that the final driver-amplifier stage experienced. Poor performance

Fig. 8 Three types of beam amplifiers.



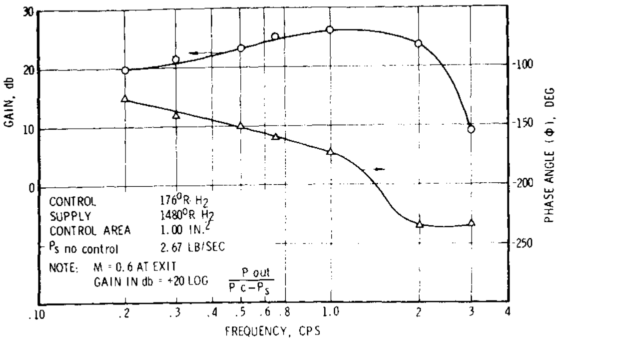


Fig. 9 Open-loop frequency response for 30-in. vortex valve.

when working into an uneven impedance (back pressure), led to the design of a recirculating jet ejector to boost engine-dome return-leg pressure, and to create the effect of an equal-output back pressure for both amplifier legs.

Unvented beam amplifiers were chosen because their performance characteristics were considered the most amenable to the required type of operation. Detailed surveys were required, however, since the flow magnitude and gain into

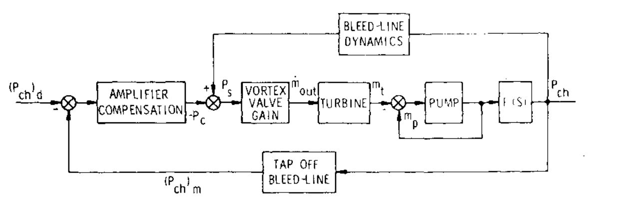


Fig. 10 Initial analysis basic block diagram for fluidic chamber-pressure control subsystem.

each amplifier stage must be balanced, and pressure recovery above 60% was mandatory. Based upon this largely empirical investigation, basic amplifier flow-passage designs were fabricated from photosensitive plastic and tested with ambient nitrogen. Amplifier pressure ratios between control and outlet flow were maintained equal to those of the engine preliminary design requirements. Use of ambient nitrogen for simulation of 200°R hydrogen is somewhat realistic on a viscosity basis, and Mach-number effects for the secondary

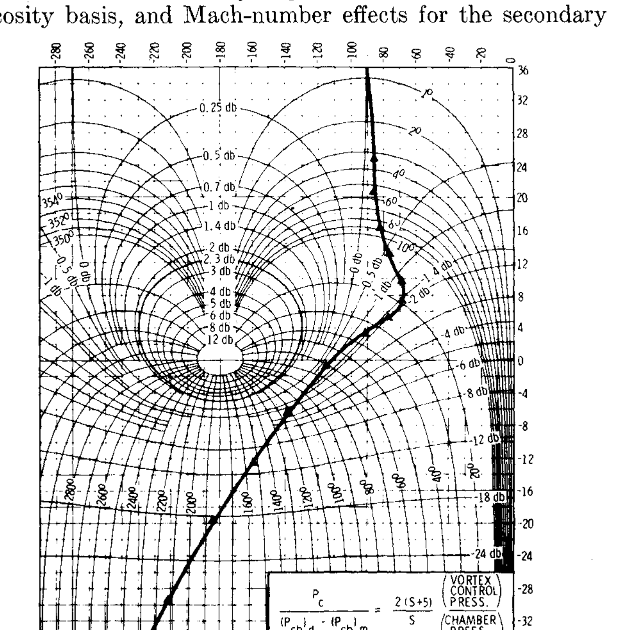


Fig. 11 Closed loop response for fluidic chamber-pressure control subsystem.

Table 1 Comparison of Amplifier Designs

	Type A-1	Type B-1	Type C-1
Flow gain	Good	Poor	Excellent
Pressure gain	Good	Excellent	Good
Pressure recovery	Good	Excellent	Fair
Control range	Good	Poor	Excellent

injection design should be comparable on a pressure-ratio basis.

Subsystem Dynamic Performance

System design must consider dynamic as well as static requirements. The frequency response of the assembly was determined during full-scale parametric vortex-valve tests (which were made with simulated engine downstream impedance characteristics). A digital computer program was employed (Guilleman's method) to determine impulse response to an arbitrary input. The results are shown in Fig. 9, relating outlet pressure (P_{out}) to the difference between control and supply pressure. The magnitude curve shows a cutoff frequency between 2–3 Hz, and corresponds closely to the predicted capacitative volumetric characteristics of the valve. The phase is negative because of the effect of decreasing control pressure to increase outlet pressure.

A cursory examination was made of subsystem closed-loop-response characteristics, based upon the block diagram shown in Fig. 10. The results for a selected value of amplifier compensation are shown in Fig. 11, a Nichols plot that demonstrates adequate phase and gain margin. The transfer function, $F(s)$, shown in Fig. 10 represents coupled NERVA engine system characteristics as determined from open-loop tests.

Conclusions

This program has provided a first step toward the evolution of a workable fluidic control subsystem. It is suspected that this work can be extended and applied to evolve a practical flight-engine control system delivering the promised advantages of fluidic systems. While the hot-bleed nuclear-rocket engine cycle is not currently being considered for flight-engine application, the engineering approach and fluidic component parametric data presented are generally applicable to the development of fluidic controls for the topping-cycle engine.

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