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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents data and operating experience information on many commonly used laminar gain blocks from two to eight stages. In addition, as an aid to design, a short computer program is presented, suitable for use with a pocket programmable calculator. Outputs from this program are individual stage data including nominal supply pressures and flows and staged gain. Also available is the net gain and the bandwidth at 90 deg of phase shift. Several

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20. Abstract (cont'd)

examples of this program are given to cover multiple-stage gain blocks. As an example of the utility of the program, a step-by-step tradeoff study is presented for the Massachusetts Institute of Technology fluidic servovalve, for which an attempt is made to maximize bandwidth and minimize leakage flow.

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APPENDICES

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FIGURES (Cont'd)

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1. INTRODUCTION

In developing fluidic systems, it is most often necessary to provide a certain amount of gain. Whether it is to boost sensor outputs to useful levels or to provide high gain feedback, each application requires amplification of differential pressures. Since the gain of a single standard laminar proportional amplifier (LPA) is about 10, it is necessary to stage LPA's if more gain is desired.

Staying LPA's has been dealt with extensively in the literature;[1-6] however, performance of preferred topologies has not in general been discussed. Certain advantages, not specifically obvious, lie with certain specific designs.

The most commonly used gain block is the self-staged gain block. Although one of the most important operational advantages of such a device is that the high single-stage LPA input-to-output resistance ratio is maintained, perhaps the most compelling reason for its use is the ease with which assembly and manifolding of supply pressure occur since only one supply pressure is needed. Other topologies, however, use a single common supply pressure to each amplifier, and most gain blocks use a single supply which is then manifolded down. Therefore, this report presents experimental data for many different gain blocks. Although operational characteristics are stressed, a design rationale where it is not obvious is presented. A simple program, developed for use with a pocket programmable calculator, provides the basis for the design of a gain block and is treated first.

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

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

[3]*T. M. Drzewiecki, D. Wormley, and F. M. Manion, A Computer-Aided Design Procedure for Laminar Fluidic Systems, J. Dyn. Sys. Meas. Control, 97, Series G, No. 4 (December 1975).*

[4]*G. Mon, Flueric Laminar Gain Blocks and an Operational Amplifier Scaler, Harry Diamond Laboratories, HDL-TR-1730 (December 1975).*

[5]*T. M. Drzewiecki, A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).*

[6]*M. Cycon and D. Shaffer, Design Guide for Laminar Flow Fluidic Amplifiers and Sensors, contract with Garrett Pneumatic Systems Division, Harry Diamond Laboratories, HDL-CR-82-286-1 (March 1982).*

2. SIMPLE STAGING DESIGN PROGRAM

The in-stage gain of a standard LPA is determined by the operating bias pressure and the load that the LPA is driving. The sensitivity of gain to bias pressure is given by the relationship[7]

$$G_{biased}/G_{zero\ bias} = 1/[1 + 0.6(P_{bias}/P_s)] \quad , \qquad (1)$$

which is shown in figure 1 for some typical amplifiers.

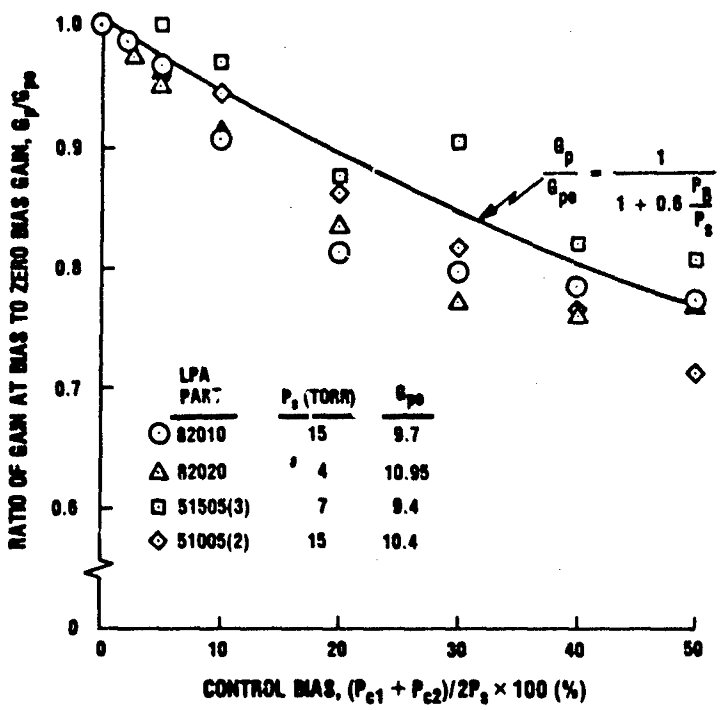

Figure 1. Gain as function of bias for standard laminar proportional amplifier of Harry Diamond Laboratories.

If one assumes that under most loading conditions the recovered pressure of a preceding stage is at least 33 percent (for aspect ratio, $\sigma > 0.7$), then the expression for gain can be approximated in terms of the preceding (n - 1) stage supply pressure, so that

$$G_{biased}/G_{zero\ bias} = 1/[1 + 0.2(P_{s(n-1)}/P_{sn})] \quad . \qquad (2)$$

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

The gain of an LPA is also determined by the load into which the amplifier is operating so that

$$G_{load}/G_{blocked} = 1/\left[1 + \left(R_o/R_L\right)\right] \quad , \qquad (3)$$

where R_o is the LPA output resistance and R_L is the load resistance. Since the output resistance for almost any case is[5] $R_{on} = 0.5P_{sn}/Q_{sn}$ and the in-stage load is the input resistance of a succeeding (n + 1) stage,[5] then

$$R_L = R_{i(n+1)} = 0.75P_{s(n+1)}/Q_{s(n+1)} \quad .$$

In such a manner, equation (3) becomes

$$G_{load}/G_{blocked} = 1/\left[1 + 0.667\left(P_{sn}/P_{s(n+1)}\right)\left(Q_{s(n+1)}/Q_{sn}\right)\right] \quad . \qquad (4)$$

The phase shift for small phase angles is determined by the signal transport lag in the device. The total gain block phase shift, as a minimum, is the sum of the phase shifts of each stage:

$$\phi_n = 360 \ \tau f \qquad (5)$$

and

$$\phi = \sum_{n=1}^{N} \phi_n \qquad (5a)$$

so that

$$\phi = 360f \sum_{n=1}^{N} \tau_n \quad , \qquad (5b)$$

where ϕ is in degrees, τ is the signal transport time across an LPA (equal to twice the particle transport time),[5] and f is the frequency in hertz. The signal transport time is

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[5]*T. M. Drzewiecki, A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).*

$$\tau = 2x_{sp}/c_d(2P_s/\rho)^{1/2} \quad . \tag{6}$$

Since in the standard LPA the nozzle-to-splitter distance, x_{sp}, is eight nozzle widths ($8b_s$), τ becomes

$$\tau = 16b_s/c_d(2P_s/\rho)^{1/2} \quad . \tag{7}$$

To determine the frequency at which total phase shift is ϕ degrees, one uses equations (5b) and (7) to get

$$f = (\phi/360)/\left[16 \sum_{n=1}^{N} b_{sn}/c_d(2P_{sn}/\rho)^{1/2}\right] \quad , \tag{8}$$

where c_d is the LPA discharge coefficient (c_d = 0.7 for the nominal operating point) and ρ is the fluid density.

Equations (1), (3), and (8) can be written in a program for N stages. Just such a program, written in BASIC, is shown in appendix A. The bulk of the program is taken up by setting up the arrays for all the input data. Flow consumption is based on a nominal 0.3 liters/min (LPM) for an LPA with b_s = 0.5 mm at a modified Reynolds number, N_R' = 120.

$$N_R' = N_R/[2(1 + 1/\sigma)^2]$$

and

$$N_R = b_s(2P_s/\rho)^{1/2}/\nu \quad ;$$

in air,

$$N_R = 1000b_s\ (\text{mm})\ [P_s\ (\text{torr})]^{1/2} \quad .$$

Sample printouts are shown in appendix A for nine runs.

Verification of the validity of the results of this program is left to the following sections, in which they are used as a design guide.

3. COMMONLY USED GAIN BLOCKS

In trying to present the information logically, it is easiest to use the number of stages as the primary delineating factor. What follows, therefore, is a compendium of gain blocks and their performance, starting with two stages and ending with eight. Stacking orders for some of the more commonly used circuits are given for standard Harry Diamond Laboratories (HDL) integrated format parts in appendix B.

As a rule, the nominal gain of a single standard LPA is about 10 at $\sigma N_R = 1000$. This value, however, varies depending on the manufacturing process used, the accuracy to which the nominal dimensions are kept, and the aspect ratio. As a result, a normal span of gain variation is from 7 to 12. As the aspect ratio gets below 1, the gain decreases from a nominal 10 to as low as 7 at an aspect ratio of 1/3.

The currently accepted methods for fabrication are photochemical etching, fineblanking, and wire electrodischarge machining.[8,9] These manufacturing methods are designated by numerical prefixes to the four-digit designation numbers as 5, 6, and 8, respectively, forming a five-digit LPA part number. The two digits immediately following the manufacturing prefix correspond to the nozzle width in mils, and the last two digits are the lamination thickness in mils. Alphanumeric suffixes in brackets may designate special dimensions or functions; for example, [R] refers to a rectifier. In this fashion, a fineblanked LPA with b_s = 0.5 mm (0.020 in.) and σ = 0.75 is designated as P.N. 62015, and an etched LPA with b_s = 0.25 mm (0.010 in.) and σ = 0.5 is designated as P.N. 51005.

In the following sections describing gain blocks, the average value of a single-stage blocked-pressure gain is given to provide a yardstick against which to evaluate possible alternative performances. The reader should remember that net gain is the product of the blocked single-stage gain raised to the power N (where N is the number of stages) multiplied by the net losses. The losses generally remain the same, independent of the blocked gain, so that if one is interested in the performance of a gain block made up of LPA's of gain different from those reported here, one merely multiplies by the ratio of new gain to old gain raised to the Nth power. For example, a three-stage gain block is reported here to have a gain of 200 using LPA's with a blocked single-stage gain of 8, but is reproduced by using components with a gain of 10. The new gain block has a gain of $(10/8)^3$ higher, or 391.

[8] *L. Scheer, J. Roundy, and J. Joyce, Manufacturing Techniques for Producing High Quality Fluidic Laminates in Production Quantities, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).*

[9] *R. M. Phillippi, A Study of Fineblanking for the Manufacture of Flueric Laminar Proportional Amplifiers, Harry Diamond Laboratories, HDL-TM-77-8 (May 1977).*

3.1 Two-Stage Gain Blocks

Several two-stage gain blocks have been implemented at HDL, but two are most common. The first is a self-staged gain block, and the second is a moderately pressure-staged gain block that is extensively used in fluidic capillary pyrometer circuits.[10]

3.1.1 Two-Stage Self-Staged Gain Block

Figure 2 shows a collection of data for various size and aspect ratio two-stage self-staged gain blocks. Representative transfer characteristics are given at the nominal operating point in figure 2(a), and the gain as a function of normalized supply pressure is given in figure 2(b). Also shown in figure 2(b) are the computed values of gain using the program given in appendix A. As may be observed, there is good correlation. A generic stacking order is given in appendix B.

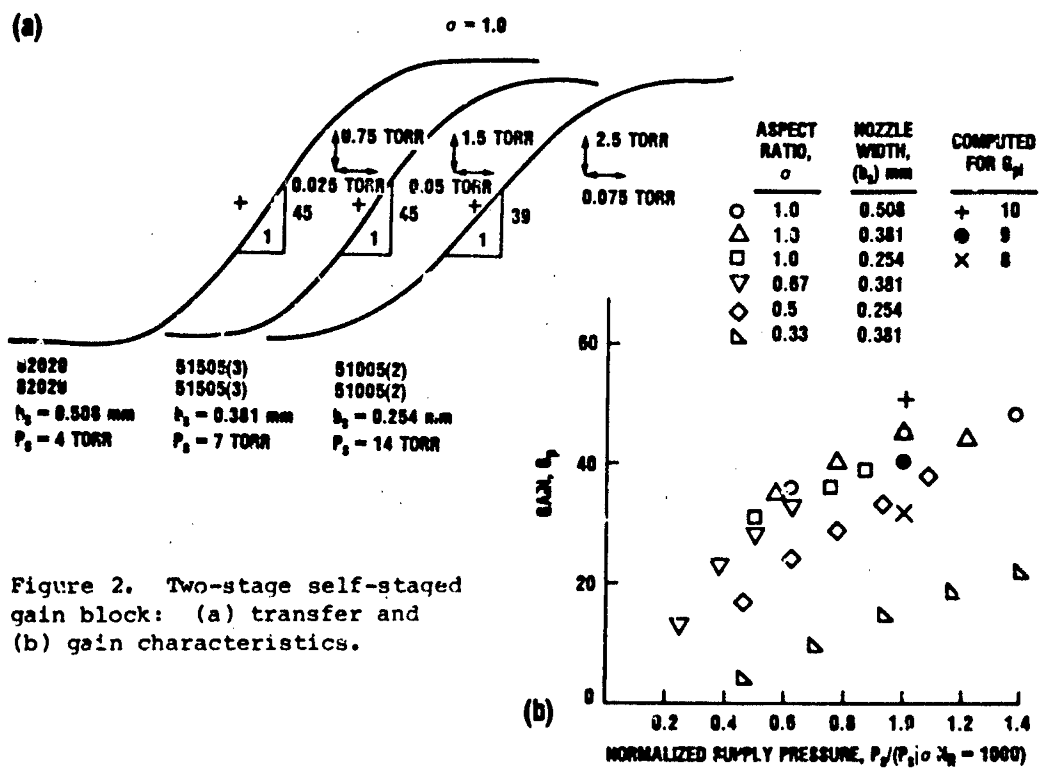

Figure 2. Two-stage self-staged gain block: (a) transfer and (b) gain characteristics.

[10] R. M. Phillippi, T. M. Drzewiecki, T. Negas, and H. S. Parker, *Design of a Fluidic Capillary Pyrometer for Contact Duty at Temperatures to 2750°C, Proceedings of 6th International Symposium on Temperature, Washington, DC (15 to 19 March 1982).*

3.1.2 Two-Stage Moderately Pressure-Staged Gain Block

To get more gain using low-aspect-ratio, small-size devices with high impedance and high output pressure, some slight amount of pressure staging is obtained by cascading a device with an aspect ratio of 0.33 with one of 0.67 for the first stage. These stages operate at different pressures, so to operate the device from the common last-stage pressure, a dropping resistor must be employed.

The computer program generates values for nominal supply pressure and flow so that values of dropping resistors can be estimated by taking the difference between last-stage pressure and desired-stage pressure and dividing by the desired-stage supply flow. In this manner,

$$R_d = (P_N - P_i)/Q_i \quad ,$$

where P_N is the common supply pressure (pressure to the last stage), P_i is the pressure to the stage of interest, and Q_i is the flow to the stage of interest.

For the case at hand, $P_1 = 16$ torr, $P_2 = 64$ torr, and $Q_1 = 0.225$ LPM (see example A-1 in app A). This requires a resistance of about 200 torr/LPM between the common supply and the first-stage supply. Standard available resistances, at a nominal flow rate of 0.05 LPM, are 35, 200, 300, and 500 torr/LPM. These correspond to P.N. 5221a nozzles with $b_s = 0.51$ mm and $\sigma = 0.5$, $b_s = 0.56$ mm and $\sigma = 0.23$, $b_s = 0.51$ mm and $\sigma = 0.25$, and $b_s = 0.51$ mm and $\sigma = 0.20$.

The 35 and 300 resistors are available in fineblanked parts, and the 200, 300, and 500 resistors are available etched. For flow rates above 0.05 LPM, the orifice term adds resistance so that a nominal 200-torr resistor at 0.225 LPM has too high a resistance for this job. By using two 300-torr resistors in parallel at a flow rate of 0.112 LPM each, the net 150 torr/LPM is increased so that it is close to 200. (It is good practice always to use dropping resistors in parallel to cut supply noise. Keeping the flow to less than 0.05 LPM per resistor further reduces noise.)

Figure 3(a) shows typical transfer characteristics and figure 3(b) shows the gain versus the supply pressure for this fluidic capillary pyrometer gain block using fineblanked parts of nominal gain just under 9. The computed value of 61, shown in appendix B using a single-stage gain of 8.5, is in good agreement with the value of 62 actually obtained.

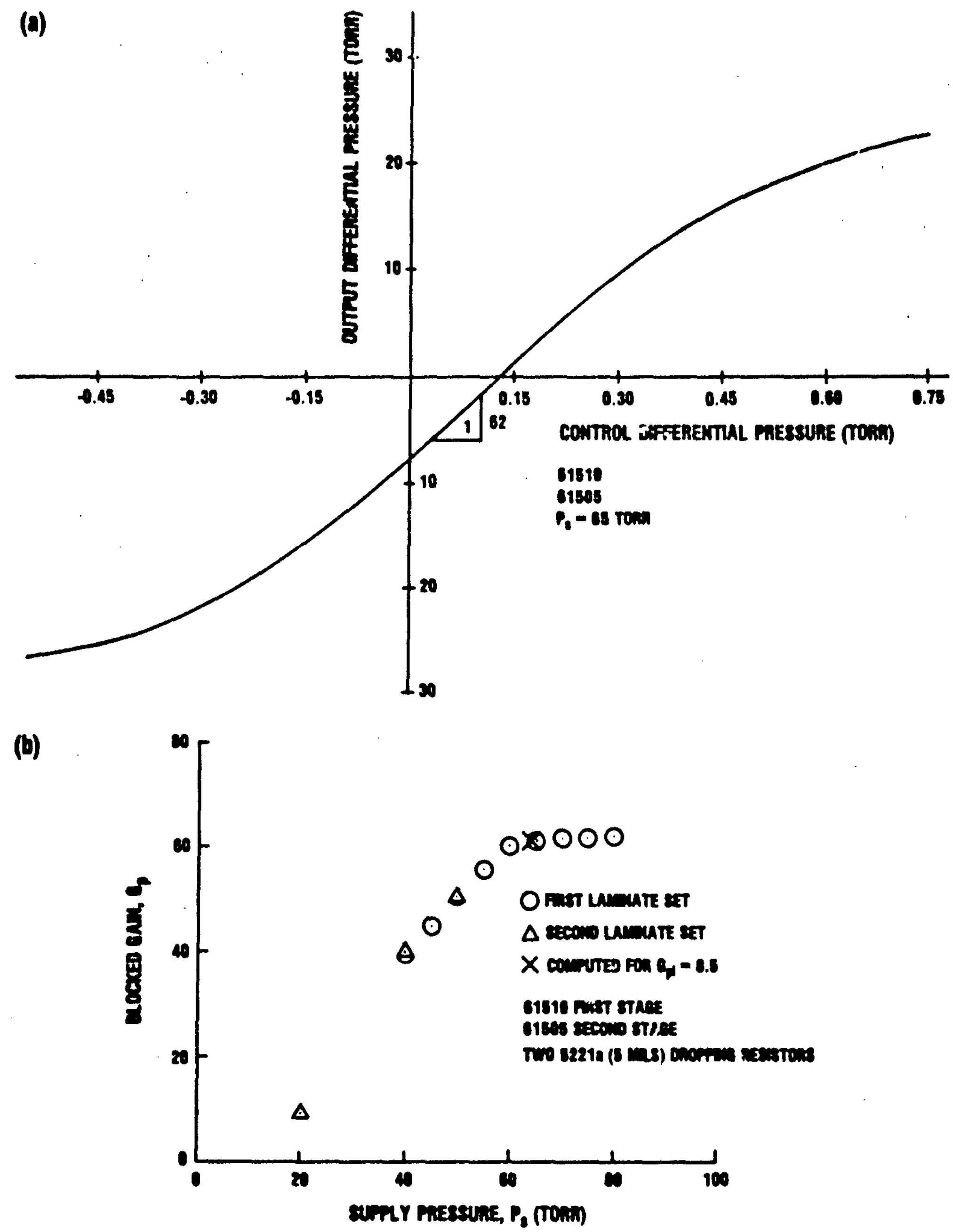

Figure 3. Fluidic capillary pyrometer gain block: (a) transfer and (b) gain characteristics.

The stacking order for standard C format assembly is given in appendix B.

3.2 Three-Stage Gain Blocks

Perhaps the most commonly used generic gain block is composed of three stages. Gains from 100 to 1000 are readily obtainable with frequency response well past the normal AM radio/telephone range (>3 kHz). Typical use involves reducing the noise floor of commercial pressure transducers or driving of pressure-controlled oscillators. For example, a typical ±1 psi (±50 torr) pressure transducer with a signal-to-noise ratio of 2000 can discriminate 0.001 psi (0.05 torr). (This corresponds to 5 mV of noise for a 10-V output.) Typical threshold signals of fluidic sensors are two to three orders of magnitude below 0.05 torr. A no-noise gain block with a gain of 500 boosts the signals above the equivalent electronic noise floor, so that the transducer can effectively discriminate signals of 2×10^{-6} psi (10^{-4} torr).

As with two-stage devices, the most common device is the self-staged gain block. Other topologies that follow are pressure or flow staged to one extent or another.

3.2.1 Three-Stage Self-Staged Gain Blocks

The reference gain block is composed of three stages of LPA's with $\sigma = 1$. Since LPA's come in standard sizes--b_s = 0.75, 0.5, 0.375, and 0.25 mm (corresponding to 0.03, 0.02, 0.015, and 0.01 in.)--the performance of the three most commonly used sizes is presented in figure 4a at nominal operating conditions.

Figure 4b shows the variation of gain with supply pressure and computed values from the program. Agreement is good.

The standard components used comprise C format amplifiers 63030, 82020, three stacked 51505's, and two stacked 51005's. The stacking order is similar to that given in appendix B for the two-stage device. There are several guidelines to follow in the assembly of three and more stage gain blocks. The last stage (highest pressure if not self-staged) should be closest to the supply pressure source to minimize high-pressure leaks. The supply flow should be manifolded in such a way that the last stages are fed first with the first stage receiving only that flow which it needs. More succinctly, it is not desirable to have excess flow rushing past the first stage, where it can generate noise that can be amplified through the stack. Furthermore, the first stage vents should always be isolated or decoupled from the rest of the stack, if possible, to prevent spurious latter-stage vent flows from producing noise that can be amplified up the stack (example B-1, use of 5022a plate).

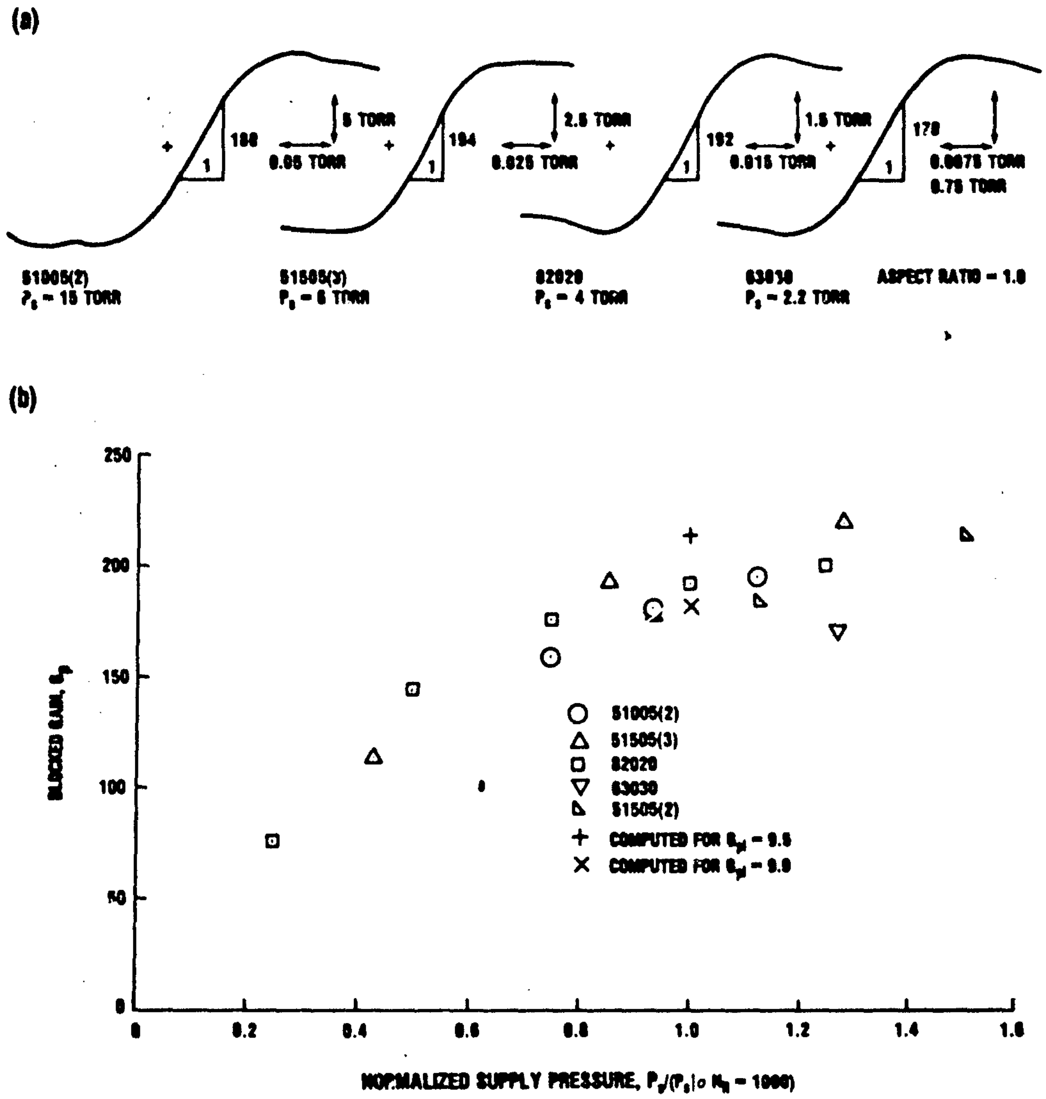

Figure 4. Three-stage self-staged gain block: (a) transfer and (b) gain characteristics.

It is possible to build self-staged gain blocks of different aspect ratios; the gain stays about the same, but the operating pressure changes. For example, a 63020 gain block ($\sigma = 0.67$) has a supply pressure of 2.5 torr and a measured gain of 255 with a single-stage normal gain of 11.1.

3.2.2 Common Supply Pressure Gain Blocks

The tremendous advantage of the self-staged gain block is not having to drop supply pressures. This advantage extends to another class of topologies. Since LPA's of the same height, no matter what the nozzle width, operate at the same supply pressure, a moderate increase in staged gain can be achieved by increasing succeeding stage input impedance by decreasing plan view size. In this manner, the four LPA's of standard nozzle width can be staged in various combinations of three or more to get more gain than in the self-staged case. Two such devices are the 63020-62020-51005(4)* and the 62015-51505(3)-51005(3) gain blocks. Figure 5 shows typical transfer and gain characteristics.

Instead of decreasing size, to increase input impedance at constant supply pressure, one may decrease the number of parallel elements per stage and achieve a similar increase in gain. Although this method has the added advantage of requiring only one plan view size amplifier, the cost is a considerable increase in flow consumption. An easy configuration to examine is a first stage with four parallel elements, the second with two, and the third with only one.† In this gain block, the input impedance of each succeeding stage is doubled. Figure 6 shows the gain characteristics of this device.

The gain of these blocks, which varies from 300 to 400, is considerably higher than the nominal 200 to 250 gain that the self-staged block exhibits. However, a penalty must be paid for this gain increase in an increased output-to-input impedance ratio. In increasing the output-to-input impedance ratio by paralleling early stages, an additional penalty in flow is exacted for using amplifiers that are all the same size. However, a side benefit of this scheme may be the dramatic reduction in null offset due to cancellation in the multiple elements of the first stage, especially when an even number of parallel

**Metal etched laminates usually come in either 0.1-mm (0.004-in.) or 0.125-mm (0.005-in.) thickness. Since the smaller amplifiers are not available in fineblanked single laminates, the number of laminates used is given in parentheses.*

†Designation of the number of parallel elements appears as a numerical prefix in brackets to the part number. Hence, four parallel elements of the metal etched parts with $b_s = 0.254$ mm and $\sigma = 1$ is designated as [4]51005(2).

stages is employed. Care must be taken to decouple the power supplies in the parallel stages to eliminate power-supply coupling and cross talk that promotes early transition to turbulence. This decoupling moderately increases the manifolding complexity, but still is easier to implement than using dropping resistors.

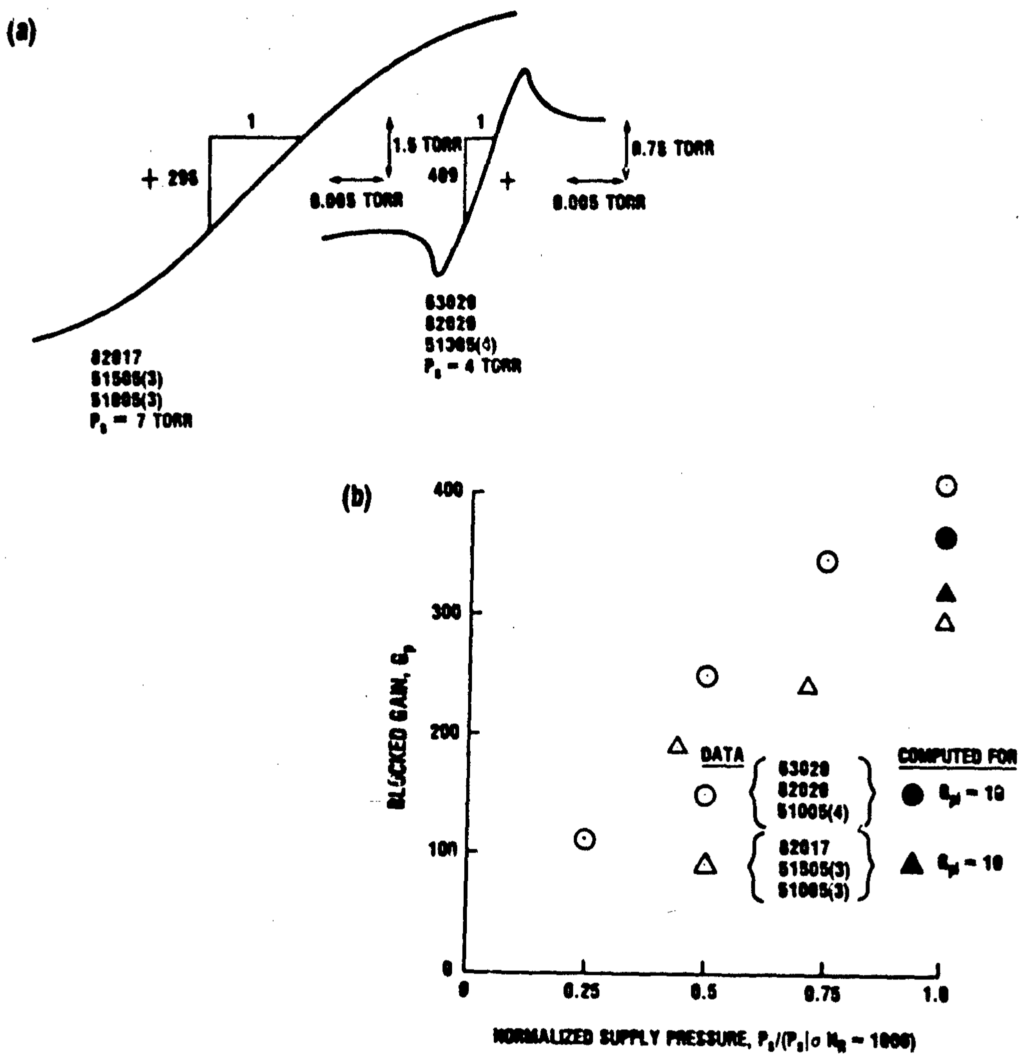

Figure 5. Three-stage common supply pressure gain block: (a) transfer and (b) gain characteristics.

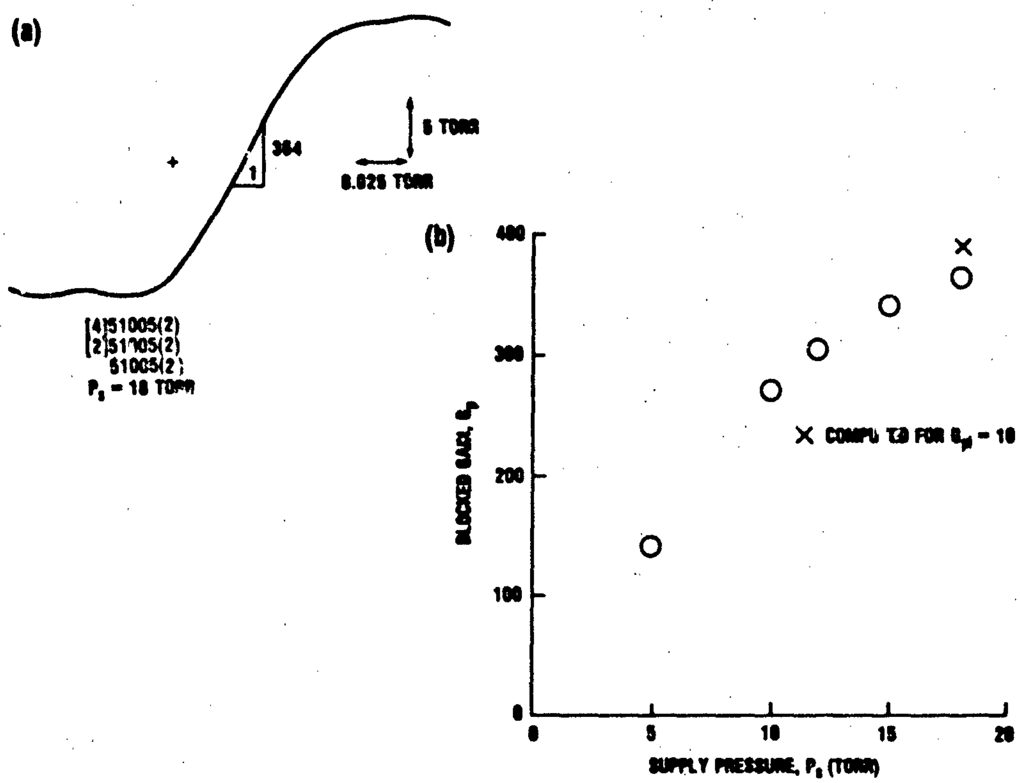

Figure 6. Three-stage, parallel-element, common supply pressure gain block: (a) transfer and (b) gain characteristics.

3.2.3 Pressure-Staged Gain Blocks

Drzewiecki[5] derives the staging conditions for maximum staged gain and maximum dynamic range as

$$\left(\sigma_n/\sigma_{n-1}\right)^2\left(b_{sn}/b_{sn-1}\right) = 1/G_{pn(\text{staged})} \quad . \tag{9}$$

[5] T. M. Drzewiecki, *A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).*

Since under optimum loading (almost blocked) the staged gain is nominally 10, then for the same size plan view amplifiers the aspect ratio must decrease by approximately three in each stage to produce maximum gain and dynamic range. When dynamic range is maximized, the jets all deflect the same amount so that the null offset of the gain block is the same percentage as that of the first stage alone. In other words, there is no deflection angle gain in the block. In the self-staged gain block, there is a deflection angle increase; hence, the more stages used, the worse the null offset.

Maximum dynamic range gain block.--By using the lowest aspect ratio to start with for the final stage, one can work backward and determine the aspect ratios for the earlier stages. Normally, $\sigma = 0.4$ is the lowest available for $b_s > 0.5$ mm (neglecting single-laminate metal etched parts with $\sigma = 0.2$ and 0.25). The next-to-last-stage aspect ratio should then be $\sigma = 1.2$, and the one before that should be 3.6. With further increase in σ, operating pressure becomes ridiculously low (such as $\sigma = 10.8$ and $P_s = 0.03$ torr). Therefore, the practical limit for a maximally pressure-staged LPA is three stages for a single plan view size. Figure 7 shows the gain characteristics for a three-stage gain block with $\sigma_1 = 3.6$, $\sigma_2 = 1.2$, and $\sigma_3 = 0.4$ with $b_s = 0.5$ mm. (Appendix A has printouts of nominal predicted and design operation, and appendix B lists stacking orders.)

This high gain unit has an excellent null characteristic, linearity, and gain. However, the first stage operates at a very low supply pressure ($P_s = 0.3$ torr) and consequently limits the bandpass to approximately 117 Hz. In addition, the output resistance's being considerably higher than the input (40 to 1) makes it difficult to use this device in a feedback configuration.

By compromising in the staging makeup, other configurations are possible. The three following gain blocks illustrate such compromises.

High-input-impedance gain block.--In an effort to increase the input impedance and the bandpass of the gain block, the first- and second-stage aspect ratios can be reduced. Figure 8 shows data taken for a gain block made up of $\sigma_1 = 0.75$, $\sigma_2 = 0.5$, $\sigma_3 = 0.4$, and $b_s = 0.5$ mm. This typical gain block is used as a preamplifier for laminar jet angular rate sensors and sometimes for the photofluidic interface. (The photofluidic interface most commonly uses a second-stage aspect ratio, $\sigma = 0.6$, but this use does not materially change the characteristics from the block discussed here.)

Gain is about half of the maximum dynamic range device, but the output-to-input resistance ratio is reduced to about 3.

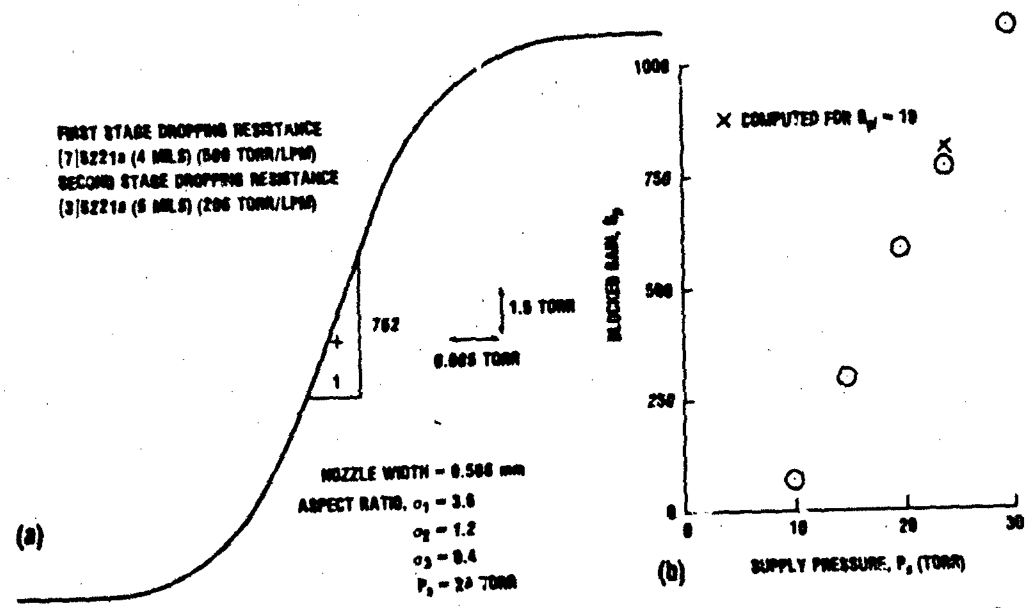

Figure 7. Three-stage maximum dynamic range gain block: (a) transfer and (b) gain characteristics.

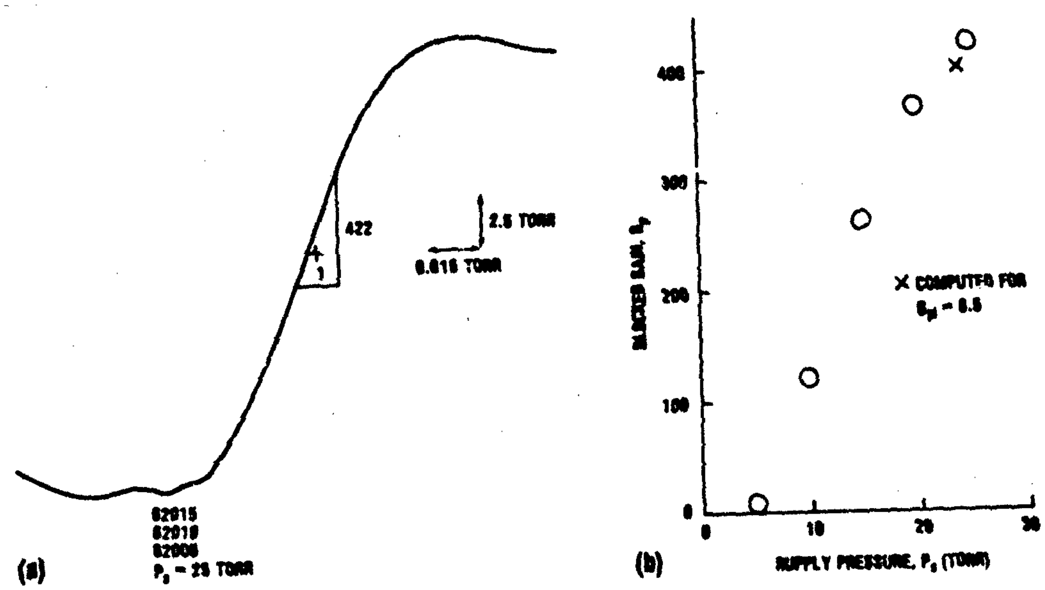

Figure 8. Three-stage high-input-impedance gain block: (a) transfer and (b) gain characteristics.

Change-in-size moderate-pressure staging gain block.--In a modification of the common supply pressure gain block with varying sizes, the gain can be increased by lowering the aspect ratio of the final stage. This device requires only one dropping resistor to supply the common first- and second-stage pressure. (The resistor must now accommodate flow for two stages and must be appropriately sized so that the flow per laminate does not exceed 0.1 LPM.) Shown in figure 9 are the characteristics for a gain block mode up of 63020, 62020, and 81008 LPA's.

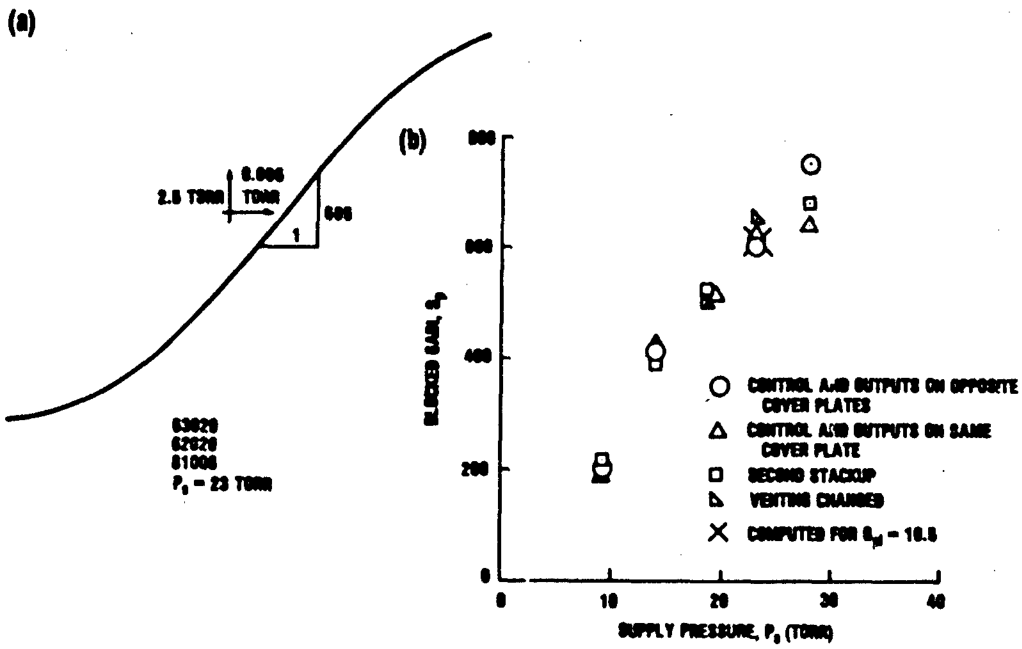

Figure 9. Three-stage preamplifier for laminar jet angular rate sensor: (a) transfer and (b) gain characteristics.

The dropping resistor is required to drop 24 to 4 torr or 20 torr at a flow rate of 0.75 LPM or R = 27 torr/LPM. This drop is readily achieved with eight 200-torr/LPM resistors.

The gain of 605 compares favorably with the design goal of 608 from the program in appendix A at G = 10.5 and is 20 to 25 percent higher than the previous case. However, the input-to-output resistance ratio is worse and the bandwidth is down.

Fluerie servovalve amplifier.--The flueric servovalve[11,12] is a three-stage LPA with multiple parallel elements in each stage. As configured in C format, it consists of a first stage containing two 63020 parallel elements, a second stage containing three 62010 parallel elements, and a third stage containing six 61505 parallel elements. The design program predicts a gain of 335, a bandpass of 281 Hz, a leak flow of the first two stages of 1.757 LPM, and an output-to-input resistance ratio of 9.5 (example A-8). Figure 10 shows a Bode plot taken at the Massachusetts Institute of Technology for operation in hydraulic oil. (Note that the volumetric flows in air and oil are the same, the pressures are different, and the dynamics are esentially the same since the kinematic viscosities are similar.) Agreement between the prediction of the design program and the data is good.

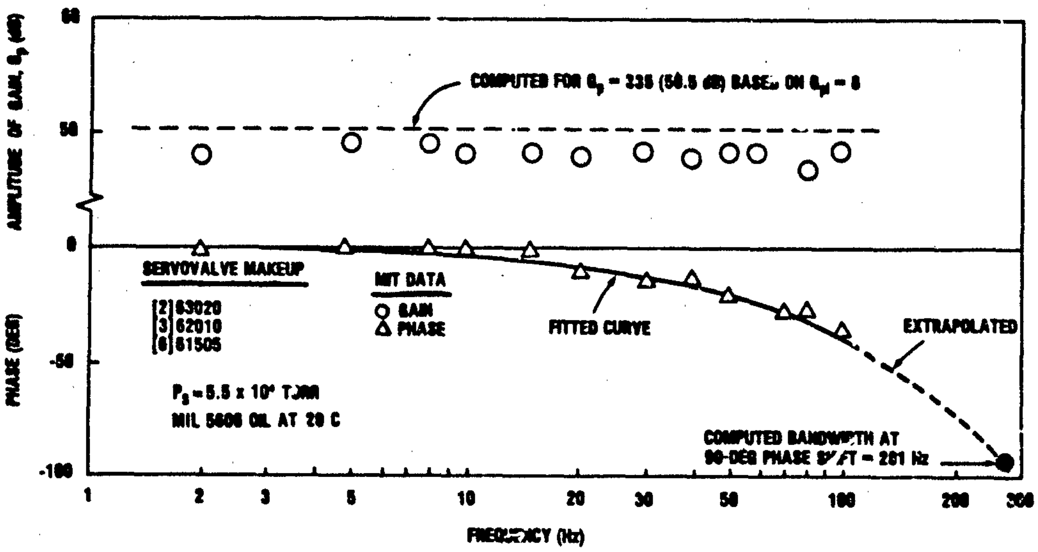

Figure 10. Bode plot of flueric servovalve three-stage gain block.

Five parameters are of interest in the design of a flueric servovalve:

- leakage flow
- bandpass
- gain
- input-to-output resistance ratio
- pressure recovery

[11]*D. N. Wormley, D. Lee, and K. M. Lee, Development of a Fluidic, Hydraulic Servovalve, Massachusetts Institute of Technology, contract with Harry Diamond Laboratories, HDL-CR-81-216-1 (February 1981).*

[12]*D. Lee and D. N. Wormley, A Fluidic Hydraulic Servovalve, J. Dyn. Sys. Meas. Control,* 103, *No. 4 (December 1981).*

Given the plan view of the standard LPA and the sizes available, the thinnest lamination with a reasonable aspect ratio gives rise to either $\sigma = 0.375$ for $b_s = 0.375$ mm or $\sigma = 0.5$ for $b_s = 0.25$ mm so that operation in air at 64 torr is possible, corresponding to 5.5×10^4 torr in oil (1100 psi). Pressure recovery is thus fixed. Pressure recovery can be increased by changing LPA geometry, but that increase is not within the purview of this report. Thus, let us examine the optimization or increase in performance of the other three parameters at the expense, if any, of gain. By using the design program, some changes can be easily tried out. Table 1 shows design parameters as they are affected by various changes.

TABLE 1. OPTIMIZATION OF FLUERIC SERVOVALVE FOR LEAKAGE FLOW, BANDPASS, OUTPUT-TO-INPUT RESISTANCE RATIO, AND GAIN

Trial	Gain block makeup	Geometric changes from previous case	Leakage flow (LPM)	Bandpass (Hz)	Output-to-input resistance ratio	Gain
1	[2]63020 [3]62010 [6]61505	(Baseline)	1.76	281	9.5	335
2	[3]62020 [4]62010 [10]51005	$\sigma_1 = 1$ $b_{s1} = 0.5$ mm $N_1 = 3$ $N_2 = 4$ $N_3 = 10$ $b_{s3} = 0.254$ mm $\sigma_3 = 0.5$	2.07	376	7.2	320
3	[2]62020 [3]62010 [10]61505	$N_1 = 2$ $N_2 = 3$ $b_{s3} = 0.37$ mm	1.49	363	4.0	285
4	[2]62016 [2]62010 [12]61505	$\sigma_1 = 0.8$ $N_2 = 2$ $N_3 = 12$	1.19	412	2.1	229
5	[3]62016 [3]62010 [8]61505	$N_1 = 3$ $N_2 = 3$ $N_3 = 8$	1.79	412	4.7	289
6	[4]62016 [3]62010 [6]61505	$N_1 = 4$ $N_3 = 6$	2.09	412	9.5	321
7	[2]62020 [2]62010 [8]61505	$N_1 = 2$ $N_2 = 2$ $\sigma_1 = 1$ $N_3 = 8$	1.19	363	5.0	289

Notes: σ = aspect ratio, b_s = supply nozzle width, N = number of stages.

In trying to follow the rationale for the changes shown in the second column of table 1, the following arguments are set forth.

- First change (trial 2).--Increase the first-stage bandwidth by decreasing LPA size, but keep the input resistance the same by using more elements.[3] Decrease the output resistance by increasing the number of output elements to 10. Keep the gain up by reducing second-stage resistance relative to the third-stage resistance by increasing the number of parallel elements in the second stage and decreasing element size in the third stage.

  Result.--The bandpass increases at the expense essentially of leakage flow.

- Second change (trial 3).--Increase the input resistance by reducing the number of elements in the first stage. Decrease the output resistance by increasing the element size back up to baseline. Reduce leakage by reducing the number of elements in the second stage.

  Result.--Leakage flow and the output-to-input resistance ratio decrease at the expense of gain.

- Third change (trial 4).--Further increase the input resistance by reducing the first stage aspect ratio to 0.8, thereby also increasing the bandpass. Further decrease leakage flow by reducing the number of elements in the second stage to two. Decrease the output resistance by increasing the number of output elements to 12.

  Result.--Leakage flow and the output-to-input resistance ratio decrease and the bandpass increases at the further expense of gain.*

- Fourth change (trial 5).--Bring the gain back up by reducing the input resistance by adding an element to the first stage, increase the output resistance by decreasing the number of output elements, and increase the second- to third-stage gain by increasing the number of second-stage elements to three.

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[3] *T. M. Drzewiecki, D. Wormley, and F. M. Manion, A Computer-Aided Design Procedure for Laminar Fluidic Systems, J. Dyn. Sys. Meas. Control, 97, Series G, No. 4 (December 1975).*

**Reduction in gain is not altogether unacceptable when it is noted that in a feedback arrangement the overall performance is dependent somewhat on closed loop gain, which increases with a decreasing output-to-input resistance ratio. Since gain is down 32 percent but the input-to-output resistance ratio is up over 400 percent, this case may be more desirable.*

Result.--Leakage flow is back up to baseline, but the bandpass is still high at a slight expense to the input-to-output resistance ratio. The gain is up, but is still down from the baseline.

- Fifth change (trial 6).--Examine the condition in which the output-to-input resistance ratio bandpass is high, by increasing the number of elements in the first stage to four and in the third stage to six.

Result.--The bandpass is high at the expense of leakage flow. The gain is back at the baseline.

- Final change (trial 7).--Decrease leakage flow by reducing the number of elements in the first and second stages to two each. Keep the gain up by increasing the first-stage aspect ratio to one. Decrease the output resistance by increasing the number of output elements to eight.

Result.--Leakage is reduced to 68 percent of the baseline, the bandpass is increased by 29 percent over the baseline, and the output-to-input resistance ratio is halved, with only a 14-percent penalty in gain.

Preliminary tests at the Massachusetts Institute of Technology have verified this capability to increase bandwidth and decrease leakage flow.

3.2.4 Power- or Flow-Gain Gain Blocks

In some applications, pressure gain is not important. However, the ability to deliver flow at a given pressure is important when, for example, a positive displacement actuator must be moved at a given rate. It is clear from the arguments presented above that output impedance can be significantly reduced by employing multiple parallel elements. One gain block that has been tried for driving small actuators involves a common supply pressure arrangement consisting of LPA's with $b_s = 0.5$ mm and $\sigma = 0.4$ with a first stage of three parallel elements, a second stage of four, and a third stage of eight. The unit makeup is designated as [3]62008, [4]62008, [8]62008. The measured gain of 75 compares favorably with the 70 computed by using a single change gain of 8.

The output resistance of 5.84 torr/LPM indicates that at the roughly 6-torr maximum power point the unit can deliver about 1 LPM of flow.

3.3 Four-Stage Gain Blocks

Gain blocks with more than three stages are not very common in dc applications primarily because as the gain becomes high, even a small initial null offset can be devastating. In ac applications where high-pass filters are commonly used, a dc null offset does not affect operation. One such example is in the fluidic intercom system described by this author.[5] In that case, a four-stage LPA is composed of a three-stage, self-staged preamplifier of $b_s = 0.25$ mm and $\sigma = 1.2$ and a power fourth stage composed of two parallel elements with $b_s = 0.25$ mm and $\sigma = 0.8$. The gain of this device is about 60 dB for 1 to 2 kHz.

One dc application in which a four-stage device is used, however, is a pressure regulator.* Since it is used in a feedback configuration, it is important that the input and output resistances be comparable, that the gain be relatively high, and that it be capable of delivering sufficient flow to a load at, in this case, 6 torr. For these reasons, at least four stages are required. The gain block designed for this application is composed of a first stage of one element of $b_{s1} = 0.5$ mm and $\sigma = 0.75$ (62015), a second stage of two elements of $b_{s2} = 0.375$ mm and $\sigma_2 = 0.67$ ([2]61510), a third stage of three elements of $b_{s3} = 0.375$ mm and $\sigma_3 = 0.67$ ([3]61510), and a fourth stage of six elements of $b_{s4} = 0.375$ mm and $\sigma_4 = 0.33$ ([6]61505). The transfer characteristics and the gain as a function of supply pressure to the last stage are shown in figure 11 (p. 26). The very low gain of 61505 LPA's is the reason that the average single-stage gain is 7.5. The gain would be considerably increased by using components with better gain, say, 9 to 10. This use would increase the gain 100 to 200 percent.

3.4 Five-Stage Gain Block for Public Address System

The only currently used five-stage gain block is in a flueric public address system at HDL. This device is designed to have high gain and bandpass and very low output impedance in order to drive large exponential horns. To provide good matching between stages, it was decided to operate each stage at the same impedance despite changes in size or supply pressure. The design program was exercised with the result shown in figure 12. As can be seen, three different size LPA's

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[5] *T. M. Drzewiecki, A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).*

**T. M. Drzewiecki, Some Active Fluidic Compensation Circuits, submitted for American Society of Mechanical Engineers, 1982 Winter Annual Meeting, Phoenix, AZ (November 1982).*

are used in an almost perfect impedance matching scheme. The dc gain was not available since the device is high passed between the first and second stages and between the fourth and fifth stages with inductive shunts designed for passing a frequency of 600 Hz. The device works well and with minimum distortion over a 600- to 3000-Hz frequency band.

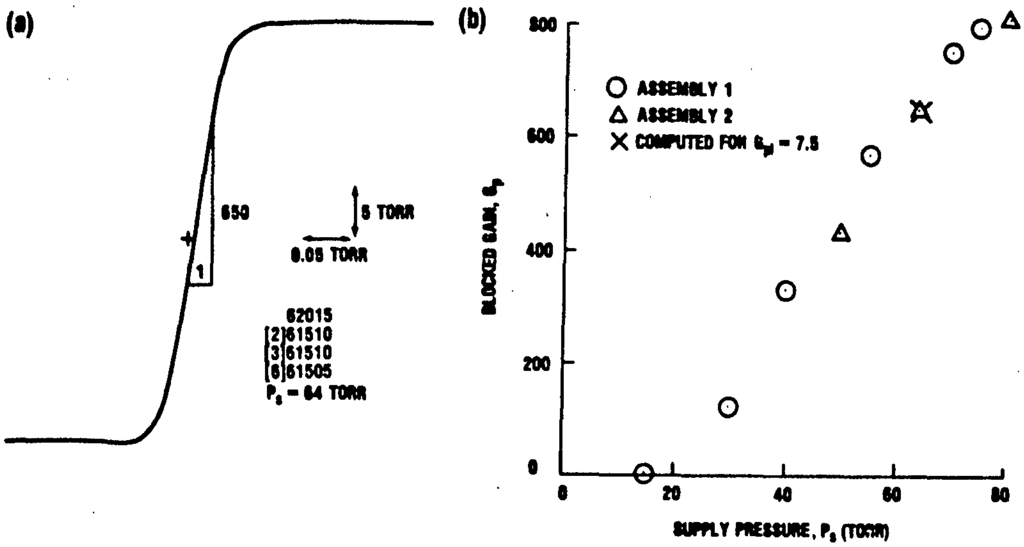

Figure 11. Four-stage pressure regulator gain block: (a) transfer and (b) gain characteristics.

3.5 Eight-Stage Gain Block

There are no commonly used gain blocks of six or seven stages. However, there is one device of eight stages that was used in the stabilization system of an M48 tank.[13] This device was designed by Charles Paras (formerly of HDL) and as implemented used some turbulent final stages. Table 2 shows the makeup.

The design program does not allow σN_R to be any other value than 1000. However, since the individual gains are not greatly different from their nominal values and only the resistances change in the final two stages, it should not give a bad estimate. For an individual

[13] *C. L. Abbott, T. B. Tippetts, S. M. Tenney, and C. Paras, A Study of Fluidic Gun Stabilization Systems for Combat Vehicles: Final Report, AiResearch Manufacturing Company of Arizona, contract with Harry Diamond Laboratories, HDL-CR-80-100-1 (April 1980).*

```
IS YOUR LPA GAIN 10 ? YES
NUMBER OF STAGES? 5
STAGE  1  ASPECT RATIO? .75
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .508
STAGE  1  SUPPLY PRESSURE =  6.888902666694  TORR
STAGE  1  SUPPLY FLOW = .3110204081646 LPM
STAGE  1  SUPPLY RESISTANCE = 22.14935896762 TORR/LPM
STAGE  2  ASPECT RATIO? .5
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 2
STAGE  2  NOZZLE WIDTH IN MM? .508
STAGE  2  SUPPLY PRESSURE =  15.50003100006  TORR
STAGE  2  SUPPLY FLOW = .5644444444422 LPM
STAGE  2  SUPPLY RESISTANCE = 27.46068484274 TORR/LPM
STAGE  3  ASPECT RATIO? .66667
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 3
STAGE  3  NOZZLE WIDTH IN MM? .381
STAGE  3  SUPPLY PRESSURE =  15.49987600082  TORR
STAGE  3  SUPPLY FLOW = .6858006858039 LPM
STAGE  3  SUPPLY RESISTANCE = 22.60113808818 TORR/LPM
STAGE  4  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  4 ? 4
STAGE  4  NOZZLE WIDTH IN MM? .254
STAGE  4  SUPPLY PRESSURE =  15.50003100006  TORR
STAGE  4  SUPPLY FLOW = .6349999999976 LPM
STAGE  4  SUPPLY RESISTANCE = 24.40949763798 TORR/LPM
STAGE  5  ASPECT RATIO? .5
NO. OF PARALLEL ELEMENTS IN STAGE  5 ? 20
STAGE  5  NOZZLE WIDTH IN MM? .254
STAGE  5  SUPPLY PRESSURE =  62.00012400025  TORR
STAGE  5  SUPPLY FLOW = 2.822222222212 LPM
STAGE  5  SUPPLY RESISTANCE = 21.96854787418 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  6.50198537992
STAGE  2  PRESSURE GAIN =  5.072692711794
STAGE  3  PRESSURE GAIN =  5.151701658716
STAGE  4  PRESSURE GAIN =  4.786223675775
STAGE  5  PRESSURE GAIN =  9.523809523819
PRESSURE GAIN OF THE  5  STAGE GAINBLOCK = 7745.312407647
GAINBLOCK INPUT RESISTANCE =  16.61201922572 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  10.98427393709 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  305.1565742289 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? NO
```

Figures 12. Design program output for Harry Diamond Laboratories flueric public address system.

nominal gain of 10 per stage, the program computes a value of gain of 2.72×10^6 (example A-9). This is in excellent agreement with the measured value of 3×10^6.

This then indicates the power of the design program for estimating off-design points.

TABLE 2. MAKEUP OF EIGHT-STAGE GAIN BLOCK FOR M48A5 GUN STABILIZATION SYSTEM

Stage	Aspect ratio	Nozzle width (mm)	σN_R
1	1.07	0.76	701
2	1.00	0.76	983
3	0.83	0.76	884
4	0.67	0.76	977
5	0.53	0.76	957
6	0.33	0.76	1403
7	0.45	0.51	4000
8	0.30	0.76	4617

Note: σN_R = aspect ratio times Reynolds number.

4. DISCUSSION AND CONCLUSIONS

This report presents gain and transfer characteristic data for most of the currently used gain blocks. These gain blocks have all been implemented in C format using standard HDL LPA's.

During collection of data, it was discovered that certain LPA's did not conform to the desired characteristics of bias insensitivity as designed[7] in the original HDL model 3.1.1.8. These were specifically the fineblanked devices. Although they operated well and pretty much as predicted in pressure-staged configurations, they operated poorly in self-staged configurations. This behavior extended to metal etched parts manufactured from the same program that made the fineblanking dies. Subsequently, LPA's designed specifically to HDL dimensions were made by electrodischarge machining and metal etching and were found to be as desired. Consequently, no fineblanked parts exist, at this writing, that are suitable for proper high-bias or self-staged operation.

The computer design-guide program has been shown to be an effective tool for gain-block design, optimization, and off-design estimation. Optimization has been specifically demonstrated on the flueric servovalve amplifier.

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

Interestingly, high gain can be implemented with considerably fewer stages if one uses positive feedback. Typically, gains of 150 to 500 can be obtained in two stages at the expense of bandwidth. By using the first amplifier as a buffer or preamplifier and a second stage with feedback, the loss in bandwidth can be minimized. An example of using positive feedback is the three-stage servovalve in which gain is increased from 335 to over 1500.

Finally, design guidelines for amplifier stacking and implementation and a format for stacking orders have been presented.

The reader is encouraged to use the results presented here as a basis for a private library of gain blocks. Other useful devices should be logged, documented, and reported, as soon as practicable.

ACKNOWLEDGEMENTS

This report would have been far leaner for data had it not been for the diligence and hard work of our co-op student, Bill O'Brien, who was responsible for generating most of the gain information. The able assistance and encouragement of James Joyce also are greatly appreciated.

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(12) D. Lee and D. N. Wormley, A Fluidic Hydraulic Servovalve, J. Dyn. Sys. Meas. Control, 103, No. 4 (December 1981).

(13) C. L. Abbott, T. B. Tippetts, S. M. Tenney, and C. Paras, A Study of Fluidic Gun Stabilization Systems for Combat Vehicles: Final Report, AiResearch Manufacturing Company of Arizona, contract with Harry Diamond Laboratories, HDL-CR-80-100-1 (April 1980).

APPENDIX A.--BASIC PROGRAM AND REPRESENTATIVE EXAMPLES

This appendix contains the computer program, written in BASIC, that yields design approximations for multistage laminar proportional amplifiers. The program is based on a single-stage block-loaded gain of 10, but allows the user to insert different corresponding gain values where appropriate.

Following a listing of the program, nine different sample runs are presented.

```
10 DIM P(10),Q(10),K(10),A(10),B(10),G(10)
20 G0=10
30 PRINT "**********************************************************
*******"
40 PRINT "THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAG
E LPAS"
50 PRINT "BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BL
OCKED"
60 PRINT "SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN
AIR."
70 PRINT "FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO
AND       NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD O
F THE     PREVIOUS, E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1."
80 PRINT "**********************************************************
*******"
90 PRINT
100 INPUT "IS YOUR LPA GAIN 10 ",Y$:IF STR(Y$,1,1)="Y"THEN 120
110 INPUT "WHAT IS YOUR GAIN",G0
120 INPUT "NUMBER OF STAGES",N
130 FOR M=1TO N
140 PRINT "STAGE ";M;" ASPECT RATIO";:INPUT A(M+1)
150 PRINT "NO. OF PARALLEL ELEMENTS IN STAGE ";M;:INPUT K(M+1)
160 PRINT "STAGE ";M;" NOZZLE WIDTH IN MM";:INPUT B(M+1)
170 P(M+1)=1/(A(M+1)*B(M+1))^2
180 PRINT "STAGE ";M;" SUPPLY PRESSURE = ";P(M+1);" TORR"
190 Q(M+1)=2.5*SQR(P(M+1))*B(M+1)^2/(1+1/A(M+1))^2*K(M+1)
200 PRINT "STAGE ";M;" SUPPLY FLOW =";Q(M+1);"LPM"
210 PRINT "STAGE ";M;" SUPPLY RESISTANCE =";P(M+1)/Q(M+1);"TORR/
LPM"
220 NEXT M
230 INPUT "FIRST STAGE BIAS PRESSURE IN TORR",P0
240 P(1)=P0*3
250 PRINT "ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA"
260 PRINT "A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0"
270 INPUT "LOAD NO. OF PARALLEL STAGES",K(N+2)
280 INPUT "LOAD ASPECT RATIO",A(N+2)
290 INPUT "LOAD NOZZLE WIDTH(MM)",B(N+2)
300 IF B(N+2)=0 THEN 310:P(N+2)=1/(A(N+2)*B(N+2))^2:Q(N+2)=2.5*S
QR(P(N+2))*K(N+2)*B(N+2)^2/(1+1/A(N+2))^2:GOTO 320
310 P(N+2)=1:Q(N+2)=0
320 L=0
330 FOR J=1 TO N
340 G(J)=G0*(1/(1+.20*P(J)/P(J+1)))*(1/(1+.667*P(J+1)*Q(J+2)/P(J
+2)/Q(J+1)))
350 PRINT "STAGE ";J;" PRESSURE GAIN = ";G(J)
360 L=L+B(J+1)/SQR(P(J+1))
370 IF J=1THEN 400
380 G=G(J)*G
390 GOTO 410
400 G=G(J)
410 NEXT J
420 PRINT "PRESSURE GAIN OF THE ";N;" STAGE GAINBLOCK =";G
430 PRINT "GAINBLOCK INPUT RESISTANCE = ";.75*P(2)/Q(2);"TORR/LP
M"
440 PRINT "GAINBLOCK OUTPUT RESISTANCE = ";.5*P(N+1)/Q(N+1);"TOR
R/LPM"
450 PRINT "GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = ";157.5/L;
"HERTZ"
460 INPUT "DO YOU WANT TO MAKE ANOTHER CALCULATION",I$:IF STR(I$
,1,1)="Y" THEN 470:GOTO 480
470 PRINT :PRINT :PRINT :PRINT :GOTO 120
480 STOP :END
```

BASIC PROGRAM

APPENDIX A

```
************************************************************
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BLOCKED
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND
NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD OF THE
PREVIOUS, E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1.
************************************************************

IS YOUR LPA GAIN 10 ? N
WHAT IS YOUR GAIN? 8
NUMBER OF STAGES? 2
STAGE  1  ASPECT RATIO? .667
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .381
STAGE  1  SUPPLY PRESSURE =  15.4845425861  TORR
STAGE  1  SUPPLY FLOW = .2286228417162 LPM
STAGE  1  SUPPLY RESISTANCE = 67.72963921655 TORR/LPM
STAGE  2  ASPECT RATIO? .667
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 1
STAGE  2  NOZZLE WIDTH IN MM? .381
STAGE  2  SUPPLY PRESSURE =  15.4845425861  TORR
STAGE  2  SUPPLY FLOW = .2286228417162 LPM
STAGE  2  SUPPLY RESISTANCE = 67.72963921655 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  4.799040191962
STAGE  2  PRESSURE GAIN =  6.666666666666
PRESSURE GAIN OF THE  2  STAGE GAINBLOCK = 31.99360127974
GAINBLOCK INPUT RESISTANCE =  50.79722941243 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  33.86481960827 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  813.3449550178 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP
```

Example A-1. Two-stage, self-staged gain block.

```
**************************************************************
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BLOCKED
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND
NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD OF THE
PREVIOUS, E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1.
**************************************************************

IS YOUR LPA GAIN 10 ? N
WHAT IS YOUR GAIN? 8.5
NUMBER OF STAGES? 2
STAGE  1  ASPECT RATIO? .66667
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .381
STAGE  1  SUPPLY PRESSURE =  15.49987600082  TORR
STAGE  1  SUPPLY FLOW = .2286002286013 LPM
STAGE  1  SUPPLY RESISTANCE = 67.80341426453 TORR/LPM
STAGE  2  ASPECT RATIO? .333333
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 1
STAGE  2  NOZZLE WIDTH IN MM? .381
STAGE  2  SUPPLY PRESSURE =  62.00024800074  TORR
STAGE  2  SUPPLY FLOW = .1785936607044 LPM
STAGE  2  SUPPLY RESISTANCE = 347.1581676315 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  7.520315831375
STAGE  2  PRESSURE GAIN =  8.09524272106
PRESSURE GAIN OF THE  2  STAGE GAINBLOCK = 60.87878199401
GAINBLOCK INPUT RESISTANCE =  50.85256069842 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  173.5790838157 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  1084.998915014 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP
```

Example A-2. Two-stage gain block of fluidic capillary pyrometer.

APPENDIX A

```
**********************************************************
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BLOCKED
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND
NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD OF THE
PREVIOUS. E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1.
**********************************************************

IS YOUR LPA GAIN 10 ? Y
NUMBER OF STAGES? 3
STAGE  1  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .508
STAGE  1  SUPPLY PRESSURE =  3.875007750016  TORR
STAGE  1  SUPPLY FLOW = .3174999999988 LPM
STAGE  1  SUPPLY RESISTANCE = 12.20474881899 TORR/LPM
STAGE  2  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 1
STAGE  2  NOZZLE WIDTH IN MM? .508
STAGE  2  SUPPLY PRESSURE =  3.875007750016  TORR
STAGE  2  SUPPLY FLOW = .3174999999988 LPM
STAGE  2  SUPPLY RESISTANCE = 12.20474881899 TORR/LPM
STAGE  3  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 1
STAGE  3  NOZZLE WIDTH IN MM? .508
STAGE  3  SUPPLY PRESSURE =  3.875007750016  TORR
STAGE  3  SUPPLY FLOW = .3174999999988 LPM
STAGE  3  SUPPLY RESISTANCE = 12.20474881899 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  5.998800239952
STAGE  2  PRESSURE GAIN =  4.99900019996
STAGE  3  PRESSURE GAIN =  8.333333333333
PRESSURE GAIN OF THE  3  STAGE GAINBLOCK = 249.900029992
GAINBLOCK INPUT RESISTANCE =  9.153561614246 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  6.102374409497 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  203.437906875 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? Y
```

Example A-3. Three-stage, self-staged gain block.

```
NUMBER OF STAGES? 3
STAGE  1  ASPECT RATIO? .6667
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .76
STAGE  1  SUPPLY PRESSURE =  3.895039849219  TORR
STAGE  1  SUPPLY FLOW = .4560045596449 LPM
STAGE  1  SUPPLY RESISTANCE = 8.54166864527 TORR/LPM
STAGE  2  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 1
STAGE  2  NOZZLE WIDTH IN MM? .508
STAGE  2  SUPPLY PRESSURE =  3.875007750016  TORR
STAGE  2  SUPPLY FLOW = .3174999999988 LPM
STAGE  2  SUPPLY RESISTANCE = 12.20474881899 TORR/LPM
STAGE  3  ASPECT RATIO? 2
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 1
STAGE  3  NOZZLE WIDTH IN MM? .254
STAGE  3  SUPPLY PRESSURE =  3.875007750016  TORR
STAGE  3  SUPPLY FLOW = .1411111111105 LPM
STAGE  3  SUPPLY RESISTANCE = 27.46068484275 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  6.817517773488
STAGE  2  PRESSURE GAIN =  6.422303400955
STAGE  3  PRESSURE GAIN =  8.333333333333
PRESSURE GAIN OF THE  3  STAGE GAINBLOCK = 364.8680631895
GAINBLOCK INPUT RESISTANCE =  6.406251483952 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  13.73034242139 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  203.9674795827 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? Y
```

Example A-4. Three-stage, common supply gain block.

APPENDIX A

```
******************************************************************
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BLOCKED
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND
NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD OF THE
PREVIOUS, E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1.
******************************************************************

IS YOUR LPA GAIN 10 ? Y
NUMBER OF STAGES? 3
STAGE  1  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 4
STAGE  1  NOZZLE WIDTH IN MM? .254
STAGE  1  SUPPLY PRESSURE =  15.50003100006   TORR
STAGE  1  SUPPLY FLOW = .6347999999976 LPM
STAGE  1  SUPPLY RESISTANCE = 24.40949763798 TORR/LPM
STAGE  2  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 2
STAGE  2  NOZZLE WIDTH IN MM? .254
STAGE  2  SUPPLY PRESSURE =  15.50003100006   TORR
STAGE  2  SUPPLY FLOW = .3174999999988 LPM
STAGE  2  SUPPLY RESISTANCE = 48.81899527596 TORR/LPM
STAGE  3  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 1
STAGE  3  NOZZLE WIDTH IN MM? .254
STAGE  3  SUPPLY PRESSURE =  15.50003100006   TORR
STAGE  3  SUPPLY FLOW = .1587499999994 LPM
STAGE  3  SUPPLY RESISTANCE = 97.63799055193 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  7.499062617173
STAGE  2  PRESSURE GAIN =  6.249218847644
STAGE  3  PRESSURE GAIN =  8.333333333333
PRESSURE GAIN OF THE  3  STAGE GAINBLOCK = 390.5273620575
GAINBLOCK INPUT RESISTANCE =  18.30712322849 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  48.81899527596 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  813.7516275003 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP
```

Example A-5. Three-stage, parallel-element, common supply gain block.

```
***********************************************************
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BLOCKED
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND
NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD OF THE
PREVIOUS, E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1.
***********************************************************

IS YOUR LPA GAIN 10 ? Y
NUMBER OF STAGES? 3
STAGE  1  ASPECT RATIO? 3.6
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .508
STAGE  1  SUPPLY PRESSURE =  .2989975115753  TORR
STAGE  1  SUPPLY FLOW = .2160680529282 LPM
STAGE  1  SUPPLY RESISTANCE = 1.383811755247 TORR/LPM
STAGE  2  ASPECT RATIO? 1.2
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 1
STAGE  2  NOZZLE WIDTH IN MM? .508
STAGE  2  SUPPLY PRESSURE =  2.690977604177  TORR
STAGE  2  SUPPLY FLOW = .3148760330576 LPM
STAGE  2  SUPPLY RESISTANCE = 8.546149346606 TORR/LPM
STAGE  3  ASPECT RATIO? .4
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 1
STAGE  3  NOZZLE WIDTH IN MM? .508
STAGE  3  SUPPLY PRESSURE =  24.2187984376  TORR
STAGE  3  SUPPLY FLOW = .2591836734683 LPM
STAGE  3  SUPPLY RESISTANCE = 93.44260814546 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  9.025253305181
STAGE  2  PRESSURE GAIN =  9.220151573197
STAGE  3  PRESSURE GAIN =  9.782608695654
PRESSURE GAIN OF THE  3  STAGE GAINBLOCK = 814.0519903724
GAINBLOCK INPUT RESISTANCE =  1.037858816435 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  46.72130407277 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  117.3680231977 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP
```

Example A-6. Three-stage maximum dynamic range gain block.

APPENDIX A

```
****************************************************************
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BLOCKED
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND
NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD OF THE
PREVIOUS, E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1.
****************************************************************

IS YOUR LPA GAIN 10 ? Y
NUMBER OF STAGES? 3
STAGE  1  ASPECT RATIO? .67
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .76
STAGE  1  SUPPLY PRESSURE =  3.85676529084  TORR
STAGE  1  SUPPLY FLOW = .4564523647292 LPM
STAGE  1  SUPPLY RESISTANCE = 8.449436543347 TORR/LPM
STAGE  2  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 1
STAGE  2  NOZZLE WIDTH IN MM? .508
STAGE  2  SUPPLY PRESSURE =  3.875007750016  TORR
STAGE  2  SUPPLY FLOW = .3174999999988 LPM
STAGE  2  SUPPLY RESISTANCE = 12.20474881899 TORR/LPM
STAGE  3  ASPECT RATIO? .8
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 1
STAGE  3  NOZZLE WIDTH IN MM? .254
STAGE  3  SUPPLY PRESSURE =  24.2187984376  TORR
STAGE  3  SUPPLY FLOW = .1567901234562 LPM
STAGE  3  SUPPLY RESISTANCE = 154.4663522404 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  6.841026366496
STAGE  2  PRESSURE GAIN =  7.922358876867
STAGE  3  PRESSURE GAIN =  9.68992248062
PRESSURE GAIN OF THE  3  STAGE GAINBLOCK = 525.1653678439
GAINBLOCK INPUT RESISTANCE =  6.33707740751 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  77.2331761202 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  226.0758627341 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? NO

STOP
```

Example A-7. Moderately pressure staged, three-stage gain block with change in size.

```
************************************************************
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS,BLOCKED
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND
NOZZLE WIDTH OF EACH SUCEEDING STAGE SHOULD BE 1/3RD OF THE
PREVIOUS, E.G.FOR BS1=BS2,AR(1)=3 AND AR(2)=1.
************************************************************

IS YOUR LPA GAIN 10 ? N
WHAT IS YOUR GAIN? 8
NUMBER OF STAGES? 3
STAGE  1  ASPECT RATIO? .66667
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 2
STAGE  1  NOZZLE WIDTH IN MM? .76
STAGE  1  SUPPLY PRESSURE =  3.895390408859  TORR
STAGE  1  SUPPLY FLOW = .9120009119738 LPM
STAGE  1  SUPPLY RESISTANCE = 4.271257142088 TORR/LPM
STAGE  2  ASPECT RATIO? .5
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 3
STAGE  2  NOZZLE WIDTH IN MM? .508
STAGE  2  SUPPLY PRESSURE =  15.50003100006  TORR
STAGE  2  SUPPLY FLOW = .8466666666633 LPM
STAGE  2  SUPPLY RESISTANCE = 18.30712322849 TORR/LPM
STAGE  3  ASPECT RATIO? .3333
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 6
STAGE  3  NOZZLE WIDTH IN MM? .375
STAGE  3  SUPPLY PRESSURE =  64.01280192128  TORR
STAGE  3  SUPPLY FLOW = 1.054634762344 LPM
STAGE  3  SUPPLY RESISTANCE = 60.69665462099 TORR/LPM
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  6.922699358662
STAGE  2  PRESSURE GAIN =  6.341389575126
STAGE  3  PRESSURE GAIN =  7.630472181181
PRESSURE GAIN OF THE  3  STAGE GAINBLOCK = 334.97416948
GAINBLOCK INPUT RESISTANCE =  3.203442856566 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  30.34832731049 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  280.7632244981 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP
```

Example A-8. Flueric servovalve gain block.

APPENDIX A

```
NUMBER OF STAGES? 8
STAGE  1  ASPECT RATIO? 1.07
NO. OF PARALLEL ELEMENTS IN STAGE  1 ? 1
STAGE  1  NOZZLE WIDTH IN MM? .76
STAGE  1  SUPPLY PRESSURE =  1.512186163908  TORR
STAGE  1  SUPPLY FLOW = .4744568134623 LPM
STAGE  1  SUPPLY RESISTANCE = 3.187194536997 TORR/LPM
STAGE  2  ASPECT RATIO? 1
NO. OF PARALLEL ELEMENTS IN STAGE  2 ? 1
STAGE  2  NOZZLE WIDTH IN MM? .76
STAGE  2  SUPPLY PRESSURE =  1.731301939058  TORR
STAGE  2  SUPPLY FLOW = .4750000000058 LPM
STAGE  2  SUPPLY RESISTANCE = 3.644846187446 TORR/LPM
STAGE  3  ASPECT RATIO? .833
NO. OF PARALLEL ELEMENTS IN STAGE  3 ? 1
STAGE  3  NOZZLE WIDTH IN MM? .76
STAGE  3  SUPPLY PRESSURE =  2.495070449392  TORR
STAGE  3  SUPPLY FLOW = .4710572283805 LPM
STAGE  3  SUPPLY RESISTANCE = 5.296745913379 TORR/LPM
STAGE  4  ASPECT RATIO? .66667
NO. OF PARALLEL ELEMENTS IN STAGE  4 ? 1
STAGE  4  NOZZLE WIDTH IN MM? .76
STAGE  4  SUPPLY PRESSURE =  3.895390408859  TORR
STAGE  4  SUPPLY FLOW = .4560004559869 LPM
STAGE  4  SUPPLY RESISTANCE = 8.542514284176 TORR/LPM
STAGE  5  ASPECT RATIO? .5333
NO. OF PARALLEL ELEMENTS IN STAGE  5 ? 1
STAGE  5  NOZZLE WIDTH IN MM? .76
STAGE  5  SUPPLY PRESSURE =  6.08736927703  TORR
STAGE  5  SUPPLY FLOW = .4307936914142 LPM
STAGE  5  SUPPLY RESISTANCE = 14.12403336359 TORR/LPM
STAGE  6  ASPECT RATIO? .333
NO. OF PARALLEL ELEMENTS IN STAGE  6 ? 1
STAGE  6  NOZZLE WIDTH IN MM? .76
STAGE  6  SUPPLY PRESSURE =  15.61292769398  TORR
STAGE  6  SUPPLY FLOW = .356071763629 LPM
STAGE  6  SUPPLY RESISTANCE = 43.84769950545 TORR/LPM
STAGE  7  ASPECT RATIO? .45
NO. OF PARALLEL ELEMENTS IN STAGE  7 ? 1
STAGE  7  NOZZLE WIDTH IN MM? .508
STAGE  7  SUPPLY PRESSURE =  19.13584074082  TORR
STAGE  7  SUPPLY FLOW = .271819262763 LPM
STAGE  7  SUPPLY RESISTANCE = 70.39913413901 TORR/LPM
STAGE  8  ASPECT RATIO? .3
NO. OF PARALLEL ELEMENTS IN STAGE  8 ? 1
STAGE  8  NOZZLE WIDTH IN MM? .76
STAGE  8  SUPPLY PRESSURE =  19.23668821176  TORR
STAGE  8  SUPPLY FLOW = .3372781065064 LPM
STAGE  8  SUPPLY RESISTANCE = 57.0350931195 TORR/LPM
```

Example A-9. Eight-stage M48A5 gun stabilization system gain block (cont'd).

```
FIRST STAGE BIAS PRESSURE IN TORR? 0
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0
LOAD NO. OF PARALLEL STAGES? 1
LOAD ASPECT RATIO? 1
LOAD NOZZLE WIDTH(MM)? 0
STAGE  1  PRESSURE GAIN =  6.316119474231
STAGE  2  PRESSURE GAIN =  5.834821179151
STAGE  3  PRESSURE GAIN =  6.212174122533
STAGE  4  PRESSURE GAIN =  6.316327274507
STAGE  5  PRESSURE GAIN =  7.297506173708
STAGE  6  PRESSURE GAIN =  6.553892007645
STAGE  7  PRESSURE GAIN =  4.715178897435
STAGE  8  PRESSURE GAIN =  8.340620888182
PRESSURE GAIN OF THE  8  STAGE GAINBLOCK = 2719921.938609
GAINBLOCK INPUT RESISTANCE =  2.390395902748 TORR/LPM
GAINBLOCK OUTPUT RESISTANCE =  28.51754655975 TORR/LPM
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT =  55.2316647611 HERTZ
DO YOU WANT TO MAKE ANOTHER CALCULATION? NO

STOP
```

Example A-9. Eight-stage M48A5 gun stabilization system gain block (cont'd).

APPENDIX B.--REPRESENTATIVE STACKING ORDERS

This appendix presents the detailed stacking orders for three specific gain block configurations.

EXAMPLE B-1. STACKING ORDER FOR TWO-STAGE, SELF-STAGED GAIN BLOCK

Part	Orientation	Notes
5035	A	Transfer control signal to outer holes
5018a	H	Blocks control signal from second stage
Vent	H	5011a or 5239, depending on b_s
Kidney	A	5215a, 5237a, 5242a, or 5340a
Butterfly	A	5137a, 5236a, 5241a, or 5339a
LPA[a]	A	630xx, 620xx, 615xx, or other
Butterfly	A	--
Kidney	A	--
Vent	H	--
5022a	D	Keeps vents from communicating
5018a	A	Blocks first-stage controls from second stage
Vent	H	--
Kidney	H	--
Butterfly	H	--
LPA	H	--
Butterfly	H	--
Kidney	H	--
Vent	H	--
5040a	A	--
5117	H	Transfer control signal to first-stage inputs
5040a	A	Paralleled supply transfer for quietness.
5011a	E	(bracketed with above)
5040a	A	(bracketed with above)
5011a	E	(bracketed with above)
Cover plate	--	--

[a]*LPA: laminar proportional amplifier*

EXAMPLE B-2. GAIN BLOCK OF FLUIDIC CAPILLARY PYROMETER

Part	Orientation	Notes
5043	--	Not needed when base is "0" ringed
5005	--	Not needed with good filtration
5109	F	--
5116	H	--
5111	G	--
5221a	A	5 mils thick
5018a	A	--
5221a	A	--
5018a	A	Second-stage LPA,[a] aspect ratio = 0.33
5011a	A	
5339a	C	
61505	C	
5339a	C	
5011a	A	
5018a	H	
5011a	A	First-stage LPA, aspect ratio = 0.67
5339a	F	
61510	A	
5339a	F	
5011a	A	
5018a	A	
5118a	A	--
5018A	H	--
5114	H	--
5039	F	--
5112	B	--

[a]*LPA: laminar proportional amplifier*

EXAMPLE B-3. THREE-STAGE MAXIMUM DYNAMIC RANGE GAIN BLOCK

Part	Orientation	Notes
5239a(2)	A	Exhaust
5215a	C	Vent collector
5137a	C	Vent plate
62012(6)	C	First-stage laminar proportional amplifier, aspect ratio = 3.6
5137a	C	--
5215a	C	--
5239a(2)	A	--
5022a	B	Isolate first-stage venting
5188a(3)	C	Transfer input signal into first stage
5018a	A	} Three pairs, first-stage supply transfer
5011a	D	}
5021a	A	Block main pressure from first stage
5221a (4 mils)	A	} Four pairs, first-stage dropping resistor
5018a	A	}
5221a (4 mils)	A	--
5021a	C	Block second-stage pressure from first stage
5239a	A	--
5215a	A	--
5137a	A	--
62012(2)	A	Second-stage laminar proportional amplifier, aspect ratio = 1.2
5137a	A	--
5215a	A	--
5018a	C	Block second stage controls, transfer to third stage
5239a	A	--
5215a	C	--
5137a	C	--
62008	C	--
5137a	C	--
5215a	C	--
5239a	A	--
5018a	A	} Five pairs, second-stage dropping resistor and third-stage control blockage
5221a (5 mils)	A	}
5118a(3)	C	Transfer input signal to outer holes to transfer to first stage

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