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PROPULSION SYSTEM FLOW STABILITY PROGRAM (DYNAMIC)

PHASE I FINAL TECHNICAL REPORT

PART XVI. SURVEY OF SENSORS APPLICABLE TO THE CONTROL OF AIRCRAFT PROPULSION SYSTEMS

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FOREWORD

This report describes work accomplished in Phase I of the two-phase program, "Propulsion System Flow Stability Program (Dynamic)" conducted under USAF Contract F33615-67-C-1848. The work was accomplished in the period from 20 June 1967 to 30 September 1968 by the Los Angeles Division of North American Rockwell Corporation, the prime Contractor, and the Subcontractors, the Allison Division of General Motors Corporation (supported by Northern Research and Engineering Corporation), the Autonetics Division of North American Rockwell Corporation (supported by the Aeronautical Division of Honeywell, Incorporated), and the Pratt & Whitney Aircraft Division of United Aircraft Corporation.

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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

This part describes the results of a survey conducted to determine the present and the estimated 1970 capabilities of sensors applicable to the control of aircraft propulsion systems. The survey included electromechanical and fluid amplifier (fluidic) sensors for measurement of gas dynamic and static properties as well as for measurement of airframe dynamic parameters.

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SECTION I

INTRODUCTION

The sensor survey reported herein is one part of a coordinated program to improve the understanding of propulsion system instability problems in high performance turbine powered air vehicles and thereby provide a basis for increasing the performance capabilities of future USAF aircraft. The program is expected to accomplish the following:

1. categorization of those transients causing propulsion system instabilities,

2. numerical definition of flow distortion, and

3. development of a control concept for accommodating propulsion system transients.

To accomplish these objectives a 24-month two-phase program was initiated. The following brief discussion summarizes the goals of the two phases.

In Phase I, those transients requiring accommodation will be catalogued; flow instability generating mechanisms and component response mechanisms will be investigated, the steady state performance penalties imposed by component stability margins will be evaluated, and a propulsion system dynamic simulation program will be developed.

In Phase II, the most promising accommodation control system concepts for a current aircraft with turbojet engines and a future aircraft with turbojet derived engines will be selected. Preliminary analyses of these concepts will be accomplished by means of a propulsion system simulation program. These analyses, in conjunction with state-of-the-art surveys of sensors, actuators and computers will indicate:

1. Which concepts are most practical.

2. What the component dynamic response requirements are.

3. Where further sensor, actuator, and/or computer development is required.

As one of the tasks in Phase I, a survey was made and reported herein of currently available sensors (capable of sensing various aircraft transients and propulsion system parameters) which have potential for use in various accommodation control system concepts. The survey provides data for evaluation in Phase II of available sensors and determination of suitability in implementing the accommodation schemes. The survey also includes extrapolated data to help determine the projected 1970 sensor capabilities and limitations. Preliminary evaluations of various sensors are contained in this report.

As part of the coordinated program an investigation will be conducted in Phase II of the specific characteristics of those parameters which might be sensed for use in the various accommodation control concepts. In addition, hybrid simulation runs of the most promising accommodation control concepts will also be conducted in Phase II.

The hybrid simulation will, in addition to evaluating the sensed parameters and control concepts, define the dynamic requirements of such components as sensors and actuators. Final evaluation of the sensors surveyed will await completion of these tasks.

SECTION II

SUMMARY

The results of a survey conducted to determine the characteristics of available sensors applicable to the control of aircraft propulsion systems are set herein. Also given are estimates of the expected 1970 performance of some of the sensors. In addition to the normal control functions, these sensors are to be used to indicate an expected or existing flow transient.

The survey was limited to sensors that may be used for measuring pressure, pressure ratio, pressure difference, temperature, angle of attack, airframe angular acceleration and rate. Both electromechanical and fluid amplifier (fluidic) sensors were investigated.

Specific technical conclusions regarding the adequacy of the available sensors performance and the projected performance relative to the program goals are not meaningful at this time. This is so because selection of the control modes and the flow transient accommodation schemes and the resulting required sensors specifications will not be completed until Phase II of the research program. Two general conclusions, however, may be made at this time. The first is that increased dynamic response generally results in reduction in accuracy and life. The second is that, excluding the temperature sensors, very few sensors are currently in production for service at temperatures exceeding 400°F.

The remainder of the report is summarized briefly below:

Section III—Functional Application of Sensors to Integrated Propulsion Systems

This section discusses from a functional point of view what sensors are required and how they are applied in an integrated propulsion system. The section emphasizes the program goal of treating the engine, inlet and airframe as a total system where complete system control accommodates flow transients induced both internally (engine or inlet parameter change) and externally (airframe parameter change).

Section IV—Electromechanical Sensors

This section discusses general properties of a variety of sensors surveyed. For purposes of this report electromechanical applies to all sensors surveyed excluding fluidic sensors (fluidic sensors are reported on in Section V). Hydromechanical sensors were not surveyed.

Section V—Fluidic Sensors

This section fully discusses general properties, possible propulsion applications and some limitations of Honeywell fluidic sensors.

Section VI—Conclusions and Recommendations

Preliminary conclusions are that response characteristics of available temperature sensors represent a limiting factor in their use in control. High temperature

sensors are in development. Other considerations (sensor complexity, producibility means for calibration and checkout, interface with computer) which have not been evaluated will have to be given consideration (in addition to the environmental and performance factors which are tabulated in the survey tables in the Appendices) when sensor specifications are completed in Phase II. It is also concluded that data from a survey aids in the initial screening of sensors but independent testing to eliminate data inconsistencies is recommended. Additional error analyses of selected sensors are also recommended based upon sensing requirements to be completed in Phase II.

Appendix A — Tables of Sensor Capabilities

The characteristics of the large number of electromechanical sensors surveyed are summarized in tables in this Appendix. Further work is required in Phase II to sort through the data in light of sensors requirements to be developed in Phase II.

Appendix B — Preliminary Performance Specifications

Three preliminary specifications are included in this appendix. They are:

H-ECS-0 Functional Specifications — This specification defines the environmental conditions surrounding the propulsion control sensors.

H-ECS-1 Pressure Measurement Devices — Specifies preliminary pressure sensing performance requirements

H-ECS-2 Temperature Measurement Devices — Specifies preliminary temperature sensing performance requirements

These specifications were not used in conducting the survey.

Appendix C — Catalog of Honeywell Fluidic Sensor Characteristic Specifications

This appendix contains specifications of present capabilities and extrapolated capabilities of Honeywell fluidic sensors.

SECTION III

FUNCTIONAL APPLICATION OF SENSORS TO INTEGRATED PROPULSION SYSTEMS

Several parameters must be sensed in order to accomplish the controls tasks of an advanced propulsion system. These parameters may be classified under one of the following headings.

1. Mach Number - The aircraft Mach number, the propulsion inlet initial ramp angle Mach number and the throat Mach number
2. Terminal Shock Position - The propulsion inlet normal shock position during the started inlet operation
3. Temperature - The gas stream temperature at various points of the propulsion system
4. Pressure - The gas stream pressure at various points of the propulsion system—Also, pressure rate, difference and pressure ratios
5. Air Flow - The corrected or actual air flow through various cross-sectional areas of the propulsion system
6. Rotor Speed - The angular velocity of the rotors.

Other parameters may be required to be sensed for the purpose of accomplishing the control auxiliary functions. These functions include all the interlocking loops necessary for satisfactory propulsion system performance throughout the vehicle flight operating envelope. The propulsion and air vehicle parameters that may be required to be sensed to accomplish the control auxiliary functions may include:

1. The vehicle angular rate and acceleration
2. Compressor or fan inlet flow distortion
3. Compressor surge
4. Vehicle angle of attack
5. Combustor flameout
6. Inlet duct buzz and unstart

The actual parameters that may be sensed in order to accomplish the control functions are discussed in the following sections. Also discussed are the applicable sensing methods of such parameters.

MACH NUMBER

The Mach number at various stations within, and outside, the propulsion system boundary may be required. Such Mach numbers may include the free stream Mach number, the inlet duct initial ramp Mach number and throat Mach number. The ranges and required accuracy of these parameters are estimated in the following table.

PARAMETER	ESTIMATED RANGE	ESTIMATED ACCURACY
Aircraft (Free Stream) Mach Number	0.5 - 3.0	±1%
Initial Ramp Mach Number	0.5 - 2.5	±1%
Inlet Throat (Duct) Mach Number	0.5 - 1.5	±1%

The Mach number at any cross-sectional area may be calculated from the isentropic relationship relating the static pressure to the total pressure. This relationship is given by

$$\frac{P_t}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

where P_t = Total pressure at the cross section

p = Static pressure at the cross section

M = Mach number at the cross-section

γ = Specific heat ratio

Thus, the Mach number may be determined by sensing the total to static pressure ratio. Absolute pressures are used in computing the pressure ratio.

Even with precise pressure ratio measurement and precise function generation, the computed Mach number will be in error since the specific heat ratio is temperature dependent.

TERMINAL SHOCK POSITION

Direct and indirect sensing of the terminal shock position is possible. In the direct method, the shock is assumed to exist within the region of high static pressure gradient downstream of the inlet duct throat area. For the purpose of defining this region, several static pressure sensors are positioned along the duct. The output of such sensors may be manifolded in order to determine the shock position. Another approach is to electronically process the individual pressure sensor outputs in order to determine the shock position. In general, the pressure rise across the shock is approximately twice as much as the pressure rise across any other two sensors. The problem associated with the direct method is that boundary layer build up in the duct, unless properly controlled, may be excessive which may result in inaccurate pressure rise indication.

The indirect methods of sensing the position of the terminal shock position include the sensing of the inlet duct corrected air flow and percent pressure recovery. Such methods are not as effective as direct control because a definite and fixed relationship does not always exist between the sensed variable (such as pressure ratio) and the desired variable (shock position).

TEMPERATURE

Temperature sensing of the gas stream at various locations within the propulsion system is essential for successful control of the system. Among the propulsion temperatures that may require sensing are the following. Estimated range and required accuracy of the listed parameters are also given.

PARAMETER	ESTIMATED RANGE	ESTIMATED ACCURACY
Fan Inlet Temperature	400 - 1100°R	±5°R
Fan Discharge Temperature	400 - 1500°R	±5°R
Compressor Inlet Temperature	400 - 1700°R	±10°R
Turbine Inlet Temperature	500 - 2860°R	±15°R
Fuel Temperature	400 - 700°R	±2°R

Accurate temperature measurement of any gas stream is difficult for several reasons. Among these are the localized gradients which may exist within the cross-sectional area and, the extreme ambient range which the sensor must withstand.

Temperature sensing may be accomplished by one of two basic methods. These methods are based on:

1. Thermal Equilibrium Methods and

2. Secondary Methods

THERMAL EQUILIBRIUM TEMPERATURE SENSING METHODS

These are probably the most used methods in determining the temperature of a substance. These methods require that the substance whose temperature is to be determined and the sensing element reach thermal equilibrium. Such sensors, therefore, depend upon the ability to observe some parameter of the sensing element which varies with the temperature. Thermocouples, resistance thermometers and thermistors are examples of this method.

Inaccuracies in these sensing methods are caused primarily by the existence of temperature gradient between the sensing element and the substance. This gradient may be the result of heat transfer between the sensor and its surroundings through radiation and conduction. The compressibility of gas introduces other errors. The gas, upon coming in contact with the sensing elements, undergoes a polytropic compression. This compression increases the gas temperature to a level near, but not equal, to the gas total temperature.

Additional errors are introduced by the time lag necessary to allow the equilibrium state between the gas and the sensor element to be reached following a change in the state of the gas. This lag can be reduced by minimizing the sensor mass and also maximizing the gas mass rate of flow over the element. Other constraints, such as strength and reliability, restrict the degree to which the sensor size reduction is to be carried out.

Regardless of the temperature method used under this concept, several sensors must be used when the average temperature of a cross-sectional area is to be determined. This requirement is the direct result of the existence of temperature gradients in a propulsion system jet stream.

Sufficient accuracy can be achieved by some of the methods discussed herein for gas temperatures up to 2000°F. Above this temperature level the errors become large such that other temperature measurement methods must be used.

SECONDARY PARAMETER TEMPERATURE SENSING METHODS

The physical and thermodynamic flow properties of gas depend on the temperature of the gas. Some of these properties can be measured in an attempt to measure the gas temperature. The errors associated with these methods depend on the particular gas property being monitored. Thus, no common errors exist between the several methods available under this group of sensors.

Possible temperature sensing methods under this class of sensors are the following.

1. Pyrometry
2. Acoustic
   a. Velocity
   b. Resonance
3. Fuel to air ratio
4. Fuel to combustor inlet pressure ratio

Preliminary studies indicate that gas temperature measurement may be accomplished successfully, except for the measurement of the turbine inlet temperature, through the use of thermocouples and resistance thermometers. Dynamic compensation is required in order to provide the necessary response characteristics. Thermocouples normally act as a second order lag. Furthermore the dominant lag is very dependent on the flight conditions. In particular, it is dependent on the gas mass rate of flow around the sensor. This makes exact compensation of the lag in the temperature measurement device difficult. Even so, experience has shown that proper compensation can provide up to a thirty-fold reduction of the effective time constant of the sensor. This compensation may have to be made to be dependent on the flight condition in order to yield consistent dynamic performance.

In an advanced propulsion system, the response of all the temperature sensors must be very rapid. This requirement includes that of the engine inlet temperature sensor. Rapid temperature transients at the engine inlet may result in compressor surge unless appropriate action is rapidly carried out by the control. Such temperature transients may be the result of atmospheric temperature gradients, terminal shock wave movement, and hot gas ingestion.

PRESSURE

Total and static pressure measurements present the same general problems. Typical propulsion pressure parameters that may be required to be sensed are given below:

PARAMETER	ESTIMATED RANGE	ESTIMATED ACCURACY
Fan Inlet Pressure	2 - 25 psi	±0.5%
Fan Discharge Pressure	2 - 45 psi	±0.5%
Compressor Discharge Pressure	20 - 400 psi	±0.5%

In addition to the above, the static and total pressure of the free stream are required to be sensed. The total pressure sensor requirements are based primarily on Mach number and altitude while the static pressure sensor requirements are defined by altitude.

Other pressure sensors may be required. These sensors may be used to measure difference between two pressures, pressure rate and pressure ratio.

Accurate sensing of pressure and pressure ratio at all times provides the needed information to define the air flow characteristics through the propulsion system. To accomplish this task, several sensors are often positioned in the same plane. These sensors may be manifolded to a single plenum to yield the average pressure or may be interrogated individually in order to provide the means for determining the flow pattern through the cross sectional area of interest.

The importance of recognizing engine inlet flow distortion in a quantitative way rests on the fact that flow distortion beyond certain limits results in a significant change in compressor or fan characteristics. Specifically, the surge margin is reduced. For this reason, the flow profile across the compressor face as well as the time variant of the average flow across the compressor face must be known. Once flow distortion is detected, the control generates and implements the necessary command that will cause an increase in the compressor surge margin. To prevent compressor surge, therefore, requires rapid identification of the existence of excessive flow distortion. For this reason, rapid responding engine inlet pressure sensors must be used.

The response of the fan discharge pressure sensors and the compressor discharge pressure sensors must also be rapid. Tests have shown that the occurrence of compressor surge could be followed by a compressor discharge pressure drop to the inlet level within 60 milliseconds. This pressure rate is more likely a function of the particular engine and the flight condition since it represents the empty phase of the engine volume. Normal compressor operation, during rapid rotor deceleration for example, does not result in such rapid changes in the pressure.

In order to provide an additional intelligence to the control system regarding the existence of compressor surge, a pressure rate sensor may be used. This sensor may enable the control to issue a corrective action prior to a complete loss of power. Such a sensor must obviously be capable of sensing the rapid pressure rates. Present sensors are based on an approximate differentiation of the pressure sensor signal of interest through a washout filter. It should be clear that the pressure sensor itself must possess the response that will enable the computation of pressure rates in excess of those experienced during compressor surge.

The need for a pressure ratio sensor has been indicated earlier in connection with the Mach number computation. Pressure ratio sensing may also be required for the purpose of limiting the compressor pressure ratio during rapid acceleration. Another use of the pressure ratio sensor is in the determination of corrected air flow through a cross sectional flow area.

Pressure ratio sensing may be accomplished by one of two basic methods. The first involves the measurement of the individual pressures independently and computing the pressure ratio through electronic means. This method enables the design of fast acting pressure ratio sensors but with relatively poor steady state accuracy, especially at the lower end of the operating pressure levels.

The second pressure ratio sensing method is based on the force balance null principle. In this method, the force output of a pair of pressure sensing bellows acting at different ends of a pivoted lever is brought into balance by varying the pivot point. The pressure ratio is, therefore, uniquely defined by the position of the pivot point. Such devices are reported to be capable of sensing pressure ratio to an accuracy better than one percent of point for a pressure dynamic range of approximately thirty. The dynamic response of this method is poor, being directly dependent on the rate limit of the servo loop of the lever variable pivot point.

Pressure ratio sensor design accuracy based on the first method may be improved by reducing the dynamic range of the individual pressure sensors. To cover the entire pressure range may require the use of several pressure sensors, each acting through a narrow range, to sense a single pressure.

Evacuated bellows are used for absolute pressure measurement. The force acting on the bellows is proportional to the pressure only. Thus, the displacement of the bellows, acting like a spring, is proportional to the absolute pressure.

Differential pressure is sensed by the position of a diaphragm or a bellows across which the pressure difference is applied. In the case of a diaphragm a spring is required to provide the reaction to the applied force.

AIR FLOW

In an advanced propulsion system, the actual air flow and the corrected air flow across critical components may be required to be sensed to accomplish the component matching necessary for optimum propulsion performance. Corrected air flow through a fixed cross-sectional area is a function of the Mach number across the flow area. This relationship is expressed as

$$W_c = \frac{W\sqrt{T}}{P} = KM \sqrt{\frac{\gamma g}{R\left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma + 1}{\gamma - 1}}}}$$

where W_c = corrected air flow, K = constant

T = total temperature, g = gravitational constant

P = total pressure, R = gas constant

Thus, the corrected air flow may be computed if a Mach number sensor is available. A Mach number sensing method, based on the point total to static pressure ratio, was discussed earlier. Other Mach number sensing methods may be used for this purpose. In terms of the Mach number sensing parameters discussed earlier, the corrected air flow may be written as:

$$W_c = K\left(\frac{p}{P_t}\right)^{\frac{1}{\gamma}} \sqrt{\frac{2\gamma g \left(1 - \frac{p}{P_t}\right)^{\frac{\gamma + 1}{\gamma}}}{R(\gamma - 1)}}$$

The propulsion corrected air flow that may be required to be computed is given below. Also given are the estimated range, in terms of the sensed parameter Mach number, and the estimated accuracy.

PARAMETER	ESTIMATED RANGE	ESTIMATED ACCURACY
Fan Inlet Corrected Air Flow	0.1 - 0.5M	1%
Compressor Inlet Corrected Air Flow	0.1 - 0.5M	1%
Fan Discharge Corrected Air Flow	0.1 - 0.5M	1%
Compressor Discharge Corrected Air Flow	0.1 - 0.5M	1%

As it has been pointed out, the specific heat ratio γ is a temperature dependent parameter. Thus, temperature compensation may be required in order to meet the accuracy requirement since the propulsion system temperature at any station will vary over a wide range.

The actual air flow through particular stations may be required in order to accomplish certain control functions such as control loop gain variation and fuel to air ratio limit. The actual air flow may be computed by multiplying the corrected air flow signal by $P/\sqrt{T}$.

OTHER PARAMETERS

To accomplish the implementation of the secondary propulsion control functions may require sensing of additional parameters. In most cases, the additional parameters are sensed by an application of the methods discussed earlier.

For an advanced propulsion system, where the compressors surge margin and the inlet duct shock position stability margin are minimal, it may be necessary to provide interlocking schemes between the vehicle and the propulsion. These interlocking schemes constitute part of an integrated propulsion flow transient accommodation schemes. It is clear that any rapid vehicle maneuver, such as pitch and roll, ultimately results in a flow transient the result of which may be in the form of propulsion inlet pressure distortion or an unbalance in the steady state continuity equation. In an anticipation of this flow transient, airframe mounted sensors may be used to predict the degree of flow transient.

Such sensors may include the vehicle angular rate and acceleration, as well as the angle of attack. Upon sensing the onset of an expected rapid maneuver, the propulsion system control will react to increase momentarily the propulsion system stability margin. It appears at this time that precise measurement of the vehicle attitude and attitude rate with respect to the free stream is not essential as far as the aircraft-propulsion system interlocking schemes is concerned. What is important is the absolute level of the parameter above which a rapid vehicle maneuver is assumed to have been in progress.

Angle of attack sensing concepts are based on a single phenomenon: that the pressure distribution on a body varies as the angle of attack varies. This phenomenon is utilized in two basic sensors concepts; these are the fixed surface and the moving surface sensors. In the first concept, the relative pressures between pressure ports on the fixed surface will give the information for calculation of the angle of attack. The second angle of attack sensor concept is built around the weather vane principle. The moving surface essentially maintains zero angle of attack relative to the free stream conditions. The angular position of the vane relative to the body axis is a direct measurement of the angle of attack.

The vehicle angle of attack sensor should be capable of sensing speeds up to Mach 3. The shock pattern at the higher Mach number may cause inaccuracies in measurement that renders the sensor useless. It may be necessary to provide two angle of attack sensors covering the subsonic and supersonic flight regimes.

The secondary propulsion control function includes the detection of inlet duct buzz and unstart. A Mach number sensor is required for unstart detection. This Mach number sensor is placed at the lip of the propulsion inlet duct. During normal operation, that is, when the inlet is operating in the started mode, the Mach number sensor should read above unity. When the inlet unstarts, this Mach number reading drops below unity. For the purpose of inlet unstart detection, therefore, it is only necessary to determine whether or not the Mach number is above unity.

Inlet duct buzz detection is accomplished through the use of a static pressure measurement of the duct wall. The frequency of oscillation of the static pressure is the determining factor of whether or not a buzz operating mode exists in the inlet duct. Buzz frequency depends on the geometry of the inlet; the larger the inlet duct the smaller is the frequency. Preliminary indications are that the buzz frequency of advanced aircrafts falls between 3Hz and 40Hz. Thus, the response of the pressure sensor must be flat beyond the buzz frequency.

SECTION IV

ELECTROMECHANICAL SENSORS

This section contains a discussion of the general properties of the nonfluidic sensors surveyed. Detailed tabulations of performance characteristics obtained in the survey are contained in Appendix A. The types of electromechanical sensors specifically surveyed are listed below:

Absolute Pressure Sensor

Differential Pressure Sensor

Pressure Ratio Sensor (P/P)

Pressure Ratio Sensor ($\Delta P/P$)

Temperature Sensor

Angle of Attack Sensor

Acceleration Sensor

Angular Rate Sensor

PRESSURE SENSORS

Regardless of the type of application for which a pressure sensor is designed, i.e., applied to measurement of "static," "dynamic," absolute, or differential pressures, the basic elements common to all are a sensing element, which converts the applied pressure to a deflection or state of stress, and a pickoff element which converts the deflection or state of stress to a change in a measurable electrical property or characteristic. From this point on, there are as many designs as there are specific applications and normally, each design represents a compromise of performance characteristics to meet the specific requirements of the application. Attempts to classify pressure sensors by type of sensing element or type of pickoff can only be done in a gross sense because, apparently, performance of present sensors is more related to design and manufacturing techniques than any other factors. However, generalization about which basic sensor elements constitute the best hope for future specific designs for this program can only result from knowledge of the mechanics and limitations of the basic sensor elements.

Sensing elements for the electromechanical pressure sensors recorded in the survey include the following types: diaphragm, bourdon tube, strain tube and capsule. A special case is the piezoelectric crystal type which, being sensitive to applied pressure, can act as both sensing element and pickoff. The deflection characteristics of the sensing element are related to both physical design and Young's modulus of the material used. Assuming a sensing element represented by a zero damped spring-mass system (neglecting dynamic characteristics introduced by the sensor cavity and fluid properties), maximum response, as characterized by sensing element natural frequency, results from a low mass high spring rate device. In other words a small, stiff design. This is best characterized by the diaphragm design which, in miniaturized versions, have natural frequencies exceeding 100 KHZ. Miniaturization, in addition to improving sensor element response, can substantially improve response of the complete sensor installation, if the sensor is small enough to mount directly in the pressure probe. The major apparent limitation of miniaturized diaphragm type sensing elements is that accuracy is not as good as that obtained with larger versions of similar design.

Sensing elements are presently available in a variety of materials including both polycrystalline (metals) and monocrystalline (quartz, silicon). Polycrystalline materials, theoretically, are more subject to hysteresis, drift and creep under stress, and exhibit a non linear variation in Young's modulus with temperature, although some alloys have been developed which have a constant modulus over a finite temperature span. Monocrystalline materials tend to be brittle and more susceptible to damage from shock, vibration, and impingement of high velocity particles. Unless unique to the type of pickoff used, sensing element material is usually metallic.

Pressure sensor pickoff types recorded in the sensor survey include:

metal strain gage

semiconductor strain gage

variable transformer

variable reluctance

variable capacitance

potentiometric

piezoelectric crystal

Wire or foil metal strain gages (strain sensitive resistance characteristic) are the most common elements for converting sensing element deflection to an electrical signal. They are normally arranged electrically in a Wheatstone bridge and mounted so that deflection of the sensing element induces a strain in the gage, changing the resistance of the gage and unbalancing the bridge. Metal strain gages have low impedance and small gage factor, combining to provide a low level output. Because of the low impedance, excitation voltage must be low to avoid high current levels which would result in excessive heat generation thus reducing the accuracy and/or life of the element. As a result of the low output, signal amplification is needed for most applications, and electrical noise pickup is a problem. Metal strain gage type pressure sensors are available in configurations in which the gages are bonded, unbonded, welded, or vacuum deposited to the sensing element. Bonded designs are temperature limited by the bonding agent used. Unbonded, welded and vacuum deposited gages can have an entirely non-organic design and, in theory, are more applicable to high temperature applications. Strain gages are small, and are characterized by their accuracy in measuring small deflections with the result that they lend themselves to miniaturized pressure sensor design. The interface between the gages and the pressure sensing element provides the primary problem in producing a high accuracy over a wide operating temperature range for presently available sensors.

Semiconductor (Piezoresistive) strain gages are similar in application to metal strain gages. Primary advantage is a much higher gage factor than metal strain gages resulting in high sensor output at low strain levels. Also, they can be diffused directly into pressure sensing elements (wafers, or diaphragms) made of monocrystalline silicon, eliminating sensing element/pickoff interface problems. However, they are more temperature sensitive than metal strain gages and diffused designs must be operated well below diffusion temperatures. Temperature limits for non diffused units are apparently established by the characteristics of the bonding materials, which include cements, and eutectic compositions. A factor which may limit applications of diffused units is their fragile nature, which makes them prone to damage by direct impingement of high velocity particles.

The variable capacitance pickoff is another type which is suitable for high natural frequency sensor designs. For this type, deflection of the pressure sensing element acts to vary the air gap of a capacitor. Usually, the sensing element incorporates one plate or electrode of the capacitor. Various electrical configurations are used to convert the resulting change in capacitance to a usable electrical signal. The most common techniques include arranging the variable capacitor in a Wheatstone bridge with three fixed capacitors, or, as part of an LC circuit. Capacitance pickup in long cables is a problem with the Wheatstone bridge circuit, and the sensor electronics is usually packaged in or adjacent to the sensor, imposing a direct temperature limitation. Pickoff types other than strain gage or variable capacitor normally require an armature or wiper arm coupled to sensing element, as well as larger sensing element deflections. The effect is a lower natural frequency design. These types include the variable transformer, variable reluctance and potentiometric pickoff designs, although the variable reluctance type may use the diaphragm as the armature. In the variable transformer design, deflection of the pressure sensing element moves the transformer core to vary the magnetic coupling between primary and secondary transformer windings, resulting in a secondary voltage which varies with core position. Advantages of this technique are a high level output signal, and a developed high temperature capability. Sensors using this pickoff type are available for service to 900 F.

In the variable reluctance pickoff configuration, pressure sensing element deflection moves an armature which varies the air gap between inductors arranged in two legs of a Wheatstone bridge. This effectively varies the reluctance of the inductors, changing their impedance which unbalances the bridge, resulting in an output which is a function of armature position. Units using this type of pickoff in conjunction with a bourdon tube sensing element are presently available for operation to 500 F, and based on data quoted by the supplier, can apparently be designed and compensated to provide exceptional accuracy.

Potentiometric pickoffs are, electrically, the simplest type available, consisting of a uniformly distributed resistance and a wiper. Output is a function of wiper position, and can vary from zero, or null, to a value approaching excitation voltage level. This type of unit is usually used in conjunction with large deflections such as those provided by bellows or capsule type sensing elements. However, survey data indicates that designs are available which provide step response characteristics comparable to those using variable transformer and variable reluctance pickoffs.

Figures 1, 2, 3, and 4 provide a graphic description of selected performance characteristics of pressure sensors, illustrating survey data for natural frequency, upper operating temperature limit, ambient accuracy, and effect of temperature on

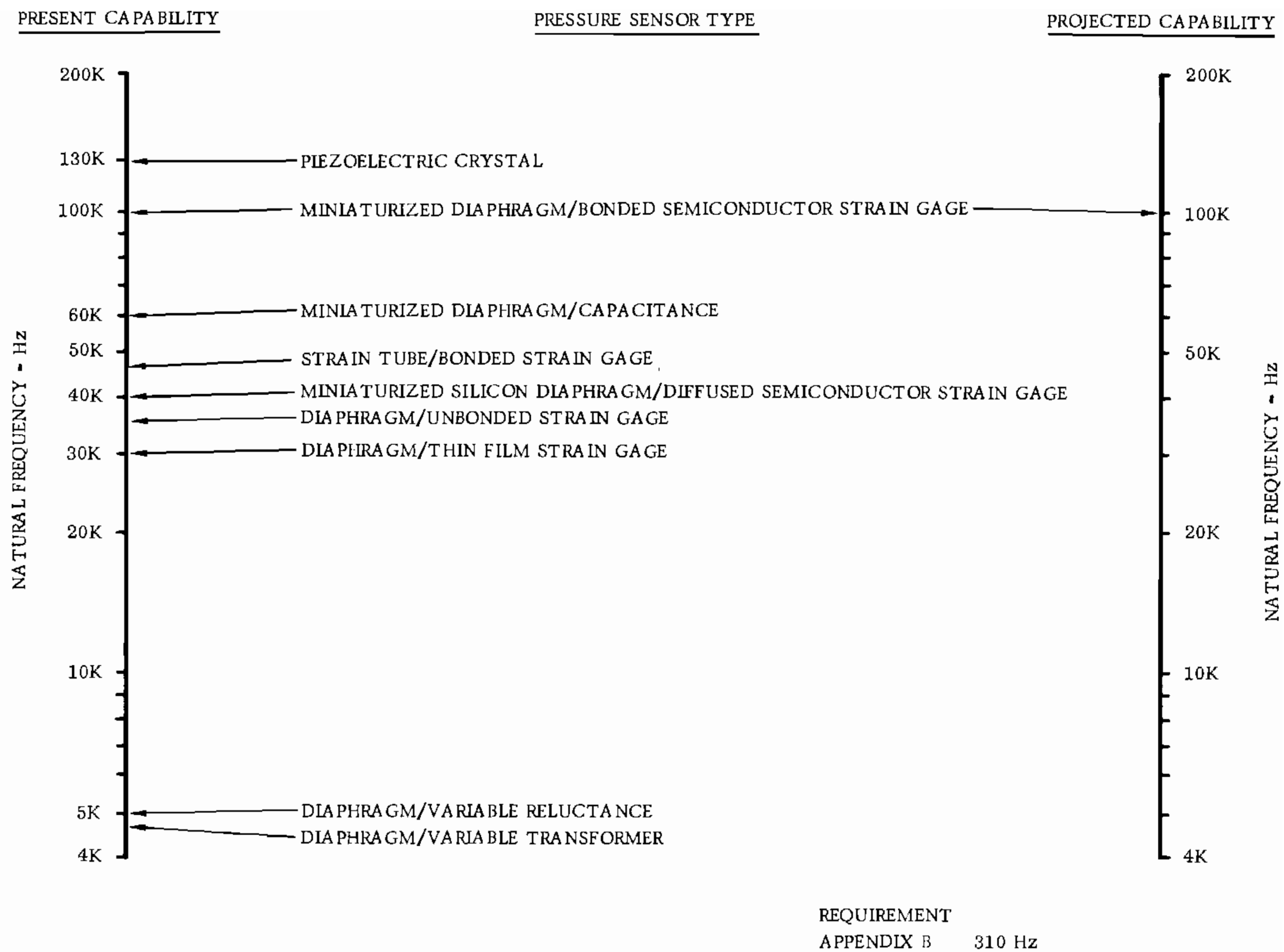


Figure 1. Pressure Sensor Natural Frequency

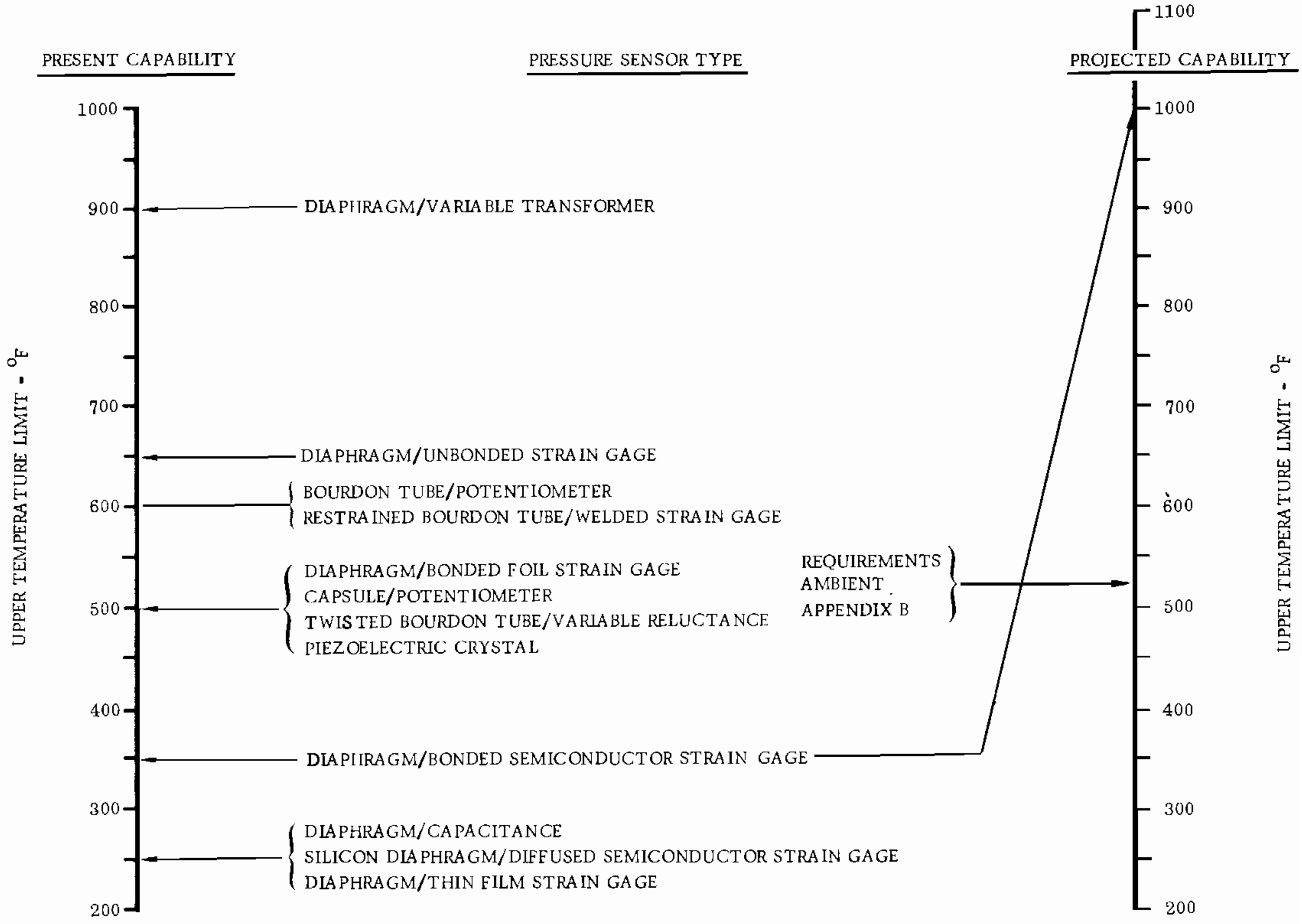


Figure 2. Pressure Sensor Service Temperature Limits

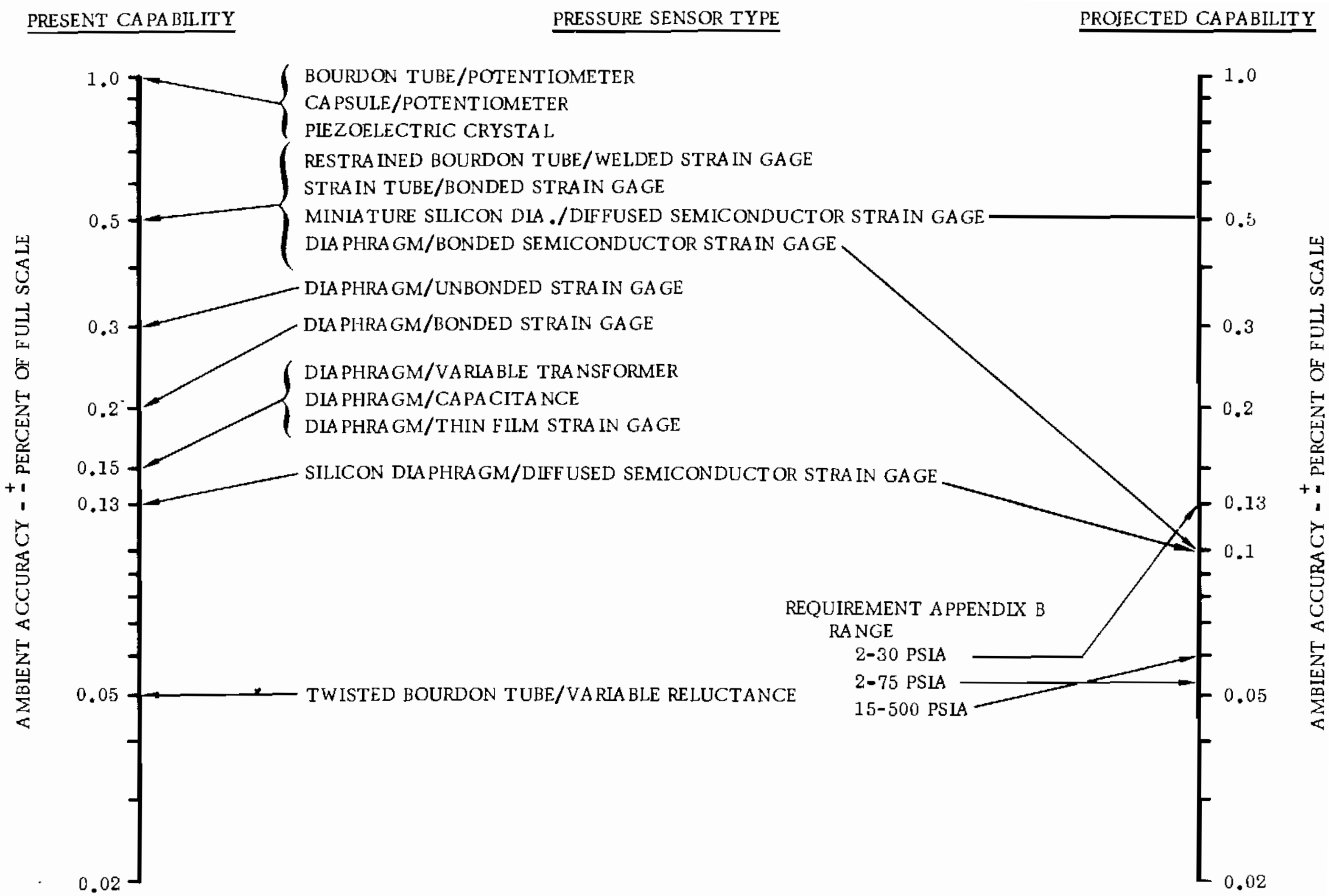


Figure 3. Pressure Sensor Ambient Accuracy

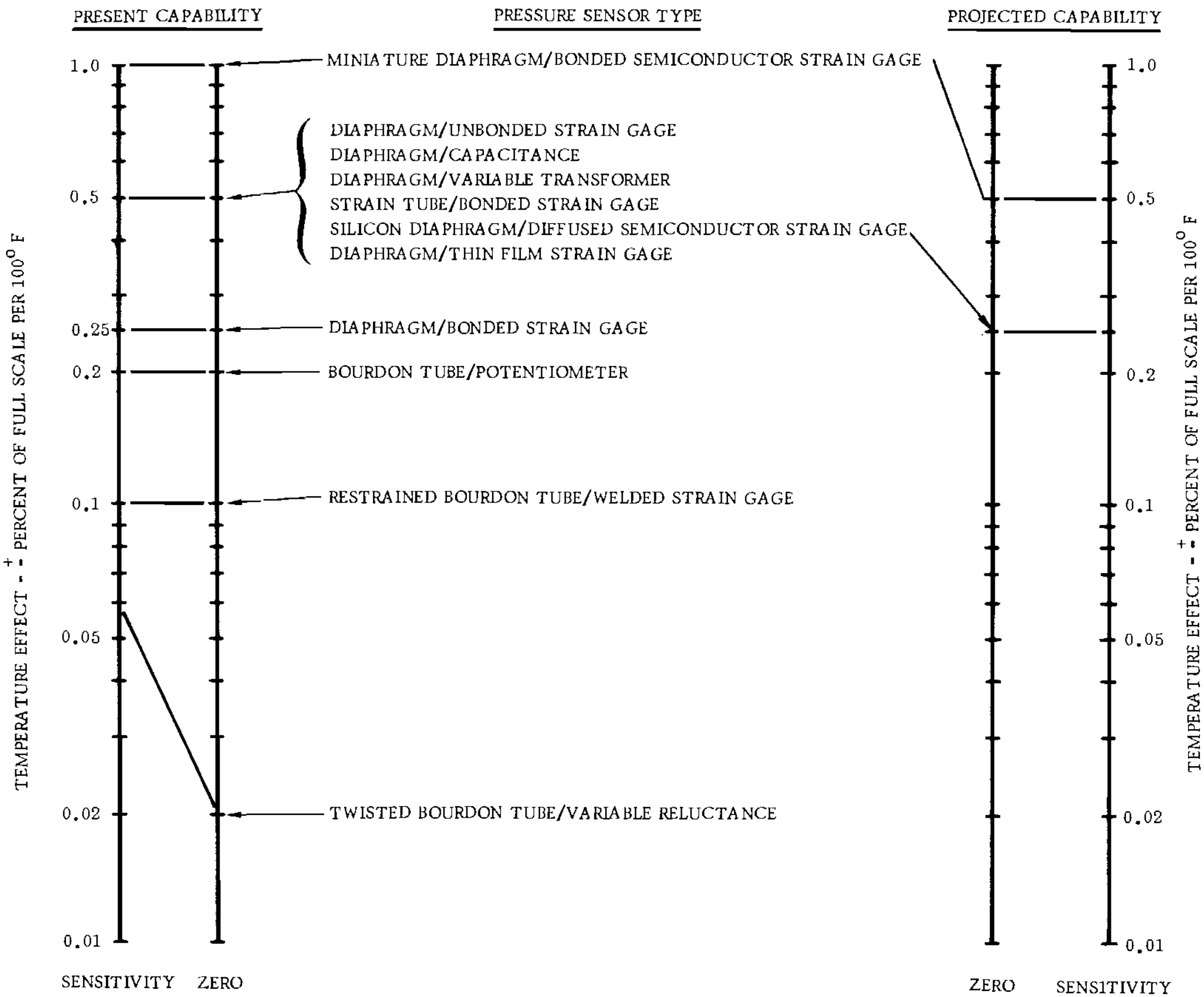


Figure 4. Temperature Effect On Pressure Sensor Accuracy

accuracy. These graphs are limited to show the best value for each sensor configuration; specific sensors shown on one figure are not necessarily carried over to the other figures if another sensor of the same configuration is better in that performance category. Present capabilities are shown to the left of each figure, projected capabilities are shown to the right.

As shown in Figure 4, the major contribution to pressure sensor inaccuracy is the effect of temperature on sensor calibration. Depending on the eventual pressure sensor requirements, several techniques may be used to improve sensor inaccuracies resulting from ambient or self generated temperature variation. These include the use of heaters to maintain the sensor at a constant temperature, or, incorporating a temperature sensor in the pressure sensor to allow adjustment of predictable temperature induced variations on calibration. Although heaters are commonly used in accelerometers and gyros to stabilize damping characteristics, warm up times may be prohibitive for certain applications. The use of temperature sensors to compensate for temperature effects requires additional electronic circuitry to correct the sensor signal. For systems with large numbers of sensors, the technique will impose complexity and cost penalties, and if the correction is done remotely, a weight penalty due to the increase in cable sizes.

PRESSURE RATIO SENSORS

Two mechanizations are presently available for measuring pressure ratio. These are the closed loop mechanization, which includes a servo for force or null rebalance, and the open loop mechanization, in which pressure ratio is electronically computed from the signals from two matched pressure sensors.

In the closed loop mechanization, two pressure sensing elements are kinematically arranged so that their resultant deflection or force is a function of the ratio of their individual deflections or forces. The resultant is sensed by a pickoff which generates an error signal to a servo which balances or renulls the device. A linearizing linkage and follower in the servo provides an output motion which, when coupled to a pickoff provides an electrical signal which is a linear function of pressure ratio. Basic advantage of this mechanization is accuracy over the entire range of pressures sensed. Response is characterized and limited primarily by the servo mechanism. Frequency response for small variation in ratio is in the range of 10 to 15 Hz, but step response is rate limited to values of one second or larger for full range steps. This mechanization is relatively large in relation to open loop pressure sensors and is limited to an upper ambient temperature of 250 F for present models.

In the open loop mechanization, where the ratio is electronically computed, response is characterized by the dynamics of the pressure sensors used. In the strictest sense, this mechanization does not sense pressure ratio, but only the pressure components comprising the ratio, and can be obtained complete with computational electronics to provide an output proportional to ratio, or with the individual pressure component signals for remote computation of ratio.

The major problem with this technique is a gross inaccuracy in the computed ratio when the pressure sensed by either sensor is near the low end of the measurable pressure range. Even though the individual pressure sensors may be very accurate, the resulting computed ratio accuracy will be poor.

Depending on future requirements, available ratio sensors may be arranged in the system to improve system accuracy and response. One technique is to use the closed loop type primarily as an in-flight calibration to periodically update information from the open loop sensor. This technique retains the response characteristics of the open loop type and the accuracy of the closed loop type. Another technique would be to use several open loop sensors for each sensing station. With this arrangement the sensors would normally cover different regions of measured pressure to reduce the pressure range for the individual sensors. An additional benefit of this method is the resulting redundancy of the sensors.

TEMPERATURE SENSORS

Data for five types of available temperature sensors were recorded in the survey. These were the wire resistance, semiconductor resistance, thermocouple , infrared, and hot wire anemometer types.

In the wire resistance type, usually utilizing platinum or nickel base sensing elements, the wire resistance varies as a function of probe temperature, and is normally mechanized as one leg of a Wheatstone resistance bridge. Lead wire resistance can be compensated by additional bridge circuitry and may require up to twelve additional resistors in the bridge circuit plus two additional lead wires to the sensor, making this a costly method for systems with many temperature sensors. Wire resistance temperature sensors are usually limited to less than 2000 F although ranges approaching 2500 F were recorded in the survey.

Primary advantage of the resistance probe is a better accuracy relative to thermocouples. Response characteristics are slow for most higher temperature applications because the resistance wire element must be protected to prevent oxidation and loss of sensitivity, and to prevent structural damage. The protection consists of imbedding the sensing element in temperature resistant materials which introduce thermal lags characterized by the physical design, thermal conductivity and heat capacity of the probe materials. Response must therefore be traded against probe life for higher temperature applications. Survey data for a compressor discharge temperature sensor indicate a life to failure of less than 1000 hours corresponding to a 1500 R temperature extreme, and a 1.5 second time constant at 12 $lb/sec/ft^2$ flow condition. The probe life problem is compounded by an apparent lack of definition of environmental conditions, within engines, which affect the probe structural design. This results in probes being environmentally qualified in the laboratory but failing in service.

The hot wire anemometer, used as a temperature sensor, is a special case of the resistance probe which, up to now, has been mainly applied as a lab or research tool due apparently to the complex control circuitry required, and delicate probe designs. The anemometer is a highly responsive instrument, used primarily as a flowmeter in flow and turbulence studies.

Semiconductor resistance temperature sensors are similar in application to the wire resistance units. At present they are available for sensing temperatures to 500 F. Advertised advantages include a dynamic response four to five times faster than comparable wire types, and a high level output, up to 20 $mv/^{o}F$, when used in a Wheatstone bridge. The faster response is attributed to a higher thermal conductivity, small size and a design having a high surface to thickness ratio, all of which are design factors related to rapid element heat transfer characteristics. From a practical standpoint, semiconductor elements are fragile, and may need structural protection for airborne application which would tend to increase thermal lag, reducing dynamic response.

Thermocouple probes are generally used for temperature sensing applications above 2000 F, and have been designed for applications approaching 4500 F. Another advantage of the thermocouple is the relatively simple electrical circuit required. Disadvantages are the characteristically low signal level and poor dynamic response, which as discussed for wire resistance probes, is a design trade off of thermal lag against service life.

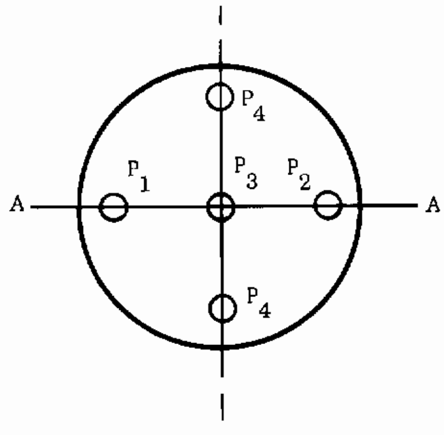
The infrared temperature sensor is a non-contact device used to remotely detect surface or combustion temperatures. Survey data (for one type) indicates a temperature range of 60 F to 3200 F. In operation, the detector is aimed at the surface or infrared source and may be a considerable distance from the source. The detector for the type surveyed must be environmentally protected having an ambient temperature limit of 120 F. Quoted response time for the device is 0.1 second.

ANGLE OF ATTACK SENSORS

Angle of Attack sensors measure local angle of the flow velocity vector relative to the sensor axis in a predetermined plane. They can be used to determine relative flow direction as well as aircraft angle of attack. From the survey, two different mechanizations are available, the vane type and the pitot probe type.

The vane type is essentially a wind vane. Flow velocity forces align the vanes along the direction of the flow velocity vector. Deflection of the vanes from a null or zero angle position is detected by a pickoff to provide an electrical output signal. The pickoff is normally a potentiometer or synchro. They can be equipped with integral heaters to avoid icing problems and are apparently available for velocities up to Mach 3, although survey data indicates present temperature limitations of less than 300 F. Response of this type of device is relatively slow.

The probe type angle of attack sensor consists of a fixed pitot probe and pressure sensors. One version of the probe is illustrated below, although other configurations, including "wedge" and "cobra" are also available.



ROSEMOUNT ENGR. ANGLE OF ATTACK PROBE

P_3 = TOTAL PRESSURE PICKUP

P_1, P_2, P_4 = STATIC PRESSURE PICKUP

ANGLE OF ATTACK MEASURED IN PLANE AA

For the configuration shown, angle of attack is proportional to the relationship $\frac{P_1 - P_2}{P_3 - P_4}$, and the system includes a pressure ratio sensor to provide an electrical output . Sensitivity per degree is relatively constant over a wide range of subsonic and supersonic Mach numbers. Response of this type of mechanization is related to the tubing size and length from probe to sensor, and the response characteristic of the sensor.

ACCELERATION SENSORS

Acceleration sensors are available in both open loop and closed loop types. The open loop accelerometer consists of a spring restrained seismic mass which reacts with an inertia force to acceleration inputs along a predetermined axis. This results in a deflection which is detected by a pickoff to provide an electrical output. The pickoffs presently used include most of those discussed for pressure sensors. The seismic mass may be suspended for either rotational (pendulus type) or translational motion. Either oil or air damping is provided to eliminate spring/mass oscillation.

The accelerometer system may be represented by a second order, single degree of freedom transfer function. Response characteristics are determined by mechanical design and size, type of damping, and damping ratio. Air damped sensors with natural frequencies to 600 Hz are presently available. Operating temperature range for available designs is less than 300 F. Because the viscosity of damping fluids is temperature dependent, the damping ratio will vary with temperature and therefore response characteristics will tend to become more oscillatory at elevated ambient temperatures and sluggish at low temperatures. Heaters can be used to maintain more consistent response characteristics.

Sources for open loop acceleration sensor inaccuracies are essentially the same as those for pressure sensors plus errors introduced by cross axis acceleration inputs. The closed loop acceleration sensor mechanication using a force balance servo, is used mainly to obtain better accuracies than those obtainable for open loop types.

ANGULAR RATE SENSORS

The conventional mechanization for angular rate sensors is the rate gyroscope constrained to one degree of freedom, which makes use of the precession characteristic of the gyro to produce an output. With this mechanization, displacement about the output axis is proportional to angular rate input at the input axis. Damping is provided in the form of viscous shears, dashpots, or eddy current devices to reduce oscillations in the output axis. Pickoff types used include variable transformer and potentiometers. Present capabilities include designs with natural frequencies to 200 Hz. Operating temperature range is limited to less than 300 F for available units. To prevent wide excursions in damping ratio in oil damped designs, heaters can be provided as part of the sensor package.

SECTION V

FLUIDIC SENSORS

SENSORS SURVEYED

During Phase I, Honeywell surveyed all its inhouse sensors and sensor concepts and their interface transducers which may be applicable to a flow distortion accommodation system. Existing data was examined and extrapolated in order to establish performance levels attainable with further development. The fluidic sensors studied are listed below:

1. Temperature Sensor
2. Pressure Ratio Sensor
3. Pressure Rate Sensor
4. Normal Shock Sensor
5. Pressure Difference Sensor
6. Accelerometer
7. Angular Rate Sensor
8. Angle of Attack Sensor
9. Flow Distortion Sensor

In succeeding paragraphs, the Honeywell fluidic sensors are described and their capabilities and limitations are explained. A brief explanation of the general characteristics and limitations which apply to all fluidic sensors is presented prior to the more detailed description of the individual sensors.

Performance data have been compiled for each of the sensors and are presented as specification sheets in Appendix C. In addition, the current performance was examined and extrapolated in order to establish performance level attainable through further development. The majority of the sensors were developed for a specific application, therefore, the data on some of the characteristics are not known for all of the sensors. The data listed are typical for the specific sensors, but simple tradeoffs are available to tailor the sensors to specific requirements when they are known. Fluidic sensors are now being developed on several different programs. Consequently, much of the performance data on the fluidic sensors are based on laboratory experimental test results and predicted performance from the development programs. The size, weight and mounting configuration many times are not presently fixed and can be designed to fit the specific application.

Fluidic angle of attack and flow distortion sensors are in the conceptual stage so that it is not possible to prepare any specifications for these sensors. No performance characteristics are known because the computational circuits have not been evaluated for this application. Since the circuits for these sensors consist of fluidic amplifiers, the environmental limitations should only be those imposed by the amplifier.

A summary of the limitations that appear critical in the application of fluidic sensors to a flow distortion accommodation control system is listed in Table I. This list points out the areas where further development is required to attain the performance listed under extrapolated capabilities in the specifications.

GENERAL CHARACTERISTICS OF FLUIDIC SENSORS

There are several characteristics or requirements that apply to the fluidic sensors in general such as certain environmental limits, contamination tolerances, and power supply requirements. Tests have been conducted in these areas on some of the fluidic sensors, with the extension of the results to other sensors because of their similarity in construction and function. These tests have been conducted during development programs, both internally funded and under Air Force contracts. The details of the results of some of the testing are available in AFAPL-TR-68-31 and are summarized here.

Fluidic sensors and/or computational elements contain no moving parts, except the fluid itself. Therefore, they have inherent high reliability and are highly tolerant of the mechanical environmental ambient conditions such as vibration and shock. The only limitation is the structural integrity of the sensor. Except for the flight control sensors, the sensors are practically solid with just small internal flow passages; thus the mounting surface or probes to which the sensors are mounted are the limiting factor.

Vibration testing of the temperature sensor has been conducted per MIL-STD-810B curve L which specifies 20 g's to 2000 cps. No deterioration of performance occurred during the test. The sensor tested included a fluid/electrical transducer which would be more susceptible to vibration than the sensor itself. Similar tests have been conducted on the pressure difference sensor (proportional amplifier) with no effect on the performance of the sensor. Many of these fluidic sensors have been mounted directly on turbojet engines and engine test stands during hundreds of hours of engine operation with no detrimental effect on their performance attributable to vibration.

The other mechanical type environmental tests such as shock and acceleration have not been conducted on the fluidic sensors. Because of the configuration of the sensors and the results of the vibration testing, it is felt that the sensors can readily meet the requirements of MIL-STD-810B for shock and acceleration.

Since temperature and altitude would affect the flow phenomena, these tests have been conducted on the individual sensors and the effects on the performance of the sensors are presented in the specifications in Appendix C.

Because fluidic devices contain small passages, contamination is a potential problem. As part of an Air Force program, reported in AFAPL-TR-68-31, contamination testing was conducted on five amplifier cascades, each consisting of three proportional amplifiers. The amplifiers were fabricated from an aluminum-filled epoxy material and all had power nozzles 0.010 by 0.020 inch. This is normally the smallest size passage used in our fluidic devices. The nozzle sizes and passages in the fluidic sensors are large compared to this. The object of the testing was to determine the

Table I. Summary of Fluidic Sensor Limitations

Sensor	Present Limitation	Development Status	
		Feasible	In Progress
Temperature Sensor	Higher temperatures	Yes	Yes
	Transient response	Yes	Yes
	Pressure sensitivity	Yes	Yes
Pressure Ratio Sensor	Temperature sensitivity	Yes (using compensation)	Yes
	Low pressure ratio sensitivity	Yes	No
	Operate over other ranges	Yes	No
	Improved accuracy	Yes	Yes
Pressure Rate Sensor	Altitude sensitivity	Yes	Yes
Normal Shock Sensor	Miniaturization to improve mounting	Yes	No
	Electrical output	Yes	Yes
	Altitude sensitivity	Yes	No
Pressure Difference Sensor	Altitude sensitivity	Yes	Yes
Angle of Attack	Fluidic mechanization	Yes	No
Flight Control Sensors			
Fluidic Angular Rate	Noise	Yes	No
	Drift	Yes	No
	Temperature sensitivity	Yes	No
Fluidic Accelerometer	Accuracy	Yes	No
	Environmental sensitivity	Yes	No
	Sensitivity	Yes	No
Flow Distortion Sensor	Fluidic mechanization	Yes	No

effects of contamination on the performance, reliability, and service life of fluidic devices.

A special test fixture capable of controlling the contaminant level of the supply air was used. The contaminant used was AC Spark Plug test dust, fine grade, with the following particle size distribution:

Size, Microns	Distribution, Percent
0 - 5	39 ±2
5 - 10	18 ±3
10 - 20	16 ±3
20 - 40	18 ±3
40 - 80	9 ±3

Figure 5 summarizes the test results. The test sequences were terminated at a point where the amplifiers were judged nonusable because of plugging of ports. Three test sequences were run. Contamination levels were 25, 5 and 1 mg of dust per cu ft of air.

Contamination data taken from two sources, measurements of the compressor discharge air of several engines mounted on test stands, and Air Force Document AFSCM80-9 (Handbook of Instructions for Aerospace Systems Design - Volume V Environmental Engineering), indicate that contamination levels on the order of 5×10^6 grams per cubic foot of air are normal for atmospheric dust. This level is three orders of magnitude lower than the MIL-E-5009B level of 0.005 gram per cubic foot of air which was the concentration level for the second test sequence.

An analysis of the test data, Figure 5, indicates approximately a factor of 4.35 increase in operating time for each contamination level reduction to 20 percent of the preceding value. These factors have been used to project the amplifier operating times for reduced contamination levels. These data are presented in Table II.

In addition to the contamination tests, further insight into the potential problem of contamination has resulted from the actual installation of temperature sensors on turbojet engines. They have been used to measure turbine inlet temperature on such engines as the J-57, J-58, T-56, and T-58. Both total pressure and static pressure probes are used to extract gas from the turbine inlet. Thus, the products of combustion are flowing through the sensor. The time accumulated on any single sensor is in excess of 300 hours operating time. Only once has there been any indication of a contamination problem. An exhaust orifice became partially plugged after 200 hours of operation on one sensor. Upon a careful examination, the plugging was attributed to flaking of internal material of the sensor and not from anything in the hot gas. The sensor was an early developmental model and since that time the material from which that sensor was fabricated is no longer used.

Fluidic control systems have been operated in ambient temperatures down to -20°F with no icing problems. The systems consisted of the angular rate sensor,

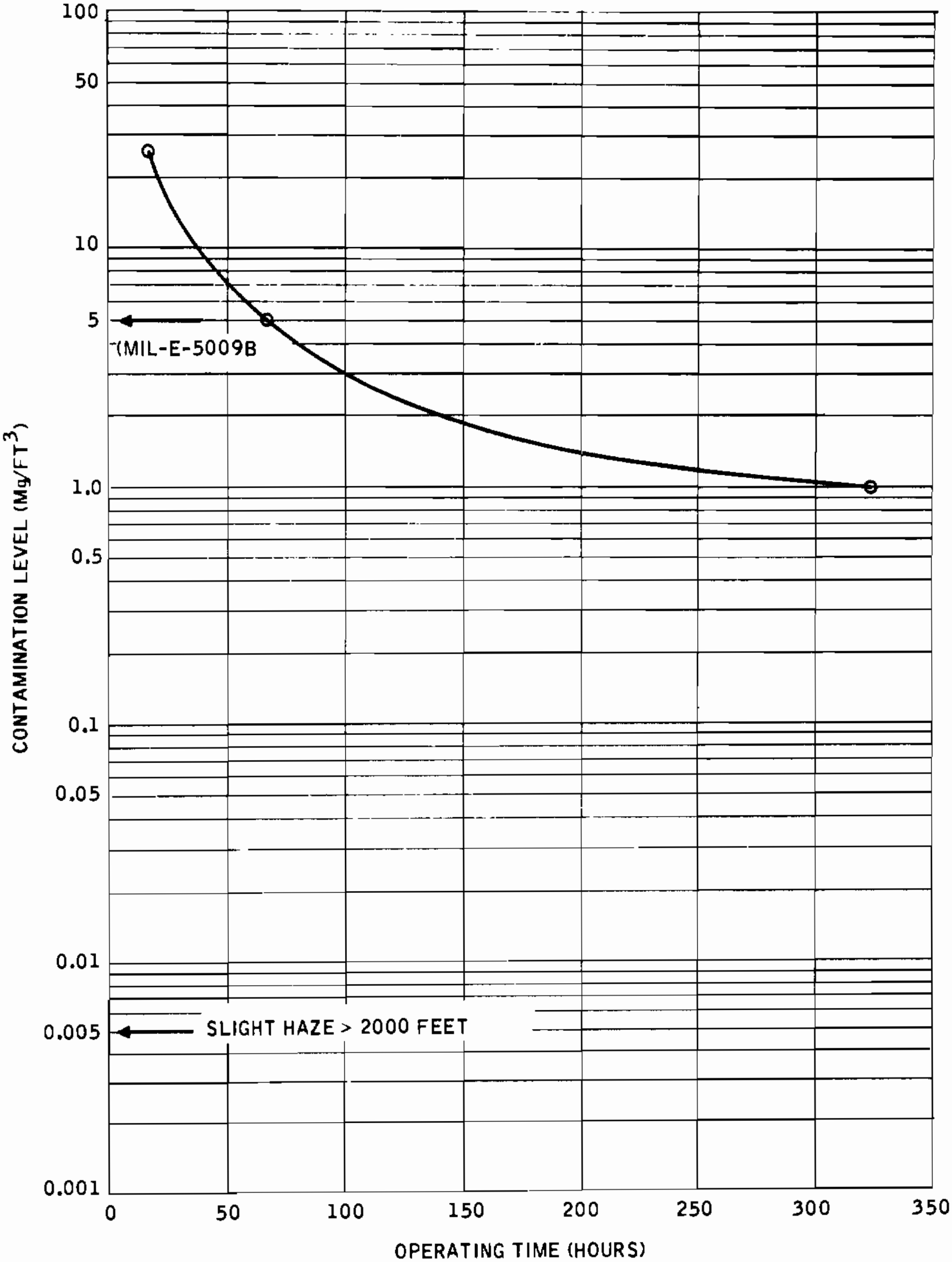


Figure 5. Contamination Test Results

Table II. Contamination Test Results and Projections

Test Sequence	Contamination Level (mg/cu ft)		Operating Time (Hours)		
	Test Value	Factor of Sequence No.1	Test Value	Factor of Sequence No.1	Calculated Value
1	25	-	16	-	-
2	5	0.2	67	4.35	69
3	1	$(0.2)^2$	306	$(4.35)^2$	303
-	0.2	$(0.2)^3$	-	$(4.35)^3$	1,320
-	0.04	$(0.2)^4$	-	$(4.35)^4$	5,850
-	0.008	$(0.2)^5$	-	$(4.35)^5$	25,000

fluidic amplifier (pressure difference sensor), pressure rate sensor, and temperature sensor. The air was supplied to the fluidic circuits by a stationary compressor located in the same ambient temperature. Supply air is not required for the temperature sensor or pressure ratio sensor since they operate directly on the pressure of the gas being measured. The pressure rate sensor, normal shock sensor, and pressure difference sensor consist of fluidic amplifiers and require a regulated supply pressure as do the angular rate sensor and accelerometer. The degree of regulation required is dependent upon the accuracy requirement of the sensor output. The specifications list the degree of pressure regulation required to attain the accuracies quoted. The sensors will operate over a wide range of supply pressures with the output levels or ranges a function of the supply pressure. A common power supply for multiple sensors is normal practice. For instance, a complete fluidic engine control system as reported in AFAPL-TR-68-31 had one pressure supply system consisting of a single regulator and filter to supply over sixty fluidic elements. The manifold, of course, must be properly designed to assure that the required supply pressure is available to all of the sensors. If a reduced pressure level is desired to an individual sensor, an orifice is placed in its supply line to drop the manifold pressure. The filtration used has been based on the contamination tests reported previously and on experience gained during development programs. A ten micron nominal filter is normally specified.

Temperature Sensor

The fluidic temperature sensor described herein is currently being developed. It is a fluidic oscillator which has a frequency of oscillation determined by the absolute temperature of the inlet gas. In operation, a submerged jet impinges on a downstream splitter, forming an edgetone frequency which is stabilized by one or more resonant cavities. The frequency of oscillation is a function of the acoustic velocity of the sample gas and the size of the tuning cavity. With the geometry fixed, the frequency of oscillation is a function only of the acoustic velocity, provided that the pressure drop across the sensor is sufficient to maintain sonic velocity through the outlet ports.

Various size sensors have been made with nominal room temperature operating frequencies from 2 KHz to 17 KHz. The operating frequency range is generally 2:1.

A typical development model fluidic temperature sensor is about 1.25 inches in diameter by two inches in length.

The frequency oscillation is a function only of the acoustic velocity,

$$C = \sqrt{kgRT}$$

where

k = adiabatic constant

g = gravitational constant

R = gas constant

T = absolute temperature °R

Since k and R are relatively constant and known for the temperatures of interest, the frequency of oscillation is

$$f = C\sqrt{T}$$

where C is a constant for operation on a particular gas.

Since the temperature sensor is basically an acoustic velocity ($\sqrt{kRT}$) sensor, there is an apparent calibration change due to operation on engine combustion products which have different k and R from laboratory air used in calibration. The gravitational constant is neglected.

Assume

$$f = K\sqrt{kRT}$$

or

$$T = \frac{Cf^2}{kR}$$

differentiating:

$$dT = \frac{2cf\ kRdf - cf^2\ (kdR + Rdk)}{k^2R^2}$$

and

$$\frac{dT}{T} = \frac{2cf\ kRdf - cf^2\ (kdR + Rdk)}{k^2R^2cf^2/kR} \quad .$$

simplifying:

$$\boxed{\frac{dT}{T} = \frac{2df}{f} - \frac{dR}{R} - \frac{dk}{k}}$$

A plot of k versus temperature is given on Figure 6 which shows the variation of k with and without combustion products over a representative temperature range. From Figure 6 at 2200R, $k|_{air} = 1.322$ and $k|_{comb} = 1.304$.

R is the gas constant, and is independent of temperature and varies by about 0.009 percent over the range of fuel air ratios of interest. Therefore, a representative calibration change for the addition of combustion products is

$$\frac{dT}{T} = -\frac{0.018}{1.322} = -1.36 \text{ percent}$$

While operating on an engine, the k will change over the operating range. For a typical turbojet engine the fuel-air ratio changes from 0.0105 to 0.0160 over the operating range. The resultant change of k is from 1.311 to 1.315 at a constant temperature. Assuming an intermediate value is chosen, then the apparent error is

$$\frac{dT}{T} = -\frac{0.002}{1.315} = \pm 0.15 \text{ percent}$$

Fluidic discrimination of the high frequency output for possible use in a fluidic circuit can presently be achieved over a relatively narrow range (about 200°F range). This is achieved by using a coupling element which extracts the acoustic signal, a resonant tube, and a fluidic amplifier whose differential pressure output is proportional to the frequency detected. Wide range discrimination of high frequency signals (>1200 Hz) has not yet been achieved fluidically.

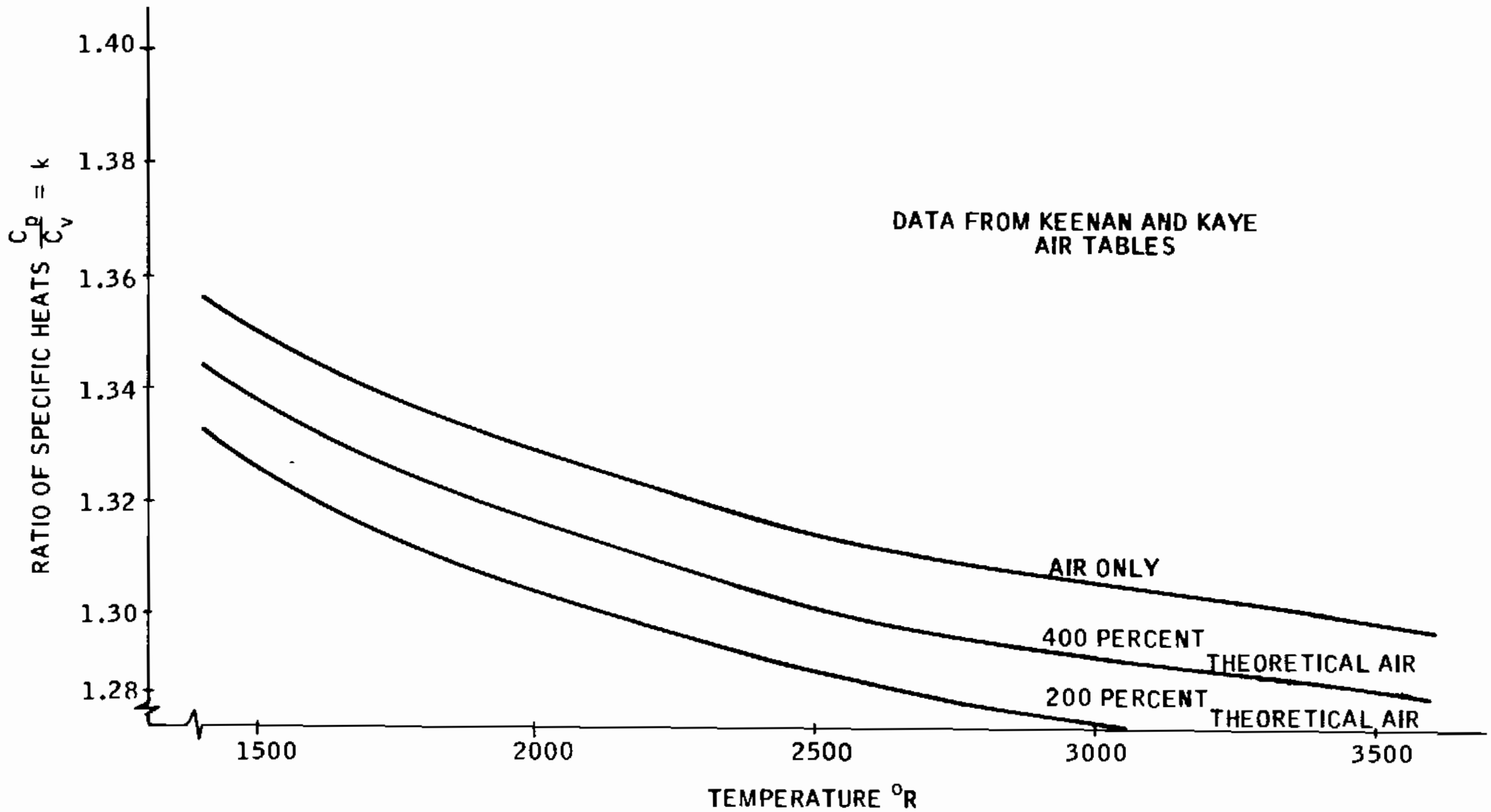


Figure 6. Ratio of Specific Heats for Various Fuel Air Ratios

A calibration curve for a typical fluidic temperature sensor is shown in Figure 7. As can be seen, the relationship between frequency and inlet gas temperature is a straight line on the log-log plot since the output frequency is a function of the square root of absolute temperature ($f = K\sqrt{T}$). Divergence of the two lines (see Figure 7) reflects an apparent pressure sensitivity caused by heat loss from the sample gas stream to the uninsulated engine boss and inlet fitting. Analyses have shown the heat loss to be relatively constant at a constant inlet temperature, but total heat input is a function of the flow rate (inlet pressures,) thus the effect of the heat loss on the output is greater at lower inlet pressure. The resulting 2.2 percent error at 2000^{o}F can be reduced by better thermal design of the gas sampling fittings. Figure 8 shows the effect of uninsulated fittings at various temperatures.

Figure 9 is a response curve of the development sensor to a step change in input temperature. The sensor output is compared to the inlet gas temperature as measured with a 5 mil instrumentation type thermocouple. These test results indicate that the transfer function of the sensor proper (less sample gas probe) is as follows:

$$\frac{T_o}{T_{in}} = \frac{0.6}{1 + 0.01S} + \frac{0.4}{1 + 10S}$$

The first time constant component represents the time required to flush the old gas from the sensor. The second component is due to the thermal inertia of the sensor and sample gas probe.

Current sensors have been made essentially insensitive to supply pressures from 5 psig to 90 psig* by employing choked converging-diverging nozzles in the outlets of the tuning cavities. Consequently, the only operating limitation on the temperature sensor is that at least a 3 psi pressure drop be maintained across the sensor to keep it oscillating. Accuracy is degraded at the very low pressures (3-5 psig) but good repeatability is experienced. The only other environmental limitations on the sensor are due to the material used in fabrication of the sensor body and the mounting to the propulsion system. Advanced sensors of ceramic materials are presently under development.

Because of the need for a temperature sensor signal which could be discriminated fluidically and a sensor that would exhibit a better dynamic response than the device just described, a dual temperature sensor was developed. The dual sensor consists of two sensors of slightly different operating frequencies and scale factor. The output signals of the two sensors are beat together and the resultant beat frequency provides the temperature information. A more complete description of the dual sensor is contained in AFAPL-TR-68-13 Part I. This lower beat frequency can be fluidically discriminated to yield a differential pressure indicative of temperature.

By proper adjustment of the dynamic response of the individual sensors it is also possible to adjust the dynamic response of the unit. The transfer function achieved is a first order lag and is presented in Appendix C. The principal disadvantage of the dual sensor is the possibility of a large steady-state error if contamination or geometry changes cause a small shift in operating frequency of one of the individual sensors. Sensors have been used to measure turbine inlet temperature on different engines for several hundred hours with no sign of contamination sensitivity.

*90 psig is not a limit but is the highest test pressure to date.

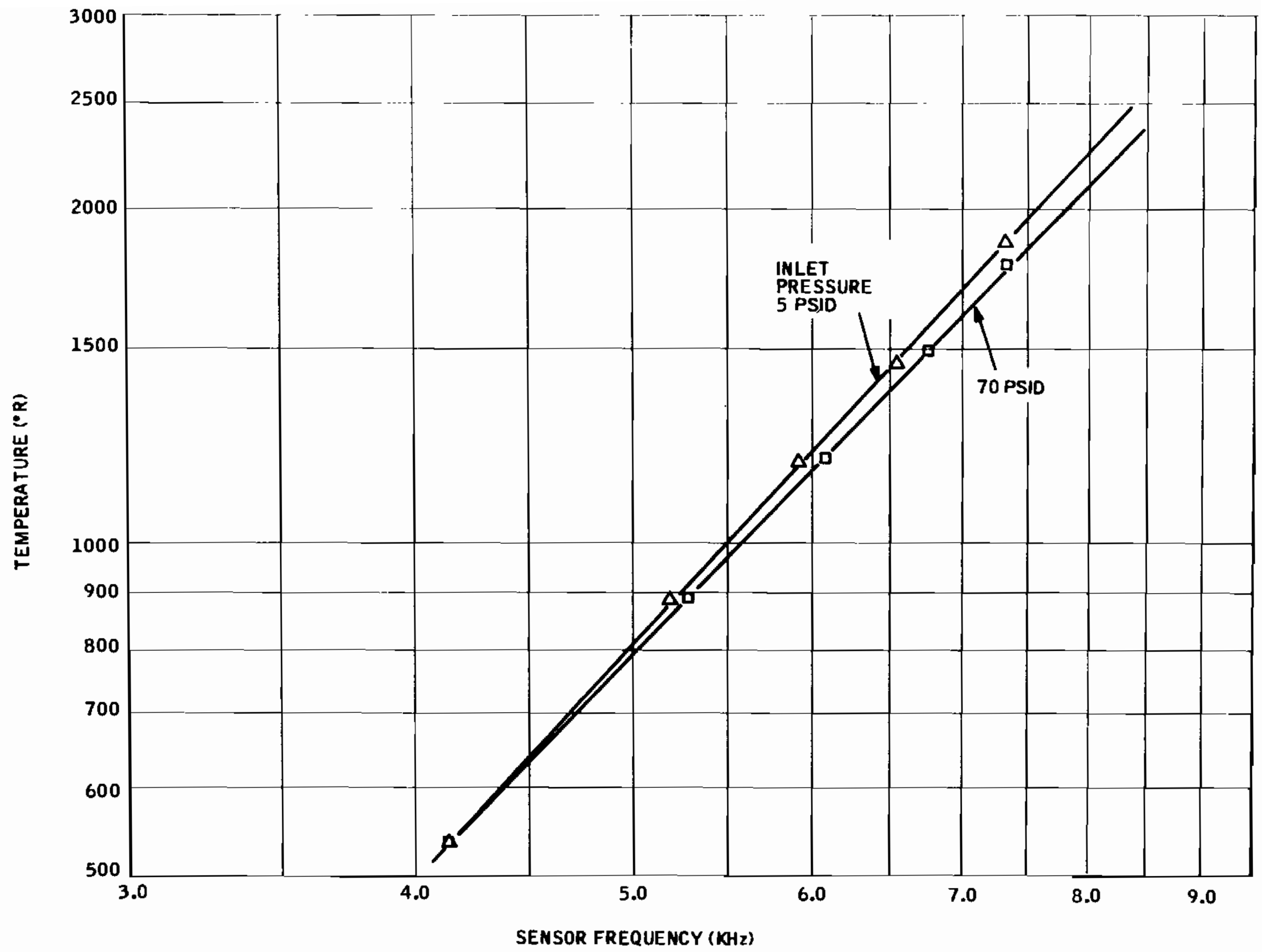


Figure 7. Temperature Calibration Curve

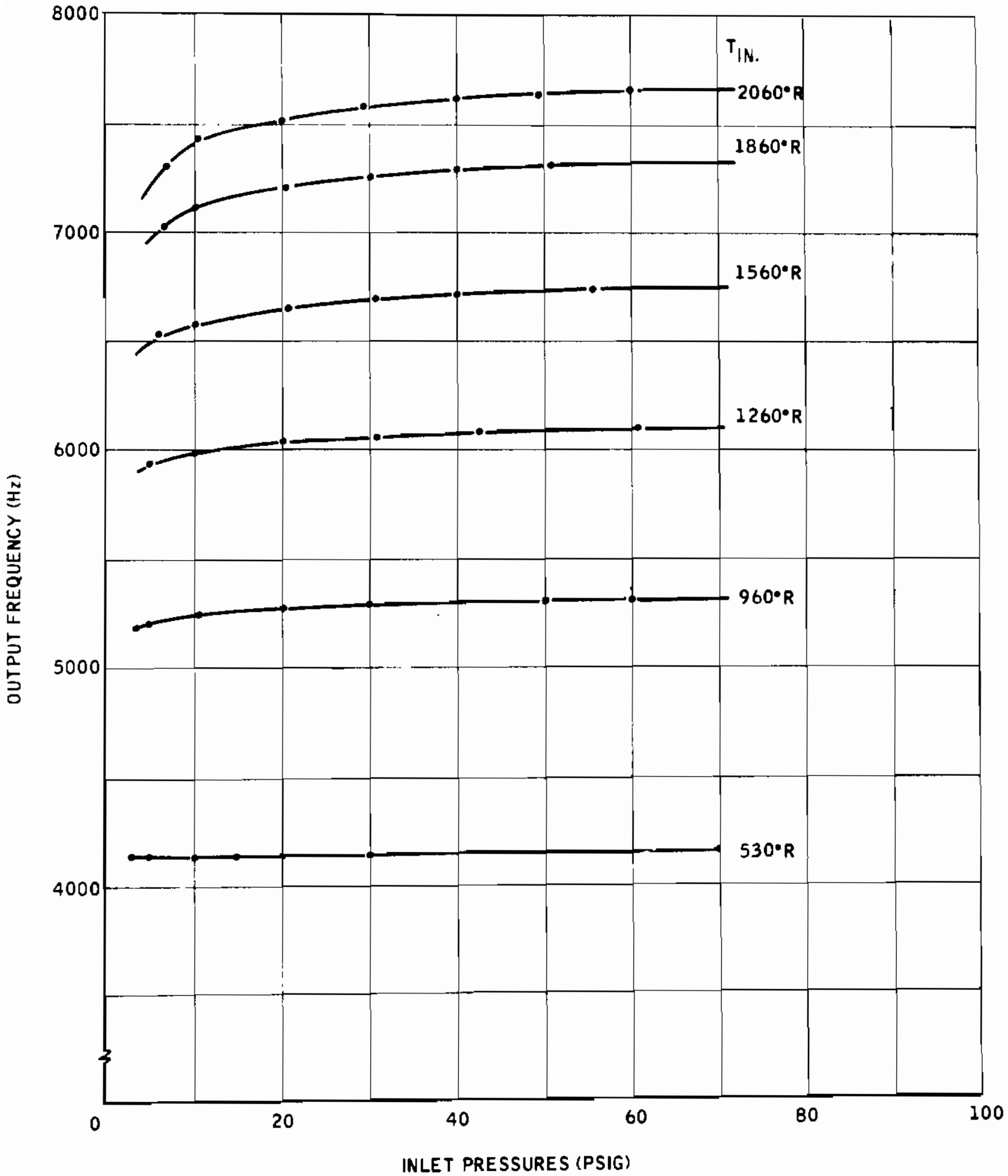


Figure 8. Heat Transfer Effects on Indicated Pressure Sensitivity due to Uninsulated Gas Sampling Fittings

For most applications to date the temperature sensor has been mounted directly on the end of a probe that extracts the gas sample from the hot gas being measured. The sensor should be mounted as close to the source as possible to minimize any apparent pressure sensitivity and thermal lag due to heat transfer effects that occur when transmitting the gas sample through a length of tubing. In some specific applications it is possible that the sensor could be inside a probe inserted in the gas stream or in a stator blade.

The frequency output of the temperature sensor is a pressure oscillation. This signal must be converted to some other form to be useful in a control system. Transducers have been developed to convert this signal to an electrical signal and/or a pneumatic pressure signal. Capacitative, inductive, and piezoelectric type pickoffs have been used to obtain the electrical signal. The resulting electrical frequency pulses are converted to a d-c voltage proportional to temperature in an electronic signal conditioner. Compensation to improve dynamic response can also be built in this package. This compensation is generally a simple lead-lag circuit of the form $(1 + A\tau s)/(1 + \tau s)$, and makes the sensor transfer function appear to be a first order lag, $1/(1 + \tau s)$.

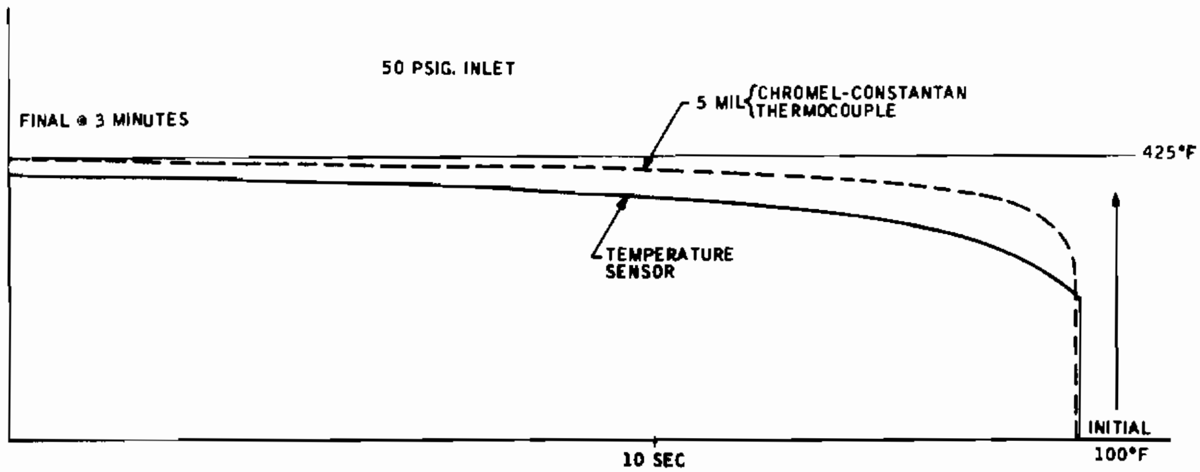


Figure 9. Recorder Trace of Temperature Sensor Response

Pressure Ratio Sensor

The fluidic pressure ratio sensors are similar in design and operating principles to thc fluidic temperature sensor described previously. A block diagram of the pressure ratio sensor is shown in Figure 10. The frequency of oscillation is a function of the ratio of the supply pressure to the reference or exhaust pressure. However, the device is sensitive to the temperature of the supply gas and compensation must be provided. This can be accomplished with either a temperature measuring device to correct the sensed frequency or with a fluidic amplifier discriminator which is designed to vary the gain at different temperature levels.

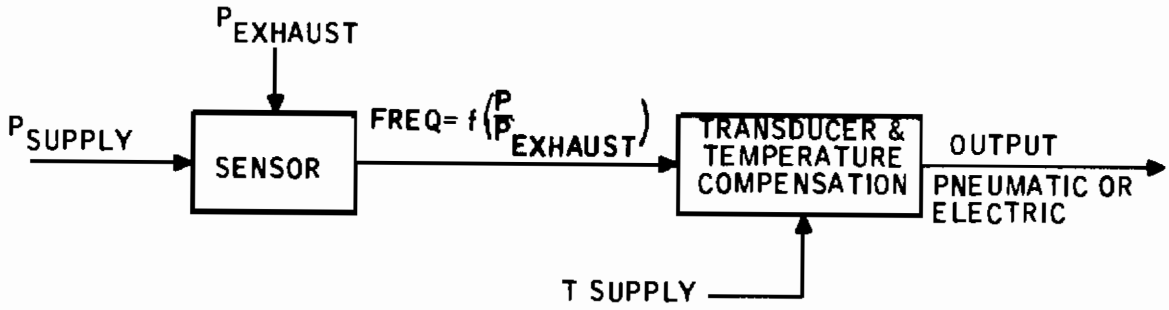


Figure 10. Fluidic Pressure Ratio Block Diagram

Two pressure ratio sensing devices which cover different ranges have been considered and are currently being developed - one an intermediate range device (1.3 to 2.5 PR) and the other a low range device (1.03 to 1.40 PR). The working model of the intermediate range device is shown in Figure 32, Appendix C. This model has a pneumatic to electric transducer mounted on it for evaluation purposes. A transducer will be neccssary for control system purposes to convert the high frequency acoustic signal to either voltage or to a pressure.

Temperature sensitivity in the intermediate range device is relatively large and compcnsation is necessary to correct for it. The sensitivity amounts to about 300 Hz per 100°F. A typical calibration curve for the sensor is shown on Figure 11.

Supply air temperature is measured with a resistance thermometer and the necessary corrections can be computed electronically. The pressure ratio sensor is surrounded with air at supply temperature in the case as shown on Figure 32, Appendix C, and maintained at exhaust pressure. The temperature sensitivity correction is a fairly complex electronic mechanization which could be accomplished in a number of ways and is considered part of the readout hardware. Therefore, no discussion of the correction circuit is included here. The possibility of using a fluidic frequency discriminator with built-in temperature compensation is also a possibility but has not been attempted at this time. The dynamics of the pressure ratio sensor - temperature compensator are unknown. The pressure ratio sensor is assumed to be a first order lag since it is similar to the temperature sensor.

The low range sensor is being developed as a duct Mach sensor for use in either a supersonic inlet control or a turbofan bypass ratio control. The range of this device is satisfactory for the present application, but for advanced propulsion systems very low pressure ratios and extreme accuracies appear necessary.

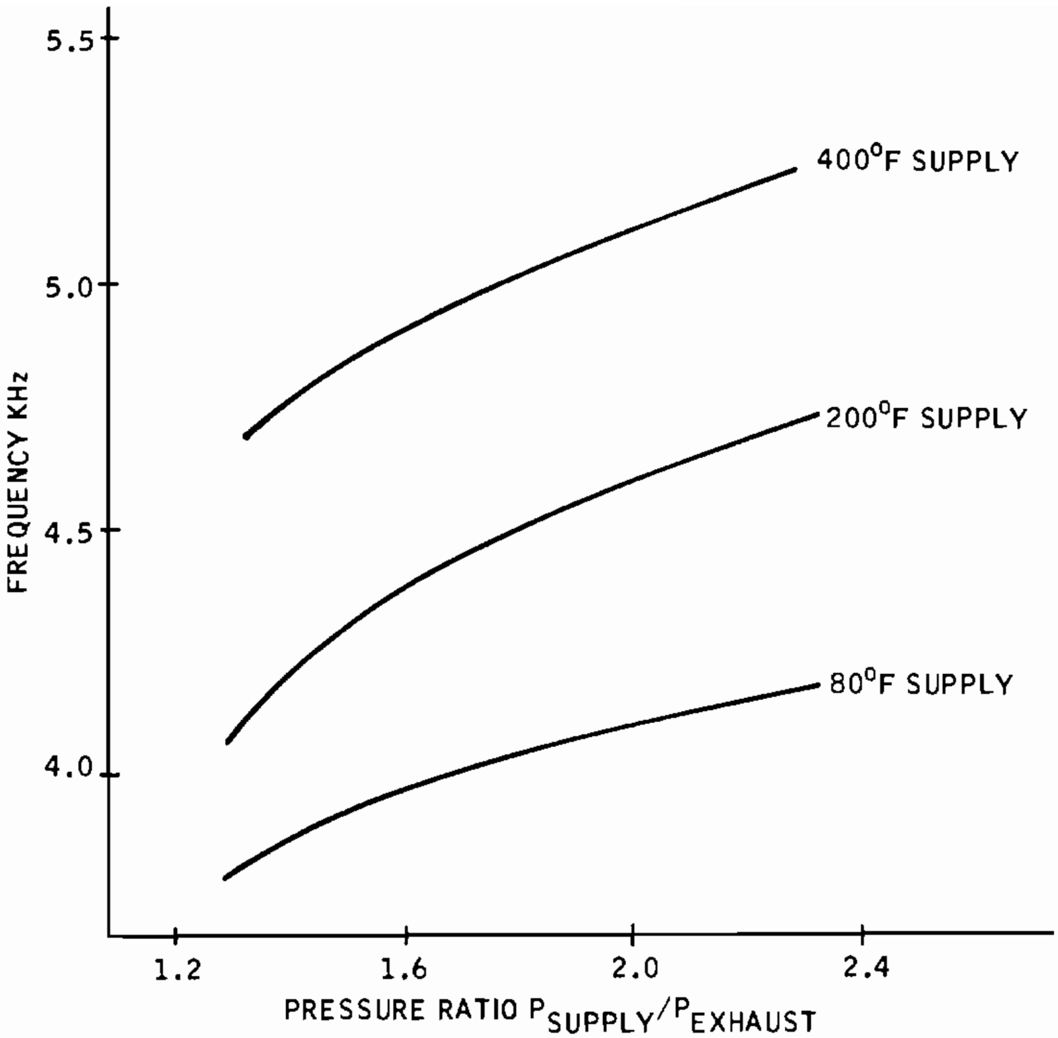


Figure 11. Intermediate Range Pressure Ratio Sensor Typical Calibration Curves

Compressor face Mach numbers down to 0.1 (1.007 PR) and accuracy requirements of better than 0.1 percent will likely be required. It is not known whether or not a sensor of this accuracy can even be built to operate at a pressure ratio of 1.007 except for laboratory or special type test instrumentation. These accuracy and range requirements presented are estimates based on incomplete information concerning supersonic propulsion systems.

Figure 12 shows a conceptual drawing with the sensor mounted in a pitot static probe. This assembly also incorporates a fluidic amplifier to transduce the acoustic signal to a differential pressure which is a function of pressure ratio.

The dynamics of this sensor-transducer combination are unknown. Preliminary tests indicate that the temperature error is very small due to built-in compensation from the fluidic amplifier frequency discriminator-transducer.

The use of a pitot-static probe as a flow through device has been investigated at Arnold Engineering Development Center and is reported in AEDC-TR-66-28. This report indicates that in the Mach number ranges intended for this device the error in measured pressure caused by flowing air through the probe is negligible.

Preliminary data on a breadboard model of the low range fluidic pressure ratio sensor is shown in Figure 13. This indicates a useful range of 1.06 to 1.20 pressure ratio units (Mach No. 0.29 to 0.52). This range, however, is adjustable within the range of 1.03 to 1.39 pressure ratio units (Mach No. 0.21 to 0.70). Further development will permit adjustment beyond this range. The accuracies determined from the preliminary data are ±1 percent with ±0.5 percent the goal of the current program.

Pressure Rate Sensor

The simplest form of a fluidic pressure rate sensor consists of a proportional amplifier with the same steady-state pressure supplied to each control port. The signal to one of the ports is "lagged" with a pneumatic RC network as shown in Figure 33, Appendix C. This creates a differential output pressure proportional to the rate of change of the pressure signal.

Since it is a dynamic element, no steady-state data is applicable. Actually the device is a high-pass unit, in that it will pass high frequency signals and will not react to slow or steady-state signals. The time constant for the device is variable depending on the size of the RC lag. Figure 34, Appendix C, shows the effect of volume and orifice area on the time constant. However, as with any fluidic amplifier ambient conditions will affect the gain of the device. The magnitude of this error depends on the amplifier design and installation configuration. Typical data for the device is shown in Appendix C.

Normal Shock Sensor

DESCRIPTION -- The position of the normal shock wave in a supersonic inlet is strongly influenced by external disturbances caused by aircraft maneuvers or internal disturbances generated by engine transients.

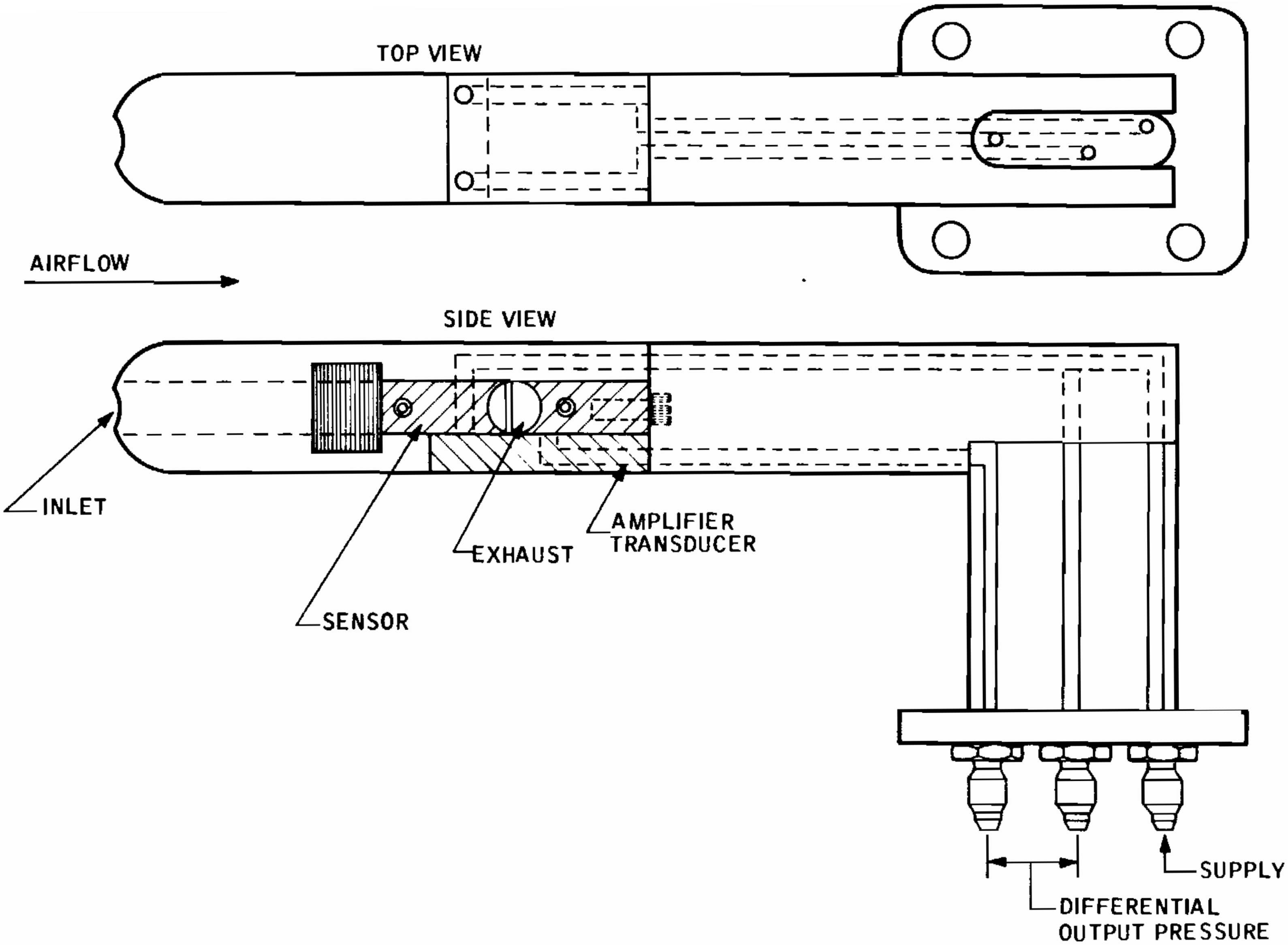


Figure 12. Low Range Fluidic Pressure Ratio Sensor

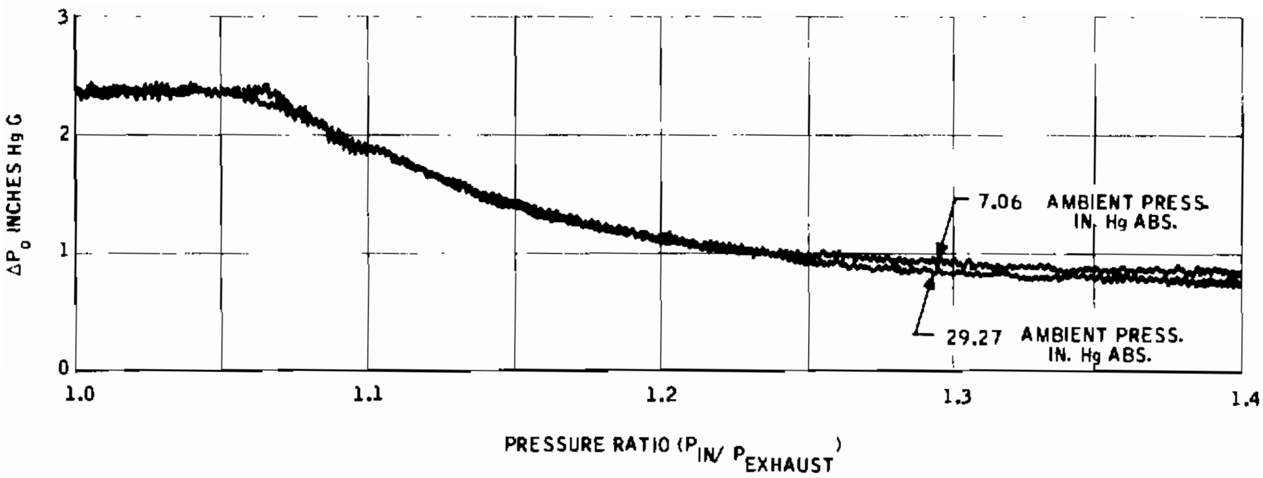


Figure 13. Preliminary Pressure Ratio Sensor Test Results

Honeywell has developed a fluidic terminal shock sensor that directly measures the shock wave location by reacting to the static pressure gradient across it. The terminal shock sensor consists of a multiplicity of bistable (flip-flop) fluidic elements. The control signals to the sensor are obtained from the static pressures along the duct wall where shock control is required. Output of the sensor depends on the position of the shock wave. To better understand its concept, assume initially that a shock wave is at position A (Figure 14). Because the static pressure is decreasing along the duct wall, all amplifiers are in the vent position. Each is experiencing the same differential control pressure direction.

As the shock moves forward to position B a high pressure from tap 1 is transmitted to the end amplifier control port, and the amplifier flow switches to the opposite output port. The flow from this port is fed into a manifold and, because of the mass flow increase, the pressure in the manifold is increased.

The shock moving to position C causes the last two amplifiers to switch and two flows are fed to the manifold, further increasing the pressure. This logic is continued as the shock moves forward and the reverse is true as the shock moves downstream. Effectively all amplifiers behind the shock wave are tripped to the manifold port while those in front are tripped to the vent port. A graph of the manifold pressure output versus amplifiers tripped is shown in Figure 15.

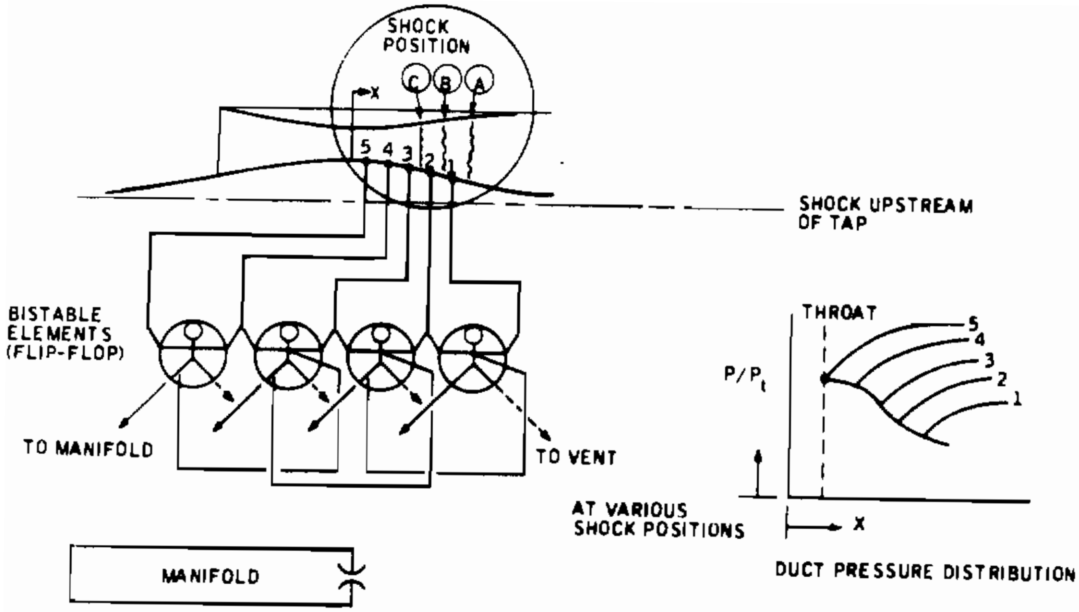


Figure 14. Schematic of Shock Sensor

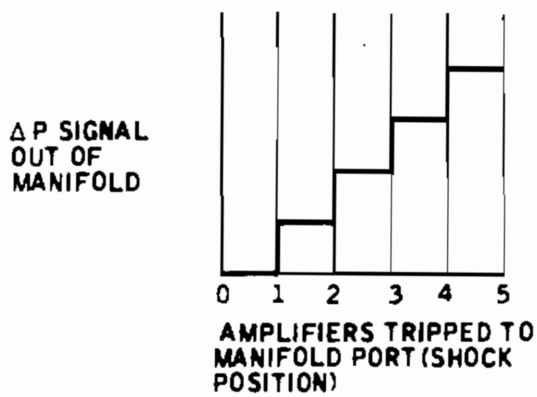


Figure 15. Shock Sensor Control Logic

Note that a feedback system between the various elements has been incorporated. The reason for this is to assure that, when two or more amplifiers are tripped and both control ports of the amplifiers downstream of the shock have about equal pressures, small perturbations existing in the duct will not trip amplifiers behind the shock and cause the sensor logic to err. The feedback network transmits a signal from the manifold leg of the last tripped amplifier to the preceding amplifier and, from that amplifier, successively aft to the last amplifier assuring that all elements behind the shock wave remain tripped. The effect of one amplifier failing due to the contamination would cause an error in the output signal of about 1/n where n is the number of amplifiers in the sensor. The rest of the amplifiers would continue to operate and the shock sensor would continue to function with a small error.

WIND TUNNEL EVALUATION -- Prototype sensors have been packaged and tested in a small induction wind tunnel test facility to determine their characteristics. Wind tunnel tests consisted of (1) investigating the sensors ability to sense a shock wave in a divergent duct and (2) measuring the response characteristics of the device. The results of these tests are depicted in the phase shift-frequency plots shown on Figure 16 and in the tabulations in Appendix C. The sensor was mounted close to the duct so that line lengths were on the order of 8 inches or less.

Tests were also conducted to establish sensor operation at reduced pressure levels by throttling the nozzle incoming air flow. During these tests the incoming nozzle total pressure was reduced to Mach 2.5, 80,000 foot conditions and satisfactory operation was obtained. Mach 2.5 sea level operation has not yet been simulated. Other tests have indicated that this shock sensing system can be powered without stringent pressure regulating requirements.

The normal shock sensor was recently evaluated in a Mach 3 inlet model at the NASA/Ames wind tunnel facility. The model was an external-internal compression inlet which had a swallowed terminal shock wave within the inlet. The objective of the NASA tests was to determine the performance of the model while varying the inlet geometry.

Sensor installation and performance observation was a courtesy provided by NASA for Honeywell personnel present during the tests in conjunction with another program sponsored by the Air Force Aero Propulsion Laboratory.

The objective of the shock sensor tests was to demonstrate the operation of the sensor in an actual inlet at free stream Mach numbers of 3.0, 3.25, and 3.5. The installation of the sensor in the inlet is shown on Figure 13. Sensor data were obtained at various angles of attack for free stream Mach numbers of 3.0, 3.25, and 3.5. At M 3.5 and 3.25 the angle of attack was varied from zero to eight degrees with intermediate steps at two degrees and five degrees. At Mach equal to 3.0 data at zero and two degrees were obtained. Results of these tests showed that the sensor functioned properly and provided five discrete output signals as the shock position was changed at zero degrees and two degrees angle of attack at each of the Mach numbers. When the angle of attack was elevated to five degrees only two amplifiers in the five amplifier cascade were actuated. At eight degrees there was no indication at all. The

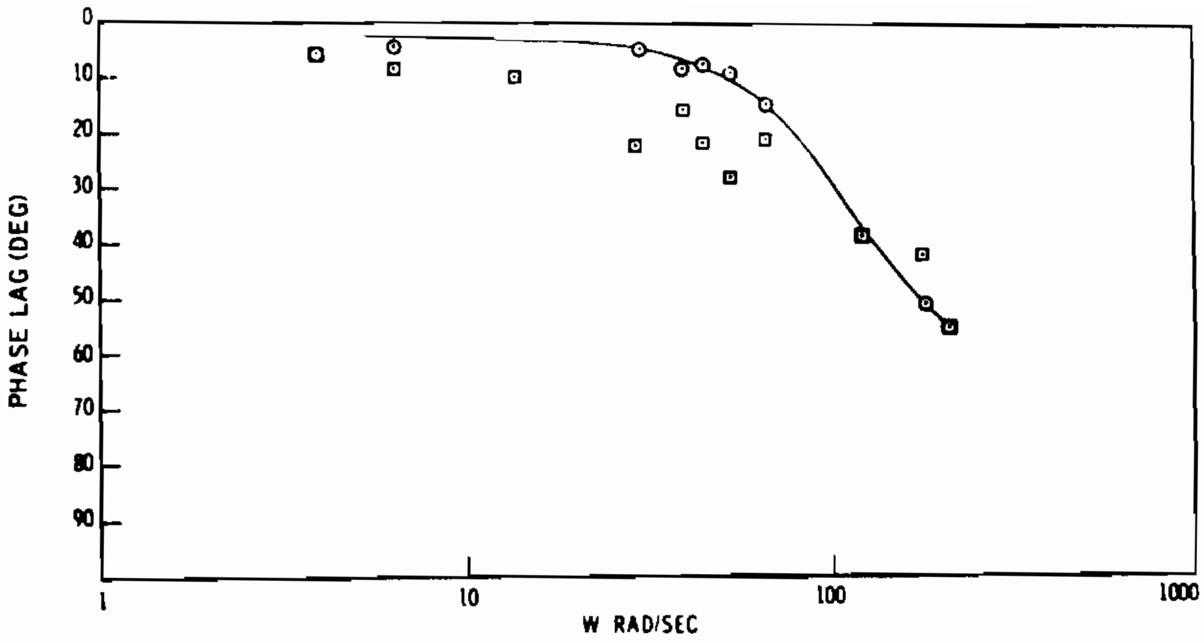


Figure 16. Sensor Response Characteristics

reason for this was that the taps were mounted on top of the model and the angle of rotation was into the tap location. Had a shock sensor been mounted at both the zero degree position and the 180-degree position, more indications would have been obtained at five degrees and also eight degrees.

Recently two additional separate wind tunnel tests on Mach 2+ inlet models were completed with a fluidic shock sensor installed on the model. The five element shock sensor was not part of any control system configuration, but was installed in the inlet duct throat for evaluation as a shock position sensor. In both tests (the inlet was different in each case) the shock was not well defined but the sensor did react to the static pressure gradients which existed. In some cases the shock covered more than one pressure tap so that amplifiers would trip two at a time. In other cases, the shock movement was very large for small airflow changes and several or all amplifiers would trip with one airflow change. Static pressure measurements from taps near the sensor taps indicate that the sensor will react to pressure differences of between 2 and 3 in. Hg. On several occasions inlet unstart and buzz were encountered. Buzz frequencies from 5 to 46 Hz were detected by the fluidic shock sensor, this agreed with that sensed by dynamic instrumentation associated with the model. The tests were run at free stream Mach numbers ranging from 1.6 to 2.4 over a wide range of angles of attack, yaw, and pitch. Both ducts were two dimensional and tap location was proper for almost all altitudes so that shock movement was detected with the sensor.

This sensor is a simple, rapid response device which can operate in hostile environments. If constructed of cement or ceramics, the sensor would not require

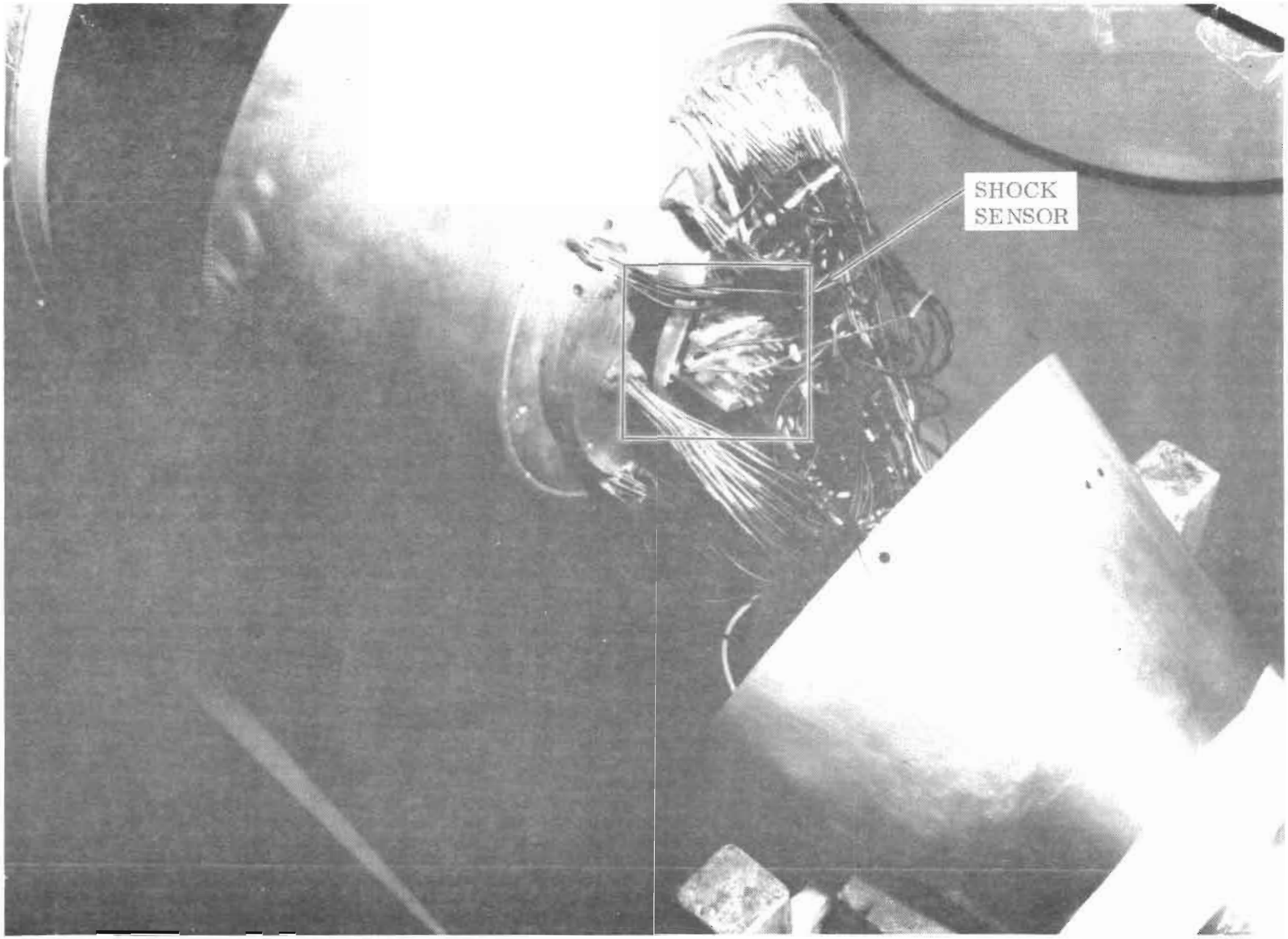


Figure 17. Shock Sensor Installed in NASA/Ames Mach 3 Inlet Model

any special cooling at extreme temperatures (1500°F-3000°F). Its response characteristics are faster than any other conventional method of measuring a swallowed shock wave such as measuring compressor face Mach number.

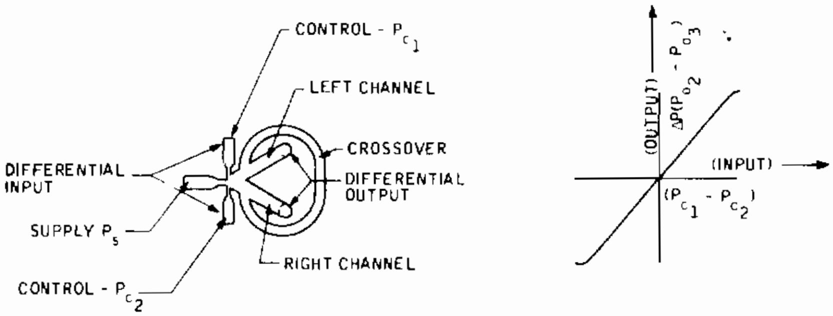
Pressure Difference Sensor

A fluidic amplifier can be employed as a pressure difference sensor. Such a sensor utilizes no moving parts, and is easily fabricated. It is capable of operation at extreme temperatures, in nuclear radiation, or in areas of severe vibration, without adverse effect on its performance as shown in the specifications, Appendix C.

A typical beam deflection proportional amplifier is shown schematically in Figure 18. The amplifier consists of (a) a power or supply nozzle which produces a jet; (b) control ports which furnish flow to deflect the power jet; and (c) receiver or output ports which collect the jet.

The input signal to the amplifier is the difference in flows or pressures present at the two control ports. The output signal is the difference in flows or pressures at the receiver ports and is proportional to the input differential. Figure 18 shows a typical input-output characteristic of a proportional amplifier. The ratio of output differential to input differential ($\partial \Delta Po / \partial \Delta Pc$) is called the gain of the amplifier and is represented by the slope of the input-output characteristic. Typically gains on the order of 2 are generally employed. This fluidic device is the backbone of any fluidic control system. It is usually made as a summing amplifier. A summing amplifier is an element having more than one set of control ports. The output of this device is an amplified replica of the algebraic sums of the individual inputs. Two and sometimes three sets of input ports can be accommodated in the basic amplifier configuration. The addition of more than two sets of ports presents problems due to space limitations in the interaction region and the need for isolation between the sets of control ports. Where additional summing inputs are needed, combinations of two or more summing amplifiers can be used.

Performance parameters such as gain, signal to noise ratio and linearity are affected by variations in supply and ambient pressures and supply air temperatures.



- CROSSOVER EQUALIZES PRESSURES ON THE SIDES OF THE STREAM, AND HENCE PREVENTS THE STREAM FROM LOCKING ONTO EITHER WALL
- STREAM IS DEFLECTED AT AN ANGLE PROPORTIONAL TO THE CONTROL PRESSURE DIFFERENTIAL
- DEFLECTION CAUSES DIFFERENTIAL FLOW AND DIFFERENTIAL PRESSURE IN OUTPUT CHANNELS
- OUTPUT DIFFERENTIALS ARE PROPORTIONAL TO CONTROL DIFFERENTIALS

Figure 18. Proportional Fluid Amplifier Schematic

These effects can also be biased by amplifier configurations but for this sensing application, only one configuration is being considered — an amplifier with a 0.020 inch x 0.020 inch power supply throat. The gain variation with supply air temperature and altitude is shown in Appendix C. Gain variations with increasing supply pressure are also shown in Appendix C. This amplifier is well suited for use as a sensor due to its relatively constant gain characteristics over a wide range of supply pressures.

Linear range and output noise are shown as a function of supply pressure in Appendix C, Figure 39. Noise generally decreases with temperature and altitude and the linear range is not seriously affected. For the application considered here a supply pressure of 5.0 ±0.25 psig with 10 micron nominal filtration are recommended. Effects of contamination have been discussed earlier in this document as well as pressure regulation. Complete specifications are contained in Appendix C.

Fluidic amplifiers are made of plastics, metals, or ceramics and are generally machined, molded, etched, or electroformed. The materials and fabrication techniques used for a specific amplifier depend upon the application and environment expected. For application up to 1200°F, electroforming of nickel over a wax mandrel has resulted in the least expensive, most reliable and repeatable method of producing amplifiers. An electroformed fluid amplifier which has been operated at 1200°F is shown in Figure 19. Honeywell has produced many of these fluidic amplifiers over the past several years for use in Honeywell fluidic control systems, but not for sale as components.

Angular Rate Sensor

The vortex rate sensor is a pure fluid device that senses angular velocity about its input axis and provides a pressure signal which is proportional to that velocity. There are no moving parts within the device and it employs a pattern of fluid flow to sense angular rotation. This pattern of flowing fluid is contained within a cylindrical chamber, and is made up of two superimposed flow fields: A "sink" flow field, as shown in Figure 20(a), where the streamlines are radial and the flow path is straight to the center output; and superimposed upon that a rate-imposed tangential flow with a resulting vortex pattern as shown in Figure 20(b). In the resulting superimposed flow pattern, the streamlines assume a logarithmic spiral as they flow towards the center outlet. This same flow pattern continues into the outlet tube. A pickoff which is sensitive only to the tangential velocity component of the flow is placed in the outlet tube. In the absence of any case rotation, the flow through the outlet tube is straight and the differential pressure signal is zero. However, with turning rates applied to the case, the stream flows over the pickoff at an angle which is proportional to the turning rate. The differential pressure generated at the pickoff is a direct function of the flow angle, thus the turning rate.

In most rate sensor applications the important performance characteristics are sensitivity, accuracy, and response time. How good these characteristics are depends upon several parameters, the most important being the dimensions of the vortex chamber and the flow rate through it. A tradeoff is generally necessary between size and power (flow rate) to obtain the best compromise between accuracy and response. The device responds as a second order system. The tradeoffs between the parameters of flow rate and size are determined by the application.

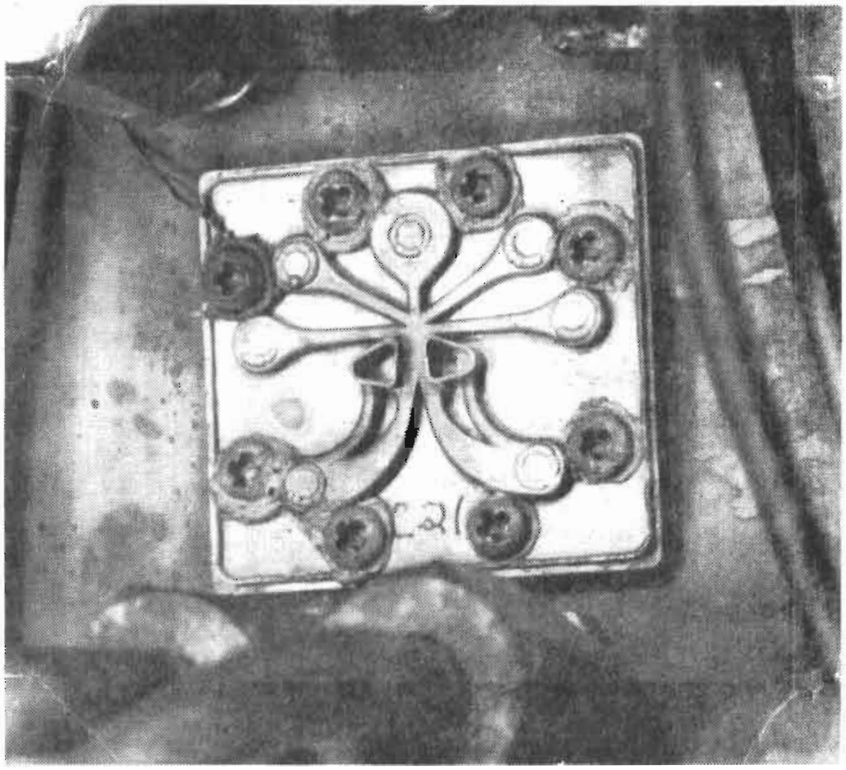


Figure 19. Electroformed Fluid Amplifier

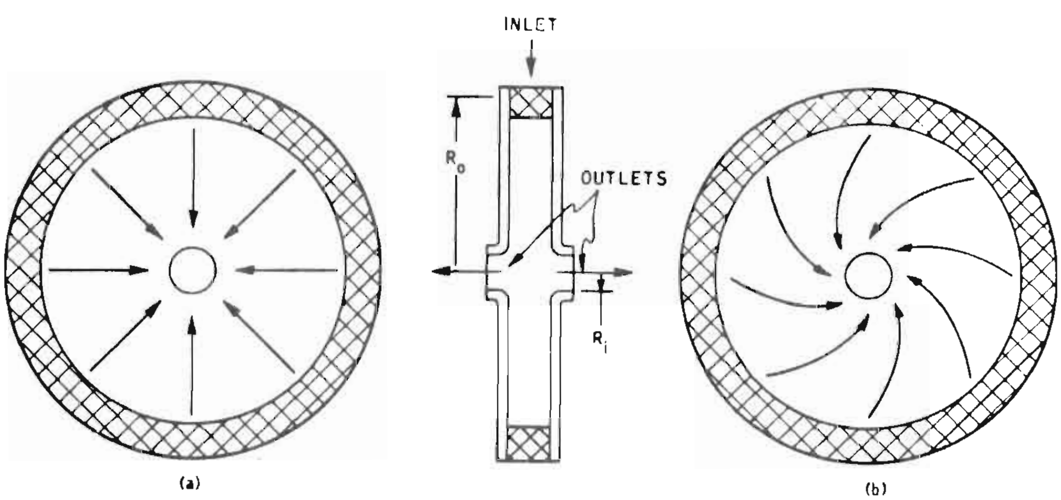


Figure 20. Fluidic Angular Rate Sensor Flow Fields

Effects of altitude, temperature and supply pressure are shown in Appendix C. The change in time response with temperature is also shown in Appendix C. This response is not seriously affected by altitude or supply pressure.

The specification in Appendix C lists typical performance data for a vortex rate sensor that could be used in conjunction with a flow distortion accommodation system. These data are from laboratory developmental testing and include predicted data from experience on similar devices where the specific test data are not available.

A rate sensor with a fluidic amplifier mounted on it is shown in Figure 21. This device has a cylindrical disc configuration with its sensitive axis parallel to the flat surface. A description of the device and its use as a rate sensor for stability control is given in AFAPL-TR-68-31.

Accelerometer

The fluidic accelerometer shown schematically in Figure 22 has a pneumatically supported inertial mass which operates against pressurized nozzles. The damping is accomplished by the squeeze film method provided by the flanges on the inertial mass.

The force developed by an acceleration on the unit's inertial mass, along the sensitive axis, is opposed by the pressure differential created by the closing of one of the pickoff nozzles and the opening of the other nozzle. The pressure differential is an accurate representation of the applied acceleration.

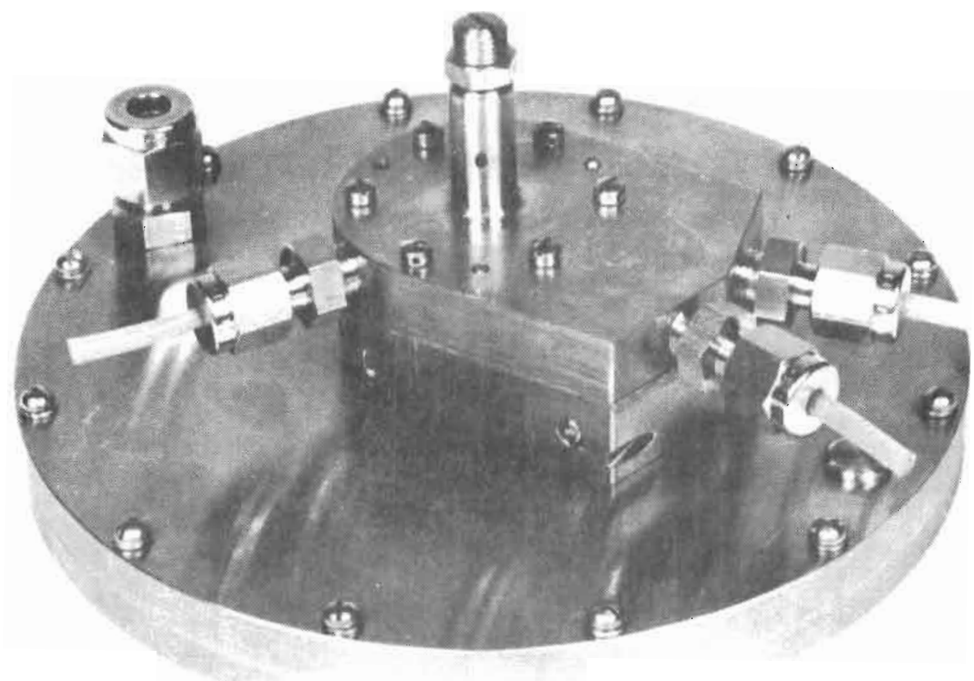


Figure 21. Typical Vortex Rate Sensor With Fluid Amplifier

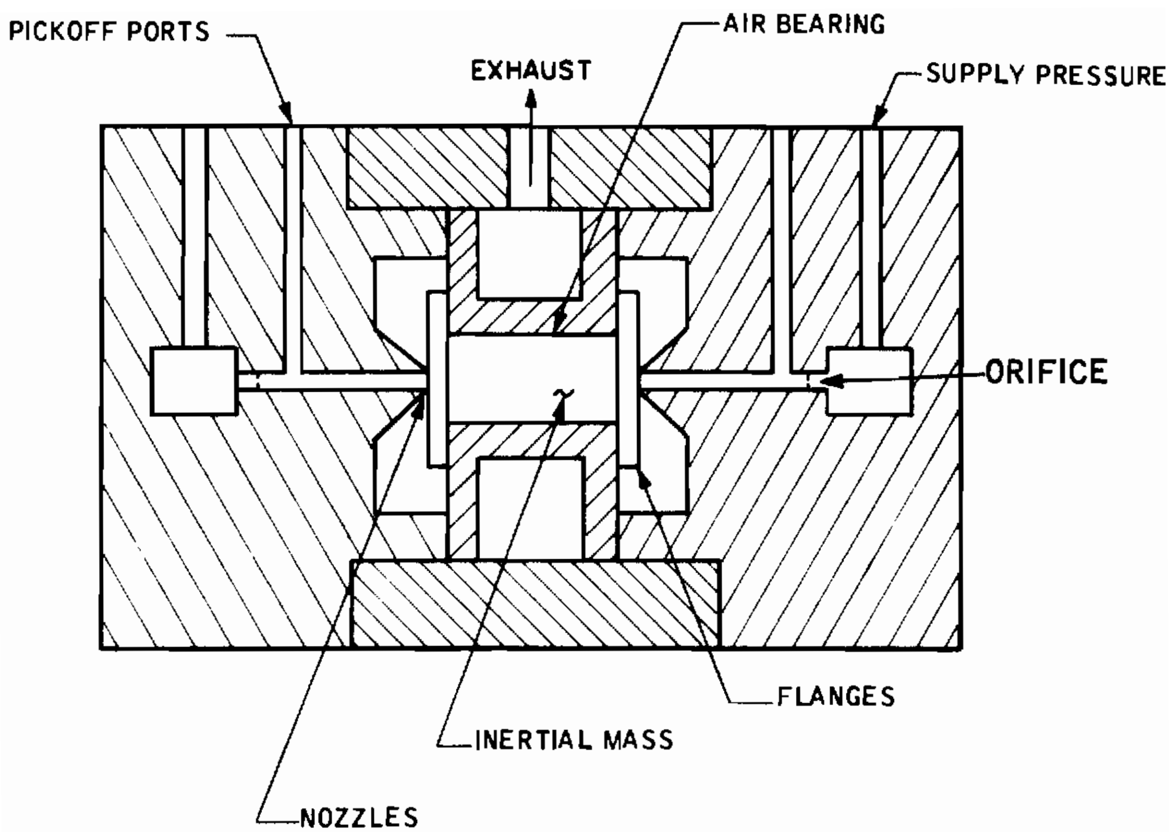


Figure 22. Fluidic Accelerometer

The rapid movement of the inertial mass is reduced by the flanges on the mass. The gas must be squeezed out between the flange and the housing before the mass can move very far. This is analogous to a sheet of plywood falling to the floor by pivoting around an edge already on the floor.

Again, as with the rate sensor, the device responds as a second order system. The performance data shown in Appendix C are from laboratory developmental testing and predicted performance from experience with similar devices where the specific test data are not available.

EXTRAPOLATED SENSOR CAPABILITIES

The fluidic sensors previously described were further studied to determine the performance levels which can be reasonably attained with further development. These extrapolated data are included in a separate column in the specification sheets in Appendix C for easy comparison with the current performance levels. The extrapolated data does not include entries for all of the characteristics listed, but only those which are pertinent to sensor performance. The data listed is typical or general in nature, but if specific requirements for a sensor are known, tradeoffs can be made to achieve the desired characteristics.

In addition to these sensors, concepts for several other sensors that may be applicable have been explored. These include a temperature sensor, flow distortion sensor and fluidic angle of attack sensor. Since these sensors are still in the conceptual stage it is not practical to write a specification, but the concepts are worthy of further consideration.

Temperature Sensor

The fluidic oscillator temperature sensor needs further development to extend the range to higher temperatures, to reduce the required pressure drop across the sensor, and to improve the dynamic response. Investigations into these problem areas are being conducted during current programs. The extent to which these performance parameters must be extended depends upon the specific application and requirements.

The high temperature to which the temperature sensor is limited is due only to the material used to fabricate the sensor. The basic phenomena which provides the intelligence is not limited by temperature. Materials such as KT silicon carbide are being evaluated up to 3200°F. Fabrication techniques to produce the configurations required for temperature sensors from the high temperature materials require further development.

The apparent pressure sensitivity at the high temperature, low pressure drop conditions can probably be improved by small geometric changes in the sensor and/or surrounding the sensor with the hot gas being measured. Such techniques have been tried and have resulted in improved performance at the expense of higher flow requirements.

The dynamic response of the temperature sensor has been improved by using dual sensor techniques. While this has improved the dynamics of the sensor, the steady state accuracy of the sensor tends to be degraded. These tradeoffs require further study. Improvement in the dynamics of a single sensor can be achieved by also surrounding the sensor with the gas being measured which reduces the second time constant.

A new temperature sensing concept which is based on the temperature dependence of viscosity is presently being explored. Since the device is still in the research stage no specifications are available, but the concept is worthy of consideration due to its inherent ruggedness and simplicity. The operation of the device relies on the principle that the pressure drop across a laminar-flow element depends only on the temperature of the gas flowing through it providing that the flow rate through the device is a function of temperature only.

Figure 23 shows a schematic diagram of a capillary type temperature sensor utilizing a proportional fluidic amplifier to detect the differential pressure created by the laminar flow element. The function of the exhaust nozzle is to maintain choked flow (flow rate function of temperature only) at the exit downstream of the laminar element over a wide range of inlet pressures. Under these conditions

$$\Delta P \propto \mu \sqrt{T}$$

where μ, the viscosity of air, is approximately proportional to $T^{0.7}$.

Then,

$$\Delta P \propto T^{1.2}$$

and is independent of pressure.

There are, however, second order pressure effects on sensor performance which are presently being analyzed. These effects must be minimized or compensated for before the device can be considered useful. Also it should be realized that this sensor will be somewhat slower in response than the oscillator described previously. However, the output signal is a differential pressure rather than a frequency which makes it more directly applicable to a control system without using complex transducing or frequency discrimination techniques.

Pressure Ratio Sensor

The electromechanical pressure ratio computer-transmitter (LG80) is a relatively slow-response device. Conceptual studies and preliminary investigations have produced a hybrid fluidic-electromechanical device which appears to have faster response. A pneumatic position pick-off, fluidic amplifiers and pneumatic motor can replace their electrical counterparts to provide a higher natural frequency and faster slew rate.

The fluidic pressure ratio sensor requires improved accuracy and lower pressure ratio sensitivity than is currently being achieved. Both of these improvements appear feasible through further development on the present configuration. Recent accomplishments during the present development program on the low range pressure ratio sensor have shown that the same basic oscillator can be used up into the range of

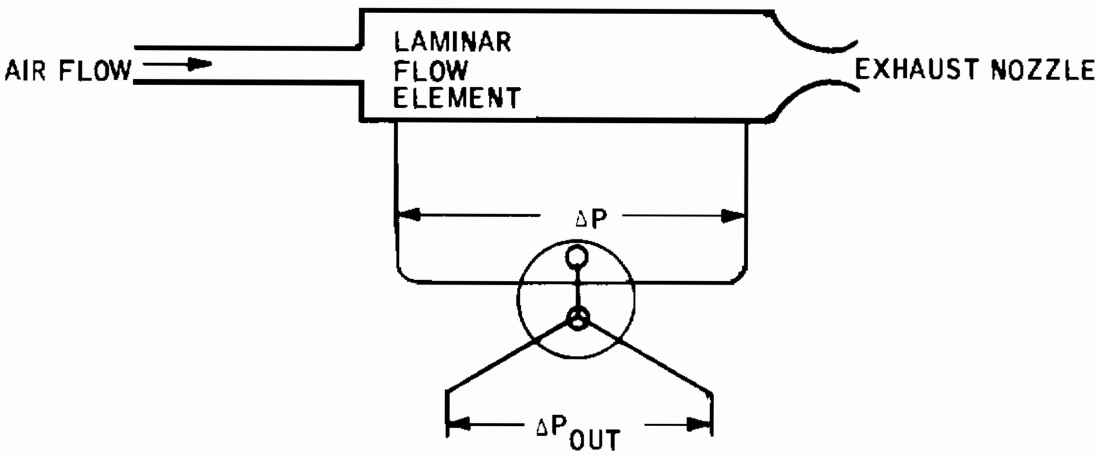


Figure 23. Schematic of Capillary Temperature Sensor Concept

engine pressure ratios (1.3 to 2.8). Further investigations are necessary to determine just how large a pressure ratio can be measured with this oscillator.

Pressure Rate Sensor

The limitations on the pressure rate sensor are those imposed by the basic limitations of the proportional fluidic amplifier. To date, the improvements in the performance characteristics of the amplifier have been those dictated by the requirements of the system in which they have been used. The primary area requiring further development for the amplifier is that of sensitivity to altitude. Individual amplifiers of slightly different configurations have shown the tendency to both increase and decrease gain with increasing altitude. The basic design normally used has a tendency to decrease gain slightly at altitudes greater than 30,000 feet. Subtle changes in the geometry of the amplifier should make it possible to eliminate this sensitivity.

Initial investigations into replacing the relatively large volume with a smaller volume containing a diaphragm has shown promise of obtaining the same time constant with a smaller volume. More thorough studies are required to determine the range of time constants attainable with this configuration.

Normal Shock Sensor

The normal shock sensor even in its current breadboard status has proved to be a useful tool during wind tunnel testing of supersonic inlet models. By miniaturizing the bistable amplifiers, a more compact package can be achieved which reduce amplifier transport time and flow rate requirements. Close mounting to the static pressure sensor taps would also improve the response time of the shock sensor.

The wind tunnel testing has also shown the desirability of having an electrical output which can be achieved by providing a switch on the output of each fluidic amplifier rather than feeding the outputs to a manifold to provide a pressure output. Concepts for miniature diaphragm switches capable of operation at 1200°F ambient have been generated.

Pressure Difference Sensor

A proportional fluidic amplifier is essentially a pressure difference sensor. The fluidic amplifier has been developed for use in fluidic control systems and as such has characteristics as required for its specific use. Consequently, altitude insensitivity to 30,000 feet is all that has been necessary. Minor configuration variations are possible to increase the altitude capabilities of the amplifier. At the same time these small geometric changes can increase linear output range of the amplifier.

In application as a computational device in a fluidic control system, the output noise level has been detrimental. Programs are continually being conducted which include investigations into this problem. These have been successful and noise is now only a problem when working with extremely small pressure signals (<0.5 in. H_2O).

Flight Control Sensors

The current electromechanical angular rate sensors and accelerometers are basically the same devices that have been made for the past ten years. Physical, mostly materials, limitations are such that state of the art, spring-restrained gyros are at or near the limit of their possible performance.

Currently under development at Honeywell is a miniature single-degree-of-freedom rate integrating gyro. It is provided with a torque generator rather than with a restraint spring. A gyro of this type may be used as a rate gyro by providing an external amplifier which amplifies the output signal from the pick-off and applies it to the torque generator. Data in the specifications are based on engineering models of this gyro.

Also under development is a new type linear accelerometer which features a single crystal of transistor-grade silicon machined into a beam which supports the seismic mass. Resistive elements required to form a four-arm strain gage are doped into the crystal lattice of the beam so that it serves both as a spring restraint support, and as a strain gage pickoff, free from effects of bond instability. The extrapolated capabilities shown are for that expected from production models based on current engineering models of this accelerometer.

Angular Rate Sensor

The extrapolated capabilities of the fluidic angular rate sensor are dependent on the operational requirements put on the device. Theoretically, there are few limitations on any performance parameter but important tradeoffs exist to obtain the required performance. Continued work in the pickoff area should decrease the drift and noise level. Also, environmental compensation currently being studied could decrease the environmental effects by a factor of ten over what is currently specified.

As with the angular rate sensor the extrapolated capabilities of the fluidic accelerometer are limited primarily by performance tradeoffs required for any specific application. For instance, the threshhold is directly proportional to the maximum acceleration capabilities. Also the natural frequency can be increased, but only at the expense of threshhold or scale factor and there is a practical tradeoff between the required machining tolerances for minimum turbine torquing and size of device. Further development on the accelerometer should improve the steady state accuracy, reduce the environmental effects and improve the sensitivity.

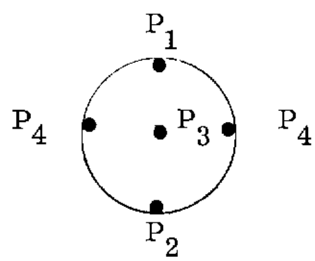
Angle of Attack Sensor

The present Honeywell electromechanical angle-of-attack sensor was designed for use in a flight control system for a specific aircraft. The angle of attack is computed by ratioing static and total pressures from a probe in a manner identical to the LG80 pressure ratio computer-transmitter. Therefore, the same fluidic-electromechanical hybrid computation device can be applied to the angle-of-attack computer-transmitter to improve the natural frequency and slew rate.

A concept has been generated for fluidically measuring the angle of attack. This concept, utilizing a probe and fluidic amplifier for computing the angle of attack, appears feasible from experience with similar computational circuits, but since it is only in the conceptual stage it is impossible to write a specification for a fluidic angle-of-attack sensor. The environmental limitations are only those imposed by the amplifiers and probe. The other performance characteristics are impossible to estimate. A description of the concept follows:

Using a five port angle of attack probe such as Rosemont Engineering Company's Model 858, the angle of attack is given by

$$P_1 - P_2 = K\alpha\ (P_3 - P_4)$$



where

P_1 and P_2 are in the plane of the angle of attack

P_4 is static pressure ports and is manifolded together

P_3 is an approximate total pressure or $P_3 - P_4$ is an approximate dynamic pressure

K is sensitivity per degree which changes with Mach number

K = 0.088/degree subsonic

= 0.075/degree supersonic

α = Angle of Attack

This expression can be in the form of a ratio

$$\frac{P_1 - P_2}{P_3 - P_4} = K\alpha$$

which is simply the ratio of two differential pressures. However, this ratio is both less than and greater than 1.0 over a fairly wide range. The fluid pressure ratio sensor computes ratios greater than 1.0 only, and at present, only over limited ranges. However, fluidic multipliers have recently been invented which may prove valuable for this application.

The fluidic multiplier is shown schematically on Figure 24 and utilizes three proportional amplifiers. The output of the first stage provides the supply pressure to the other two stages. The input signal goes to the first stage while the output is taken from signal opposing legs of the following two stages. By applying a pressure at P_{mult}, the supply pressure profile of the two stages is deflected equally. This allows a smaller percentage of recovered supply pressure and effects a greater reduction in P_{out}. The remaining two output legs from the driven amplifiers are used to provide negative feedback to the first stage. This feedback does reduce the overall gain but improves stability and linearity. Actually, the device is a gain changer which simply reduces amplifier gain as a multiple of some other control or computation function. Circuits similar to this have been used previously and are reported in AFAPL-TR-68-31 Part I.

The quantities $(P_1 - P_2)$ and $(P_3 - P_4)$ can be sensed with fluidic amplifiers. A schematic of the computation circuit is shown on Figure 25. $(P_3 - P_4)$ is multiplied by K using the fluidic multiplier. A function generator (inverter) is used to produce $1/K(P_3 - P_4)$. This signal is then multiplied by $(P_1 - P_2)$ to produce a signal proportional to α as shown on the curve Figure 26.

Flow Distortion Sensor

A parameter that will define flow distortion is not presently known. The overall results of Phase I of this program will attempt to define a parameter that is a signature of incipient flow distortion. In order to generate concepts for a possible flow distortion sensor a certain amount of assumptions and speculation must and have been made.

Flow distortion can occur in the form of radial, circumferential, or axial pressure gradients, occurring separately or simultaneously. The exact form of this distortion is not well defined and has different effects on different propulsion systems. Since the distortion is not well defined, it is difficult to propose a specific sensing system. Therefore, only general concepts are possible making it impossible to write specifications.

One means of detecting distortion would be to sense pressure differences at a number of radial circumferential, or axial stations. The differential pressures between points or stations are measured and compared to an average. Differential pressures can be averaged in a suitably designed plenum. Consider first the fluidic amplifier. Both positive and negative pressure gradients are to be sensed but only the absolute

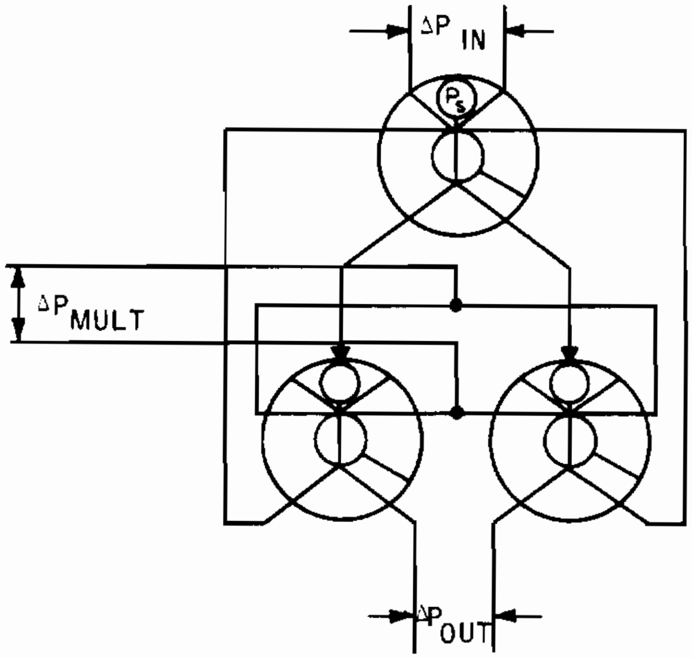


Figure 24. Fluidic Multiplier Schematic

value of the pressure gradient is of interest. A typical fluidic amplifier has both positive and negative differential pressure outputs as explained earlier in this document. Therefore, a modification to the basic amplifiers necessary to achieve an absolute value output for both positive and negative inputs. For this purpose a center dump amplifier is used. A sketch of the amplifier configuration and its output characteristic curve is shown on Figure 27. Here when the differential pressure across the control ports is zero or very small, flow is dumped through the center port. However, when a positive ($P_1 > P_2$) differential pressure is applied across the control ports flow is out the right output port. When $P_2 > P_1$ flow is out the left output port. Then when no differential pressure exists across the control ports, maximum dump port pressure is realized. With increasing differential pressure, dump port pressure decreases.

Pressure averaging can be accomplished pneumatically by simply feeding the individual pressures into a manifold or plenum. This was checked out by flowing air through tubes at different pressures into a plenum as in Figure 28.

Pressures P_1 through P_5 are measured with a pitot tube and the average pressure computed to check out the averaging capability of the plenum. The average input pressures are plotted against the measured plenum pressure on Figure 29. The plenum indicates about 76 percent of the calculated average gauge pressure and is reasonably linear.

Another possible method of sensing flow distortion by sensing pressure gradients is shown on Figure 30. Here, four center dump amplifiers are used to sense pressure gradients between five points (there could be either more or less). These points can be circumferentially located, axial stations, or points on a pressure rake probe. The

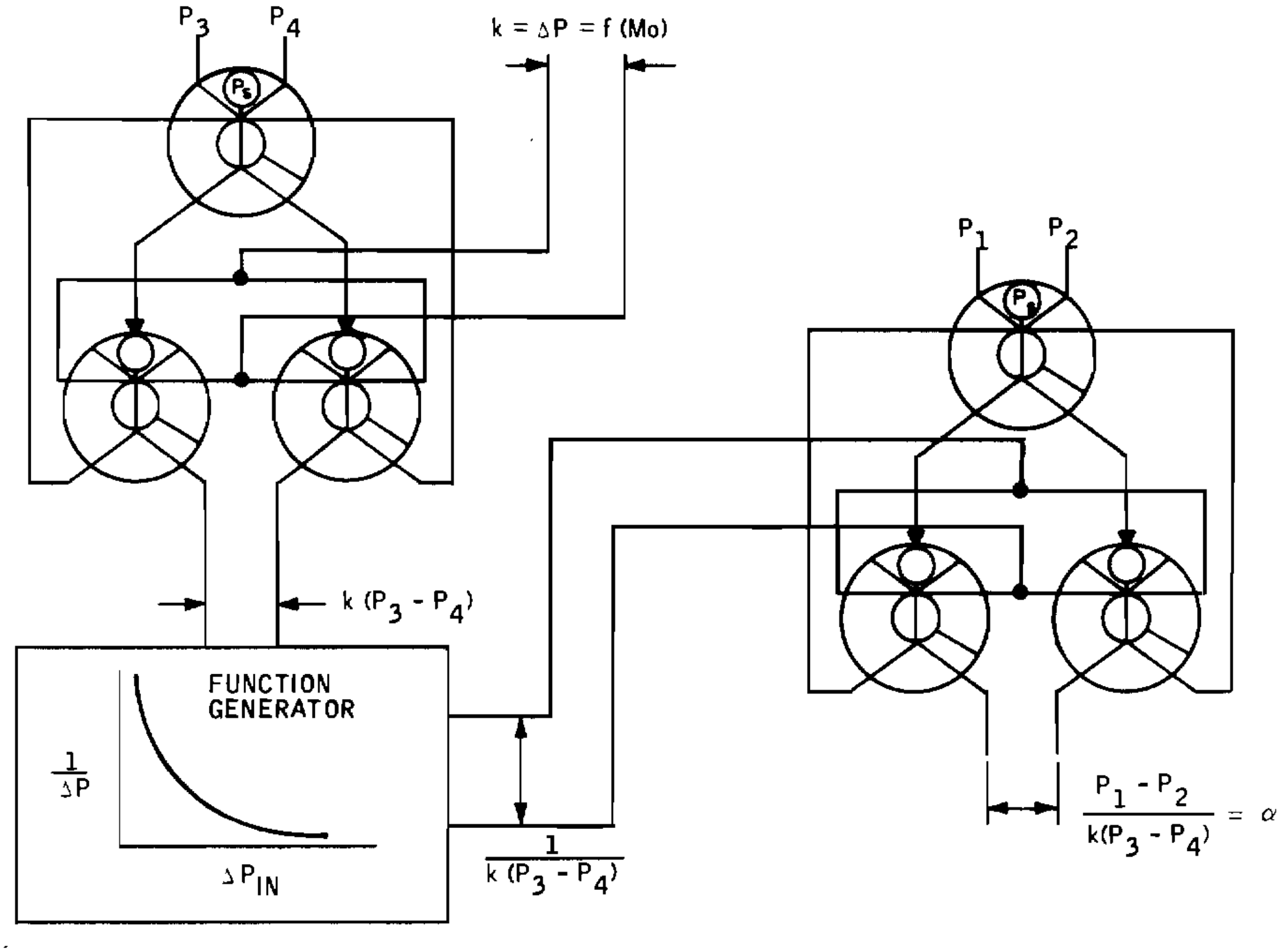


Figure 25. Angle of Attack Computer Schematic

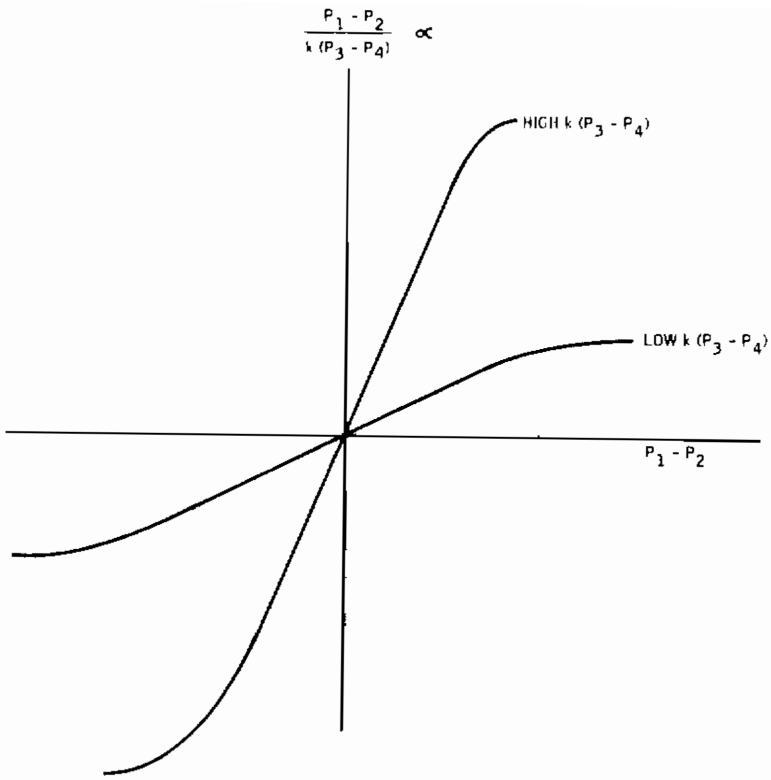


Figure 26. Angle of Attack Computer Input versus Output Curve

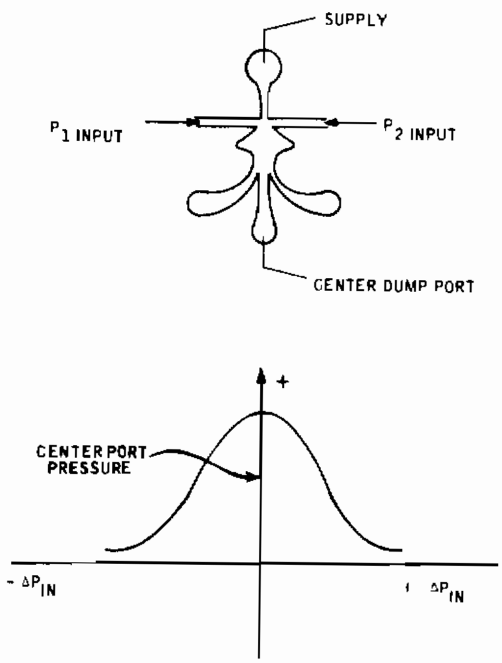


Figure 27. Center Dump Amplifier

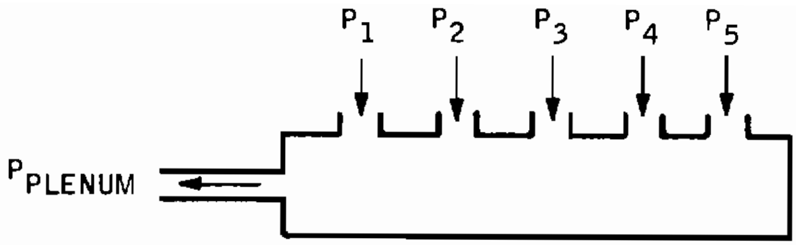


Figure 28. Pressure Average Plenum Test Schematic

pressures P_1 through P_5 are averaged in the averaging plenum. The differential pressures $P_1 - P_2$, $P_2 - P_3$, etc., are sensed and if no distortion (differential pressure) exists the amplifier will dump through the center port into a sensing plenum. If all amplifiers are dumping into the plenum, pressures are equal (some orificing and biasing will probably be necessary). When distortion occurs, the flow shifts from the center port to the output ports which are exhausted to ambient and the sensing plenum pressure will drop. A fluidic amplifier is used to sense the differential pressure in the plenums and the output is proportional to the distortion.

The scheme devised above is particularly well suited to distortion sensing at the compressor face. The point pressures being sensed could be radial locations on the inlet guide valves or static taps on the inside and outside diameters of the inlet. Also the pressure points could be axial stations in the inlet duct but since a gradient normally exists in the duct, some schedule would likely have to be employed.

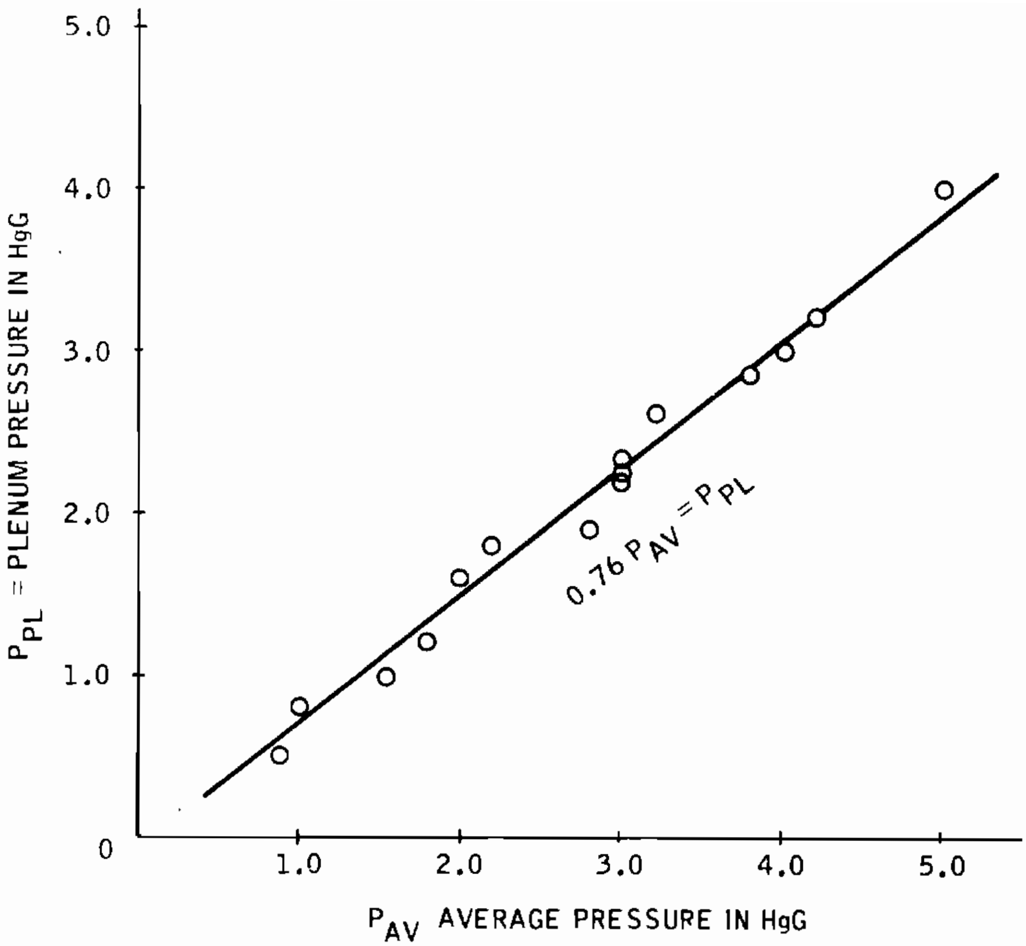


Figure 29. Averaging Plenum Characteristics

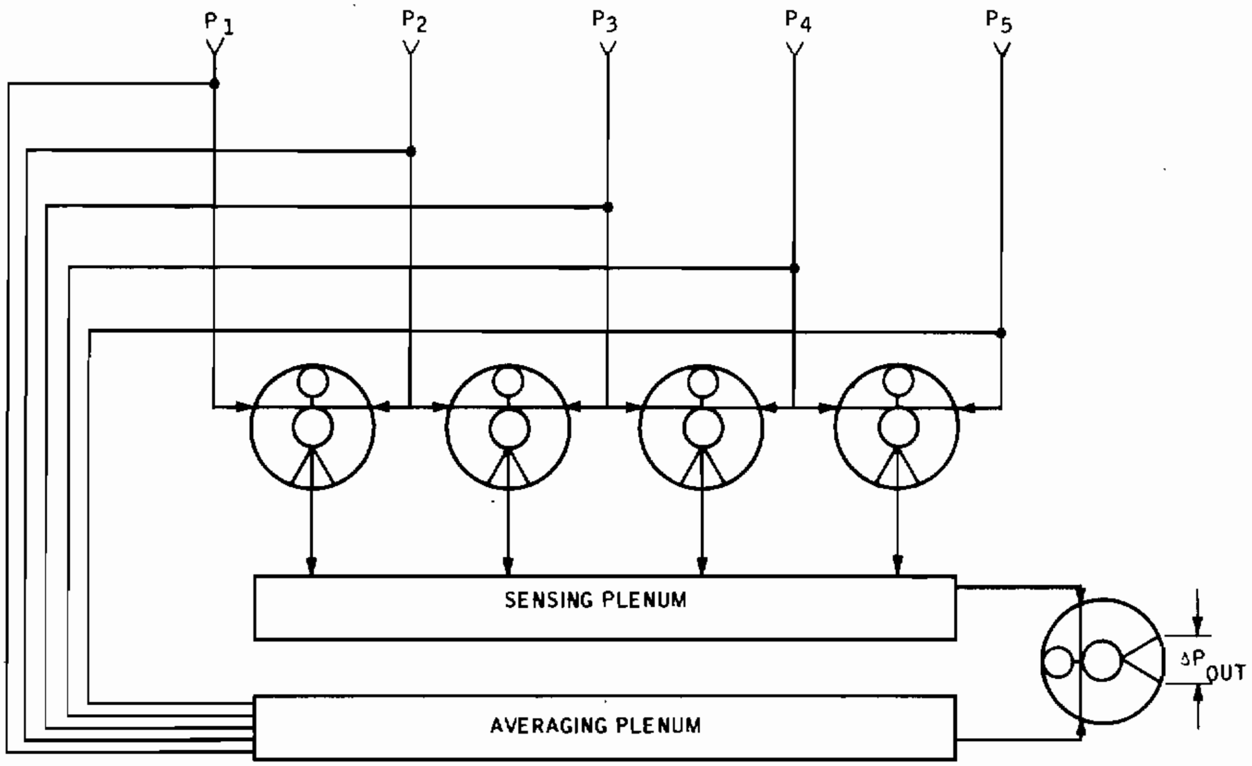


Figure 30. Pressure Distortion Sensor Concept

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Specific technical conclusions regarding the adequacy of available sensor performance and projected sensor capabilities relative to the program goals are not meaningful at this time because selection of the control modes, including the flow transient accommodation schemes, and the resulting required sensors specifications will not be conducted until Phase II of the research program. However a few general conclusions apparent from the survey data can be made.

1. Very few sensors are currently in production for service at temperatures exceeding 400°F, although a number of manufacturers are actively working toward development of high temperature units.

2. With the exception of temperature sensors, sensors can be designed and are available for applications requiring fast dynamic response characteristics. However, accuracy is usually sacrificed for high response designs.

3. The response characteristics of available temperature sensors limits their use for control functions. Fluidic techniques and developments may eventually fill this gap.

The sensor survey looked primarily at dynamic performance characteristics and performance limitations. In the background are the other considerations that relate to the selection and use of sensors in a control system. These include evaluation of the effect of a given sensor on system design (relative system complexity), producibility of a given sensor design, and means for performing in service calibration and checkout, or, perhaps an evaluation of the need to perform in service calibration and checkout functions for a given sensor. Although presently, these factors are of secondary importance to the questions of available and projected performance capabilities, as it becomes more obvious which sensors are necessary or suitable for eventual control implementation, they may become a dominant factor in system cost and will be considered in the sensor selection and specification process in Phase II.

Concerning the information recorded in the survey, it is necessary to qualify the data obtained to enable a fair interpretation of sensor capabilities. In most cases the data represents published capabilities and normal production tolerances, although in some instances, the data supplied for the survey was apparently based on selective production tolerances, estimates due to lack of actual test data, or arbitrary values that can safely be met. Published data usually represents the most economically competitive production tolerancing and is not necessarily representative of attainable capabilities. Therefore, the data presented in the survey is not a strictly true and consistent picture of sensor capabilities.

Although the survey is a necessary step in the formulation of possible system mechanizations, it is useful primarily as an initial screening of applicable sensors.

Prior to eventual implementation of the control system the following activities are recommended:

1. Sensors that have critical performance characteristics relative to the control mechanization should be tested by an independent testing agency to eliminate data inconsistencies and establish relative sensor performance and operating limits. Dependence on data provided by the manufacturer may, in certain cases, be misleading resulting in either overly conservative or overly optimistic evaluations of the sensor.

2. Based on the sensing requirements to be established during Phase II, conduct sensor analyses, trade offs and mechanization studies resulting in the establishment of preferred technical approachs for sensors requiring further development. The objective would be to relate and direct the eventual specific needs of this program to the technical capabilities available within the sensor industry by the analytical appraisal of sensor potential rather than a dependence on "make and break" development techniques and updating of historical technical solutions.

APPENDIX A

TABLES OF SENSORS CAPABILITIES

Information on various types of sensors was gathered from suppliers by questionnaires, catalogs and bulletins, and conversations with the suppliers or their representatives.

The information as obtained from the suppliers is summarized in Tables III through XVI. The description for the items in each column of these tables is as follows:

Temperature range - The safe operating range unless indicated.

Measurement range - The exact title varies for each transducer. In most cases, the range indicated is only a representative one, other ranges may be available.

Step response - The time for the transducer output to rise to 63 percent of its final value in response to a step input.

Frequency response - The frequency up to which the bode plot is flat (may be within a fixed percent). If the frequency is followed by an f_n it is the undamped natural frequency. The flat frequency response may then be assumed to be approximately 40 or 50 percent (max) of the undamped natural frequency. Superscript k means that the listed number should be multiplied by 1000.

Ambient accuracy - This includes hysteresis, repeatability and other non-linearities unless indicated. For the gyro angular rate sensors this would include mass unbalance, etc.

Temperature effect -

Zero - The shift of zero output with zero applied input

Sensitivity - The change in gain or effectively the change in slope of the output curve.

Vibration effect - Error due to random vibrations. For the accelerometers this would be the error due to acceleration normal to the sensitive axis.

Life - In most cases, it is the number of full scale (F. S.) cycles without failure. If expressed in hours, it would represent mean time between failure (MTBF).

Resolution - The smallest input that produces a recognizable change in the output.

Remarks - May include programs in which the transducer is or was used, and typical applications.

Table III. Survey Data, Absolute Pressure Sensor, Present Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Consolidated Controls Corp.	41M2	+900/-430	0-50	0.0003	500 f_n	±1.0	0.5	0.5	0.007		LVDT	0-5 vdc (a)	Infinite	Used on B-70 and Boeing SST
			0-100	0.0003	500 f_n	±1.0	0.5	0.5	0.0035		LVDT	0-5 vdc		(a) Includes signal conditioner
	41M3	+900/-430	0-500	0.0003	500 f_n	±1.0	0.5	0.5	0.001		LVDT	0-5 vdc	Infinite	
Consolidated Electrodynamics Corp.	4-316-0001	+650/-320	0-50	0.05	$7.8^k f_n$	0.5	2.0	1.0	+0.12		Unbonded	±10 mv	Infinite	
			0-100		$7.8^k f_n$	0.5					Strain Gage	±10 mv		
Microdot, Inc.	PT100	+600/-320	0-250	Range		±2.0 (a)	0.1	0.1	0.015		Welded Strain Gage Bourdon	1-3 mv/v @ 10 vdc		a) Including Temperature effects over compensated temp range of 525°F
			0-500	Dependent	400	±2.0 (a)	0.1	0.1						
Servonic Instruments, Inc.	2121	+600/-320	0-500	0.010		+1.75	1.0	comb. with zero	0.2	50^k cy, @ 1/3 F.S.	Bourdon Potentiometer			
Fairchild Controls	BA100 and BG100	+500/-320	0-15		1000+	+0.2	0.25	0.25	0.001	500^k cycles	Bonded Foil Strain Gage	0-30mv/ 10 VAC	Infinite	
Servonic Instruments, Inc.	3121 (a)	+500/-320	0-10 thru	0.010		±2.0	1.0	comb. with zero	0.5% F.S. max	50^k cy, @ F.S.	Capsule Potentiometer			a) Use in Nuclear Environment
			0-300	0.010		+2.0	1.0							
Teledyne Systems Company, Control Systems Division	TR2238-2	+500/-65 (a)	0.5-50	0.01	60	0.05	0.02	0.06	0.0025		Twisted Bourdon Tube, Variable Reluctance	0-5 vdc (b)	Infinite	a) Sensor remote from electronics. Electronic module limited to +200/-65 range. b) Includes signal conditioner
	TR2238-3		1.5-100	0.012	56	0.05	0.02	0.06	0.0025			0-5 vdc		
	TR2238-8		1.0-500	0.015	52	0.05	0.02	0.06	0.0025			0-5 vdc		
Kistler Instrument Corp.	600 and 700 series (a)	+500/-450	10 thru 3000	3 μsec	130^k	1.0		1.0	0.01 psi/g	50 hrs @ integral heat shield	Quartz Crystal, Piezo-electric	Up to 5 pico-coulomb per psi	0.1 psi	a) Integral combustion Engine monitoring Models 614, 615 and 644 Helium Bleed type b) Forced aircooling
	409	+400/ (b)	10 thru 3000	4 μsec	100^k	1.0			0.002 psi/g					
Photocon Research Products (Whittaker Corp.)	300 series	+450/-65 (a)	50	15 μsec	$13^k f_n$	2.0	0.5		0.02		Capacitance	Up to ±10 v (b)	1 part in 10,000	a) Water cooled +165/-65°F if uncooled
			100	15 μsec	$17.5^k f_n$	2.0	0.5		0.02					b) Includes signal conditioner
			500	15 μsec	$31^k f_n$	2.0	0.5		0.02					
	400 series	+450/-65 (a)	50	15 μsec	$33^k f_n$	2.0	0.5		0.1		Capacitance			
			100	15 μsec	$40^k f_n$	2.0	0.5		0.1					
			500	15 μsec	$61^k f_n$	2.0	0.5		0.1					

*Metal diaphragm unless otherwise indicated

Table III. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Photocon Research Product (Cont)	765	+450/-65 (a)	50 100 500	15 μsec 15 μsec 15 μsec	$20^k f_n$ $26^k f_n$ $45^k f_n$	2.0 2.0 2.0	0.5 0.5 0.5		0.2 0.2 0.2		Capacitance			a) Water cooled
Bytrex, Inc.	HFF (c)	+400/ Special, +250/-65 Standard	0-15 0-25 0-50 0-100		$25^k f_n$ $35^k f_n$ $35^k f_n$ $35^k f_n$	±0.5 (b) ±0.5 (b) ±0.5 (b) ±0.5 (b)	1.5 (a)	1.5 (a)			Semiconductor Strain Gage	6 mv/v		a) Over any 100° temp Range b) Non linearity c) Miniature .374 Dia x .45 long, other miniature units available
Servonic Instruments, Inc.	2501 (a) 3221 (a)	+400/-320	0-250 0-0.5 to 0-350	0.0003 0.006 0.006		±1.0 0.9 0.9	2.0 1.0	Comb. with zero	0.04 0.05	300^k cy @ 1/3 F.S. 250^k cy @ 1/3 F.S.	Bourdon Potentiometer Capsule Potentiometer			a) Used in aerospace applications
Fairchild Controls	TF061, TF125, and TF150	+350/-65	0-50 0-100 0-500		$15.8^k f_n$ $20^k f_n$ $38^k f_n$	±0.5 ±0.5 +0.5	0.5 0.5 0.5	0.5 0.5 0.5	0.001 0.001 0.001	500^k cycles	Semiconductor Strain Gage	250mv/ 20 vdc 250mv/ 20 vdc 250mv/ 20 vdc	Infinite	
Servonic Instruments, Inc.	2151	+350/-65	0-500	0.025		±1.0	0.5			100^k cycles/ @ 1/3 F.S.	Bourdon Potentiometer			
Electro Optical Systems Inc. (Whittaker Corp.)	1003-0041 (b)	+350/-65	0-100 thru 0-5000	50 μsec	$35^k f_n$ min	±0.75 (a)			0.01		Semiconductor Strain Gage			a) ±2.5% F.S. Total Error includ. thermal effect b) 0.26 diameter
Pace Wiancko (Whittaker Corp)	SP45 (b)	+350/-100	0-50 0-20		$80^k f_n$ min	±0.15(a)	±0.5	±0.5			Semiconductor Strain Gage	30 mv/v @12v		a) Linearity b) .5 dia
American Standurd, Inc.	141	+300/-320	0-50 0-100	15 μsec 15 μsec	$26^k f_n$ $26^k f_n$	0.5 0.5	0.5 0.5	0.5 0.5	insensitive insensitive		Bonded Strain Gage Bonded Strain Gage	30 mv 30 mv	Infinite	

*Metal diaphragm unless otherwise indicated

Table III. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
American Standard, Inc. (Cont)	211	+300/-320	0-100	15 μsec	$45^k f_n$	0.75	2.0	1.0	Insensitive		Strain Tube, Bonded	60 mv	Infinite	
			0-500	15 μsec	$45^k f_n$	0.75	2.0	1.0	Insensitive		Strain Gage Bonded	60 mv		
	111	+300/-320	0-100	15 μsec	$45^k f_n$	0.5	0.5	0.5	Insensitive			30 mv	Infinite	
			0-500	15 μsec	$45^k f_n$	0.5	0.5	0.5				30 mv		
Photocon Research Prod. (Whittaker Corp.)	3000, 4000, and 5000	+300/-65	0-250	15 μsec	$17^k f_n$	±1.0(a)	3.0		0.005		Semiconductor Strain Gage	0.5 v	1 part in 10,000	a) Linearity
			0-500		$24^k f_n$	±1.0(a)			0.005					
Consolidated Electrodynamics Corp.	4-312-0002	+300/-320	0-50	0.05	$8^k f_n$	±0.5	1.2	1.0	±0.03		Unbonded Strain Gage	±10 mv	Infinite	a) Miniature, .74 dia x .314 long
			0-100		$8^k f_n$	±0.5	1.2	1.0	±0.03		Unbonded Strain Gage	±10 mv		
	4-313-0002	+300/-320	0-50	0.05	$6^k f_n$	±0.5	1.2	1.0	±0.04		Unbonded Strain Gage	±10 mv	Infinite	
			0-100		$6^k f_n$	±0.5	1.2	1.0	±0.04		Unbonded Strain Gage	±10 mv		
			0-500		$6^k f_n$	±0.5	1.2	1.0	±0.04		Unbonded Strain Gage	±10 mv		
	4-325 (a)	+300/-320	0-26 thru		$15^k f_n$ to	±1.0	3.0	2.0	0.085 to		Unbonded Strain Gage	20 mv	Infinite	
			0-100		$25^k f_n$	±1.0	3.0	2.0	0.05		Unbonded Strain Gage	20 mv		
Sensotec Division Scientific Advances, Inc.	SA-SA M-6 (b)	+300/-100	0-50		$100^k f_n$	±0.50 (a)	1.0	1.0	0.001 to 0.03		Bonded Semiconductor Strain Gage	60 mv/ 3 vdc	Infinite	a) Linearity and hysteresis @ 77°F
	SA-SA M-7 (b)		0-100		$100^k f_n$	±0.50 (a)	1.0	1.0						b) Miniature to .250 dia
			0-500		$100^k f_n$	±0.50 (a)	1.0	1.0						
Servonic Instruments, Inc.	2091	+275/-65	0-500	0.007	40	±1.0 (a)	1.0	Comb.	0.05	100^k cycles @ 1/3 F.S.	Bourdon Pot.		0.25	a) Includes temp effects
	3031, 3061	+275/-65	0-10	0.004	60	±1.0 (a)	1.0	Comb.	0.1	100^k cycles @ 1/3 F.S.	Aneroid, Pot.		0.25	Used in aerospace applications
			thru 0-400	0.004	60	±1.0 (a)	1.0	Comb.	0.1	100^k cycles @ 1/3 F.S.				
	3065	+275/-65	0-10 thru	0.015			0.2	Comb.	0.05	50^k cy @ 1/3 F.S.	Aneroid, Pot.	0-5 vdc		
			0-400	0.015			0.2	Comb.	0.05	50^k cy @ 1/3 F.S.		0-5 vdc		

*Metal diaphragm unless otherwise indicated

Table III. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP.EFFECT % F.S./100°F ZERO	TEMP.EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLU-TION-% F.S.	OTHER DATA AND REMARKS
Servonic Instruments, Inc. (Cont)	3071	+275/-65	0-15 thru 0-200	0.010 0.010		±1.0 (a) ±1.0 (a)	1.0 1.0	Comb.	0.01	100^k @ 1/3 F.S.	Aneroid Pot.			a) Including temp effects
	3255	+257/-65	0-0.5 thru 0-300	0.001 0.001		±0.6 +0.6	±2.0 Environmental Error includes; Vibr., Accl, Shock and Temp.			10^6 cycl.	LVDT	0-5 vdc (b)		b) Includes signal conditioner
Consolidated Controls Corp.	41GB25 & 41PL20	+250/-65 (a)	0-60	0.005	2900 f_n	±0.2	0.5	0.5	0.006		LVDT	0-5 vdc (b)	Infinite	a) Special order, temp range to 500°F for 41GR
			0-100	0.005	4800 f_n	±0.2	0.5	0.5	0.0035		LVDT	Pulse Rate, and Digital		b) Includes signal conditioner
	41GB26 & 41PL21	+250/-65 (a)	0-600	0.005	600 f_n	±0.2	0.5	0.5	0.001		LVDT		Infinite	
Standard Controls, Inc.	100	+250/-25	0-500			±0.25 (a)	1.0	0.5			Bonded Strain Gage	4 mv/v		a) Combined non linearity and hysteresis
	800	+250/-25	0-50 thru 600			+0.25 (b)	1.0	1.0			Bonded Strain Gage	3 mv/v		b) Non linearity
	900	+250/-25	0-500			±0.25 (b)	1.0	0.5			Bonded Strain Gage	3 mv/v		
Electro-Optical Systems, Inc (Whittaker Corp.)	1003	+250/-65	0-100 thru 0-5000	50 μsec	20^k f_n min	±0.75	±3.0 max	combined	0.01	500^k hrs (a)	Bonded Semiconductor Strain Gage	15 mv/v		a) MTBF
	1028	+250/-65	0-2 to 0-99	0.2 m sec	4^k f_n min	±0.5	+1.5 max	combined	0.02	500^k hrs (a)		10 mv/v		b) ±2.5% F.S. total error including thermal effects
	1029	+250/-65	0-100 thru	0.2 m sec	25^k f_n min	±0.25	±1.5 max	combined	0.01	500^k hrs (a)		10 mv/v		
	1008-0036	+250/-65	0-100 thru 0-5000	0.0002	12^k f_n min	+0.25	±1.5 max	combined	0.01					
	1026-0047	+250/-65	0-2 thru 0-99	0.001	500	±0.5			0.02					
Pace Wiancko (Whittaker Corp.)	P1, P2, and P21	+250/-423	0-0.1 to 0-10,000		5^k f_n min	±0.5	1.0	2.0			Variable reluctance	50 mv/v @ 3000 Hz		a) Aircraft and missile flight
BLH Electronics, Inc.	DHF	+250/-65	0-50			0.25 (a)	0.5	0.5			Bonded Strain Gage	3 mv/v		a) Max nonlinearity
			0-100			0.25 (a)	0.5	0.5				3 mv/v		b) Includes signal conditioner
			0-500		14^k f_n	0.3	0.25	0.5	0.01			3 mv/v		
	DS	+250/-70	0-50								Bonded Strain Gage	1 v (b)		
			0-100									1 v (b)		
			0-500									1 v (b)		

*Metal diaphragm unless otherwise indicated

Table III. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
BLH Electronics, Inc. (Cont)	GP (a)	+250/-50	0-100	100 μsec	$5^k f_n$	0.35 (a)	0.35	0.25			Strain Gage Bonded to Tube	3 mv/v	Infinite	a) Nonlinearity
			0-500	100 μsec	$14^k f_n$	0.35 (a)	0.35	0.25				3 mv/v	Infinite	
Dynisco	PT192	+250/-65	0-50	.0002	$4.3^k f_n$	±0.3	0.5	0.5	0.023		Unbonded Strain Gage	3 mv/v	Infinite	
			0-100	.0002	$5.6^k f_n$	+0.3	0.5	0.5	0.015					
			0-500	.0002	$10^k f_n$	+0.3	0.5	0.5	0.006					
	PT193	+250/-65	0-50	.0002	$4.3^k f_n$	±0.4	1.0	0.5	0.023		Unbonded Strain Gage	3 mv/v	Infinite	
			0-100	0002	$5.6^k f_n$	+0.4	1.0	0.5	0.015					
			0-500	.0002	$10^k f_n$	±0.4	1.0	0.5	0.006					
Rosemount Engineering Company	830	+250/-65	0.1 to 5000	0.025	30	0.15	1.0	comb. with zero	0.04		Capacitance	0-5 vdc (a)	0.02	a) Includes signal conditioner
Bytrex, Inc.	MPA	+250/-65	0-100		$7.5^k f_n$	0.15 (b)	0.5	0.5 (a)	0.01		Semiconductor Strain Gage		Infinite	a) Reading
			0-200		$10^k f_n$	0.15 (b)	0.5	0.5 (a)	0.005					b) Combined non linearity and hysteresis
			0-500		$15^k f_n$	0.15 (b)	0.5	0.5 (a)	0.006					
MB Electronics	Series 151 (a)	+250/-100	0-50		$6^k f_n$	+0.2	+0.25	0.25	0.025		Bonded Strain Gage	3 mv/v		a) Used by NASA, in LEM, in Apollo Saturn
			0-100		$6^k f_n$	±0.2	±0.25	0.25	0.025			3 mv/v		
			0-500		$\sim 8^k f_n$	±0.2	+0.25	0.25	-0.013			3 mv/v		
	Series 152 (a)	+250/-100	0-50		$5^k f_n$	+0.35	+1.0	+0.35	0.025		Bonded Strain Gage	3 mv/v		
			0-100		$6^k f_n$	±0.35	+1.0	+0.35	0.025			3 mv/v		
			0-500		$\sim 8^k f_n$	±0.35	±1.0	±0.35	-0.013			3 mv/v		
	Series 500	+250/-100	0-50 0-100, 0-500		$20^k f_n$	±0.5	±1.0	±2.0	0.025		Bonded Strain Gage	5 vdc (b)		b) Includes signal conditioner
Fairchild Controls	FPT7 (a)	+250/-65	0-100 psig		$9^k f_n$	±1.0 @ 70°F				10^6 F.S. cycles	Diffused Semiconductor Strain Gage, Silicon Diaphram	200 mv	Continuous	a) Miniature 3/4 dia x 5/16 long
			0-500 psig		$8^k f_n$	±1.0 @ 70°F								

*Metal diaphragm unless otherwise indicated

Table III. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLU-TION % F.S.	OTHER DATA AND REMARKS
Fairchild Controls (Cont)	TF555	+250/-65	0-50		$15.8^k f_n$	±0.25	±2.0	±1.5	0.02	500^k cy.	Semiconductor Strain Gage	0-5 vdc (a)	Infinite	Aerospace application
	FST1	+250/-65	0-100		$20^k f_n$	±0.3	+1.0	+1.0	0.01	500^k cy.	Semiconductor Strain Gage	0-5 vdc (a)	Infinite	a) Includes signal conditioner
Statham Instruments, Inc.	PA822	+250/-65	0-50	80 µsec	$5^k f_n$	±0.3	0.5	0.5	0.03		Thin Film Strain Gage	3 mv/v	Infinite	a) Combined nonlinearity and hysteresis
			0-100	80 µsec	$10^k f_n$	±0.3	0.5	0.5	0.01		Thin Film Strain Gage	3 mv/v		
			0-500	80 µsec	$18^k f_n$	±0.3	0.5	0.5	0.01		Thin Film Strain Gage	3 mv/v		
	PA824	+250/-65	0-50	80 µsec	$5^k f_n$	±0.15 (a)	0.5	0.5	0.03		Thin Film Strain Gage	3 mv/v	Infinite	
			0-100	80 µsec	$10^k f_n$	+0.15 (a)	0.5	0.5	0.01		Thin Film Strain Gage	3 mv/v		
			0-500	80 µsec	$18^k f_n$	±0.15 (a)	0.5	0.5	0.01		Thin Film Strain Gage	3 mv/v		
	PA826	+250/-65	0-100	80 µsec	$10^k f_n$	±0.15	0.5	0.5	0.01		Thin Film Strain Gage	3 mv/v	Infinite	
			0-500	80 µsec	$18^k f_n$	±0.15	0.5	0.5	0.01		Thin Film Strain Gage	3 mv/v		
	PA829	+250/-65	0-50	80 µsec	$5^k f_n$	±0.15	0.5	0.5	0.03		Thin Film Strain Gage	3 mv/v	Infinite	
	PA861	+250/-65	0-500	80 µsec	$29^k f_n$	+0.3	0.5	0.5	0.01		Thin Film Strain Gage	3 mv/v	Infinite	
Electro-Optical Systems, Inc (Whittaker Corp.)	1025-0015 (a)	+200/-65	0-100 thru 0-5000	0.0002	$20^k f_n$	±0.25	±1.5	Combined	0.01	500^k hrs (b)	Bonded Semiconductor Strain Gage	0-5 vdc (c)		a) Aerospace and aircraft programs b) MTBF c) Includes signal conditioner
Consolidated Electrodynamic Corp.	4-390	+200/0	0-50	0.05	18^k	±0.8	1.0	1.0	0.07		Unbonded			
			0-100		24^k	±0.6	1.0	1.0	0.055		Strain Gage			
			0-500		35^k	±0.6	1.0	1.0	0.03					
Robinson-Halpern	P-60	+200/-40	0-60	0.050		±1.0	2.0	2.0			Capsule Pot.	0-5 vdc	0.25 to 0.40	
			0-100											
			0-600											

*Metal diaphragm unless otherwise indicated

Table III. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Schaevitz Engineering	PT-2	+200/-65 (b)	0-50	0.8 to	160 to	0.5 (a)	1.0	1.0			LVDT	1.1 v	Infinite	a) Hysteresis
			0-100	1.0 msec	2000 f_n	0.5 (a)	1.0	1.0				1.1 v		b) Operating range to +450°F on special order
			0-500			0.5 (a)	1.0	1.0				0.8 v		
Sensotec Division Scientific Advances, Inc.	SA-1A 8C-(b)	+160/0	0-50		100^k f_n	±0.50 (a)	6.0	6.0			Bonded	100 mv/ 5 vdc		a) Linearity and hysteresis
			0-100		100^k f_n	±0.50 (a)	6.0	6.0			Semiconductor	100 mv/ 5 vdc		b) 1/8 dia
			0-500		100^k f_n	±0.50 (a)	6.0	6.0			Strain Gage	100 mv/ 5 vdc		
Kulite Semiconductor Products	CPS 125-200 (b) LPS 200-200 (a)	+180/0	0-200		25^k	±0.5	1.0	1.0			Diffused Semiconductor Strain Gage	100 mv/ 5 vdc	Infinite	a) Used for measuring surface pressure of turbine blades 0.2 dia x .05 long
	CPL-070-25 (b)	+180/0	0-25		20^k	±1.0	1.0	1.0			Silicon Diaphragm	100 mv/ 5 vdc	Infinite	b) .07 dia x .25 long
Honeywell	PG61 (a)	+160/0	0.5-15		1-2	±0.05	±0.085	comb. with zero	comb with amb. accy.		Force Vector re-balance			a) Aircraft use
Datametrics Incorporated	511 (a)	+150/0	0-10	0.003		(a)	0.05	1.0 (read.)			Capacitance	±5 vdc (b)		a) ±2.0% reading +0.03% F.S.
			0-100	0.003		(a)	0.05	1.0 (read.)				±5 vdc (b)		Wind tunnel application
			0-1000 mmHg	0.003		(a)	0.05	1.0 (read.)				±5 vdc (b)		b) Includes signal conditioner
Robinson-Halpern	P-20 & P-21	+150/0	0-60	0.5		±0.25	1.0	1.0			LVDT	±5 vdc (a)	Infinite	a) Includes signal conditioner
	P-25 & P-26	+150/0	0-60	0.5		±0.15	1.0	1.0			LVDT	±5 vdc (a)		
	P-40 & P-41	+150/0	0-100	0.5		±0.5	2.0	2.0			LVDT	±5 vdc (a)		
			0-600											
Aerometrics Div. Aerojet-General Corp.	PT301	+130/30	0-1000		15^k f_n	0.45	0.5	0.5			Bonded Strain Gage	3 mv/v		a) Helium bleed, use in liquid rocket engine
	HB3X (a)	30 $\frac{Btu}{in^2\ sec}$			3.5^k to 9.4^k f_n	5 to 10								

*Metal diaphragm unless otherwise indicated

Table III. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	PRESS RANGE PSIA	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT %F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Conrac Corp. (Giannini Controls)	4715	+250/-320	0.5-50	0.0018 (a)	250	0.13	0.5	0.5	0.004		Silicon Diaphragm, Semiconductor Strain Gage		Infinite	a) To 90% rise
			1.5-100	0.0018 (a)	250	0.13	0.5	0.5	0.004				Infinite	
			10 -500	0.0018 (a)	250	0.13	0.5	0.5	0.004				Infinite	
	451329	+225/-65	0-15 to 0-100	0.006		±1.0	1.0	combined	0.025	50^k cycles @ F.S.	Capsule Potentiometer		0.25	
	461319	+225/-65	10-500	0.006		±0.9	1.0	combined	0.02	25^k cycles @ F.S.	Burdon, Potentiometer		0.25	
United Sensor & Control Corp.	Pressure Probes Wedge & Cobra Types					(a)								Aircraft and missile application a) Primary Probe error P_{total} - 0.1% P_{static} - 1.0%
Rocketdyne Division North American Rockwell Corp.	Sub. miniature (c)	+350/-425	0-100		40^k to $140^k f_n$	0.25 (a)	(b)	(b)			Bonded Semiconductor Strain Gage	40 mv/ma		a) Hysteresis b) Semiconductor temp. sensor mounted on sensing diaphragm to compensate for temp effects. c) Not production items d) Erodable tip only
			0-500											
	Probe type (c)	+1000/-420 (d)	0-100		15^k to $100^k f_n$	0.5 (a)					Semiconductor Strain Gage Mounted on Cylindrical Rod	0.05 to 2.0 v		
			0-200											
			0-500											
Zitzewitz Electronic Laboratories	51F10 and 51F11		160 kg/cm^2 250 kg/cm^2		Static to 100 k						Capacitance	Frequency Modulated (a)		a) Designed for use with reactance converter

*Metal diaphragm unless otherwise indicated

Table IV. Survey Data, Differential Pressure Sensor, Present Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	PRESS RANGE PSID	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT %F.S./100°F ZERO	TEMP. EFFECT %F.S./100°F SENSITIVITY	VIBR. EFFECT %F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Consolidated Controls Corp.	41M2	+900°/-430	±5	0.0003	500	±1.0	0.5	0.5	0.04		LVDT	0-5 vdc (a)	Infinite	Used in supersonic aircraft, nuclear reactors
			±30	0.0003	500	±1.0	0.5	0.5	0.012		LVDT	0-5 vdc (a)		
			±50	0.0003	500	±1.0	0.5	0.5	0.007		LVDT	0-5 vdc (a)		a) Includes signal conditioner
Consolidated Electrodynamics Corp.	4-316-0001	+650/-320	±5	0.001	$7.8^k f_n$	±1.0	2.0	1.0	0.12		Unbonded Strain Gage	±10 mv		
			±25		$7.8^k f_n$	±1.0	2.0	1.0	0.12			±10 mv		
Statham Instruments, Inc.	PM732TC	+600/+75	±5	40 µsec	$4.4^k f_n$	±0.75 (a)	1.0	1.0	0.04		Unbonded Strain Gage	±1.5 mv/v	Infinite	a) Combined nonlinearity and hysteresis
			±25	40 µsec	$7.5^k f_n$	±0.75 (a)	1.0	1.0	0.01					
			±50	40 µsec	$8.7^k f_n$	±0.75 (a)	1.0	1.0	0.01					
Consolidated Controls Corp.	41GB25	+500/-65	±5	0.005	1100 f_n	1.0	±1.5	±1.5	0.04		LVDT	0-5 vdc (a)		Military applications
			±20	0.005	1600 f_n	1.0	±1.5	±1.5	0.01		LVDT	0-5 vdc (a)		
			±60	0.005	2900 f_n	1.0	±1.5	±1.5	0.006		LVDT	0-5 vdc (a)		a) Includes signal condioner
Teledyne Systems Company, Control Systems Company	TR2232-1	+500/	±20	0.01	60	0.05	0.02	0.06	0.0025		Twisted Bourdon Tube Variable Reluctance	0-5 vdc (a)	Infinite	a) Includes signal conditioner
	TR2232-4		±50	0.012	56	0.05	0.02	0.06	0.0025			0-5 vdc (a)		
Bytrex, Inc.	HFF (c)	+400/	0-15		$25^k f_n$	±0.5 (b)	1.5 (a)	1.5			Semiconductor Strain Gage			a) Compensated over any 100°F Range
			0-25		$35^k f_n$	±0.5 (b)	1.5 (a)	1.5						b) Non linearity
			0-50		$35^k f_n$	±0.5 (b)	1.5 (a)	1.5						c) Miniature 0.25 dia x 0.45 long
Statham Instruments, Inc.	PM260TC	+400/-65	±5	40 µsec	$5^k f_a$	±0.75 (a)	1.0	1.0			Unbonded Strain Gage	±20 mv	Infinite	a) Combined nonlinearity and hysteresis
			±25	40 µsec	$9^k f_n$	±0.75 (a)	1.0	1.0				±20 mv		
Servonic Instruments, Inc.	3321	+400/-320	±5	0.006		1.0	1.0	Comb. with zero	0.05	250^k cycles at 1.3 F.S.	Capsule Pot.			
			±20	0.006		0.9			0.05					
			±50	0.006		0.9			0.05					

*Metal diaphragm unless otherwise indicated

Table IV. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	PRESS RANGE PSID	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Fairchild Controls	TDF 150	+350/-65	0-10		$10^k f_n$	±0.5	0.5	0.5	0.001	500^k cycles	Bonded Semiconductor Strain Gage	250mv/ 20 vdc	Infinite	a) 1 lb (TDF 150)
			0-20		$12^k f_n$	±0.5	0.5	0.5	0.001	500^k cycles		250mv/ 20 vdc		
			0-50		$15.8^k f_n$	±0.5	0.5	0.5	0.001	500^k cycles		250mv/ 20 vdc		
	TDF 200	+350/-55	0-5		$1^k f_n$	±0.2	0.25	0.25	0.001		Bonded Foil Strain Gage	3mv/vdc	Infinite	
			0-20		$1^k f_n$	±0.2	0.25	0.25	0.001					
			0-50		$1^k f_n$	±0.2	0.25	0.25	0.001					
Dynisco	PT69C	+300/-65	±5			±1.0 (a)	2.0	1.0			Unbonded Strain Gage	2mv/v		a) Combined non-linearity and hysteresis.
			±25			±1.0 (a)	2.0	1.0				2mv/v		
			±50			±1.0 (a)	2.0	1.0				2mv/v		b) 1 lb (PT69C)
	PT85	+300/-65	±5		$5^k f_n$	±0.75 (a)	2.0	1.0				4mv/v		
			±10		$7^k f_n$	±0.75 (a)	2.0	1.0			Unbonded Strain Gage	4mv/v		
Consolidated Electrodynamics Corp.	4-312-0002	+300/-320	±25	0.05	$8^k f_n$	±1.0	1.2	1.0	0.03		Unbonded Strain Gage	±10 mv	Infinite	
			±50			1.0	1.2	1.0	0.03		Unbonded Strain Gage	±10 mv		
	4-313-0002	+300/-320	±15	0.05	6^k to 15^k f_n	1.0	1.2	1.0	0.04		Unbonded Strain Gage	±10 mv	Infinite	
			±25			1.0	1.2	1.0	0.04		Unbonded Strain Gage	±10 mv		
			±50			1.0	1.2	1.0	0.04		Unbonded Strain Gage	20 mv		
	4-325	+300/-320	±25		$15^k f_n$	1.0	3.0	2.0	0.03		Unbonded Strain Gage	20 mv	Infinite	
			+50		$15^k f_n$	1.0	3.0	2.0	0.03		Unbonded Strain Gage	20 mv		
Sensotec Division Scientific Advances, Inc.	SA-SD M-6 M-7 (c)	+300/-100	±5		100^k	±0.50 (a)	1.0	1.0			Bonded Semi-Conductor Strain Gage	60mv/ 3 vdc		a) Linearity and hysteresis
			±30		100^k	±0.50 (a)	1.0	1.0				60 mv/ 3 vdc		b) Used in Wind Tunnel studies
			±50		100^k	±0.50 (a)	1.0	1.0				60 mv/ 3 vdc		c) 1/4 dia. x 1/4 thick

*Metal diaphragm unless otherwise indicated

Table IV. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	PRESS RANGE PSID	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F S.	TEMP. EFFECT % F. S. /100°F ZERO	TEMP. EFFECT % F. S. /100°F SENSITIVITY	VIBR. EFFECT %F. S. /g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Rosemount Engineering Company	831	+250/-65	±16	0.025	30	0.15	1.0	Combined with zero	0.04		Capacitance	0-5 vdc (a)	0.02	a) Includes signal conditioner
MB Electronics	Series 151	+250/-100	0-10		$3.4^k f_n$	0.25	0.5	0.35	0.1		Bonded Strain Gage	3mv/v		a) Used in Apollo-Saturn L. E. M.
			0-20		$3.6^k f_n$	0.2	0.25	0.25	0.03			3mv/v		
			0-50		$5^k f_n$	0.2	0.25	0.25	0.025			3mv/v		
	Series 152	+250/-100	0-20		$3.8^k f_n$	0.35	1.0	0.35	0.03		Bonded Strain Gage	3mv/v		
			0-50		$5^k f_n$	0.35	1.0	0.35	0.025			3mv/v		
Servonic Instruments, Inc.	3135	+257/-80	±5	0.005		±1.0 (a)	2% Environmental error includes acceleration, vibration, shock and temperature			10^6 cycle	LVDT	0-5 vdc (b)		a) Including friction
			±20											b) Includes signal conditioner
			±50											
Statham Instruments, Inc.	PM280TC	+250/-65	±5	0.001	$5^k f_n$	±1.0 (a)	1.0	1.0			Unbonded Strain Gage	±20 mv	Infinite	a) Combined nonlinearity and hysteresis
			±25	0.001		±1.0 (a)	1.0	1.0			Unbonded Strain Gage	±20 mv		
			+50	0.001	$9.5^k f_n$	±1.0 (a)	1.0	1.0			Unbonded Strain Gage	±20 mv		
	PM131TC	+250/-65	+5	40 μsec		±0.75 (a)	1.0	1.0			Unbonded Strain Gage	±20 mv	Infinite	
			±25	40 μsec		±0.75 (a)	1.0	1.0			Unbonded Strain Gage	±20 mv		
Standard Controls, Inc.	600	+250/-65	±500			±0.25	1.0	0.5			Bonded Strain Gage	40 mv		a) Used in Titan III, Saturn S-II, Nerva, etc.
Pace Wiancko (Whittaker Corp)	P1, P3D, P7, P21,	+250/-423	+0.1 to ±5000			±0.50	1.0	2.0			Variable Reluctance	50mv/v at 3000 Hz		a) Aircraft and missile flight application
	P2	+25/-423	0-200 to 0-10,000			±0.50	1.0	2.0			Variable Reluctance	50mv/v at 3000 Hz		
	P109D	+250/-65	±1		$5^k f_n$	±0.50	1.0	2.0	0.2		Variable Reluctance	25mv/v		
			±15		$8^k f_n$	+0.50	1.0	2.0	0.05		Variable Reluctance	25mv/v		

*Metal diaphragm unless otherwise indicated

Table IV. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	PRESS RANGE PSID	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Pace Wiancko (Continued)	CP51, CP52, CP53D, CP60	+250/-65	±0.1 to ±2500		1000	±0.5	1.0	2.0			Variable Reluctance	±5 vdc (a)		a) Includes signal conditioner
Consolidated Controls Corp.	41GB25	+250/-65	±5	0.005	1100 f_n	1.0	±1.5	±1.5	0.04		LVDT	0-5 vdc (a)	Infinite	a) Includes signal conditioner
			±20	0.005	1600 f_n	1.0	±1.5	±1.5	0.01		LVDT			
			±60	0.005	2900 f_n	1.0	±1.5	±1.5	0.006		LVDT	0-5 vdc (a)		
	41PL20	+200/-65	±5	0.005	300	1.5	1.0	1.0	0.04		LVDT	0-5 vdc (a)	Infinite	
			±20	0.005	300	1.5	1.0	1.0	0.01		LVDT	0-5 vdc (a)		
			±60	0.005	300	1.5	1.0	1.0	0.006		LVDT	0-5 vdc (a)		
Schaevitz Engineering	PT-1	+200/-65 (a)	0-5.4	0.7 to 3.5 msec	45 to 230 f_n	0.5 (b)	1.0	1.0			LVDT	1.2 v	Infinite	a) Higher temp available on special order.
			0-10.8			0.5 (b)	1.0	1.0				1.2 v		
	PT-2	+200/-65 (a)	0-25	0.3 to 1 msec	160 to 2000 f_n	0.5 (b)	1.0	1.0			LVDT		Infinite	b) Hysteresis.
			0-50			0.5 (b)	1.0	1.0						
Robinson-Halpern	P-60	+200/-40	0-6	0.050		±1.0	2.0	2.0			Capsule Pot.		0.25 to 0.40	
			0-30											
			0-60											
Crescent Tech	B-9	200/-30	0 to 5											Used in Atlas Missile.
BLH Electronics, Inc.	Series 1000	+200/0	3.6	0.02		±0.1	±0.5	±0.5	0.2		Bonded Strain Gage	1.5mv/v		a) 10 lb
			10.8	0.02		±0.1	±0.5	±0.5	0.2					
			28.9	0.02		±0.1	±0.5	±0.5	0.2					
Sensotec Division Scientific Advances, Inc.	SA-1D 8C-(c)	+180/0	± 5		100k	±0.50 (a)	6.0	6.0			Bonded Semiconductor Strain Gage	100mv/ 5 vdc		a) Linearity and hysteresis. b) Jet engine inlet studies. c) 1/8" dia.
			±30		100k	±0.50 (a)	6.0	6.0						
			±50		100k	±0.50 (a)	6.0	6.0						
Datametrics Inc.	Type 1053	+175/-40	±5		25k f_n	±0.5 (b)	±0.7(b)	0.015			Variable Capacitance Bridge	±5 vdc (a)		Rocket and Aerospace application. Possible development for a/c use temp 750°F. a) Includes signal conditioner b) % of reading
	Type 1014	+175/-40	0- 5.8	0.003		±0.25 (b)	0.05	1.0 (b)				±5 vdc (a)		
			0-19.4	0.003		±0.25 (b)								
			0-30	0.003		±0.25 (b)								

*Metal diaphragm unless otherwise indicated

Table IV. (Cont)

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	PRESS RANGE PSID	STEP RESP. SEC.	FREQ RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT %F.S./100°F ZERO	SENSITIVITY	VIBR. EFFECT %F.S./g	LIFF	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S	OTHER DATA AND REMARKS
Honeywell	PG72	+160/-65	0-500kn IAS (8.5 psid)		2 to 6	±0.07	±0.12	Incl. in zero	Incl. in amb. accy				±0.00075	a) Aircraft use.
BLH Electronics, Inc.	MM	+150/-50	±5	0.015	110 f_n	0.10 (a)	0.25	0.5			Bellows, Bonded Strain Gage	3mv/v		a) Hysteresis
			±15	0.005	330 f_n	0.10 (a)	0.25	0.5						
			±30	0.005	370 f_n	0.10 (a)	0.25	0.5						
			±60	0.005	510 f_n	0.10 (a)	0.25	0.5						
Statham Instruments Inc.	PM222TC (d)	+150/0	±5	40 μsec	7k	±1.0 (a)	2.0	5.0			Unbonded Strain Gage	±2mv/v	Infinite	a) Combine nonlinearity and hysteresis.
			±25	40 μsec	12k	±1.0 (a)	2.0	5.0				±2mv/v		b) Compensated range.
	PM385TC (e)	+150/0 (b)	±5	40 μsec		±0.75 (a)	1.0	1.0				±3mv/v		c) 6.5 lb (PM 385TC)
			±25	40 μsec		±0.75 (a)	1.0	1.0				±3mv/v		d) 0.31 dia x 0.6 long (PM 222TC)
			±50	40 μsec		±0.75 (a)	1.0	1.0				±3mv/v		
Robinson-Halpern	P-20 & P-21	+150/0	0-6, 0-30	0.5		±0.25	2.0	2.0			LVDT	5 vdc (a)	Infinite	a) Includes signal conditioner
	P-25 & P-26	+150/0	0-60	0.5		±0.15	1.0	1.0			LVDT	5 vdc (a)		
	P-40 & P-41	+150/0	0-60	0.5		±0.5	2.0	2.0			LVDT	5 vdc (a)		
	P-45 & P-46	+150/0	0-60	0.5		±0.15	1.0	1.0			LVDT	5 vdc (a)		
Decker Corp.	308	+140/0	±3.6			+1.0	5.0	5.0			Capacitance	±10 vdc (a)	2.5 mv rms noise	a) Includes signal conditioner
	360	+140/0	±3.6			+1.0	5.0	5.0			Capacitance	±5 vdc (a)	1.0 mv rms noise	
	362	+120/0	±3.6			+1.0	5.0	5.0			Capacitance	±5 vdc (a)	1.0 mv rms noise	
Conrac Corp. (Giannini Controls)	451329	+225/-65	±5, ±20, ±100	0.006		±1.0	1.0 Combined		0.025	50k cycles @ F.S.	Potentiometer, Capsule		0.25	
	461319	+225/-65	±5, ±20, ±100	0.006		±0.9	1.0 Combined		0.02	25k cycles @ F.S.	Bourdon, Potentiometer		0.25	

*Metal diaphragm unless otherwise indicated

Table V. Survey Data Pressure Ratio Sensor (P/P) Present Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	RATIO	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT. % F.S./100°F		VIBR. EFFECT. % F.S./g	LIFE	SENSING ELEMENT	OUTPUT TYPE	RESOLUTION % F.S.	OTHER DATA AND REMARKS
							ZERO	SENSITIVITY						
Honeywell	LG80A2	+250/-80	0.8 - 2.5	6.0	10	±0.5	0.2	0.25	0.05	15,400 hr. (a)	Bellows			a) Predicted MTBF
	LG80G2	+250/-80	0.8 - 7.0	5.0	15	±0.5	0.2	0.25	0.05		Bellows			
Rosemount Engineering Company	832 F1	+158/-67	2:1 5:1 40:1 (b)	0.05	2	0.5 (b)	0.5	0.5	0.04		(pressure sensors) (a)	Capacitance to dc Voltage	0.01	a) Calculated Electronically b) $P_1 - P_2 - 4$ psid $P_3 - P_4 = 2$ psid

Table VI. Survey Data, Pressure Ratio Sensor (ΔP/P), Present Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP. RANGE °F	RATIO	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT. % F.S./100°F ZERO	TEMP. EFFECT. % F.S./100°F SENSITIVITY	VIBR. EFFECT. % F.S./g	LIFE	SENSING ELEMENT	OUTPUT TYPE	RESOLUTION % F.S	OTHER DATA AND REMARKS
Teledyne Systems Company, Control Systems Division	TR2017-12	-200/-65	0.05 - 0.25	1.0	10	0.2	0.2		0.02		Bellows Force Rebalance	AC	0.08	
	TR2017-51	+200/-65	0.2 - 0.7	1.0	10	0.2	0.2		0.02			AC	0.06	
			0.3 - 0.97	1.0	10	0.2	0.2		0.02			AC	0.05	
Rosemount Engineering Company	832	+158/-67	0.05 - 0.25			1.0			0.04		Pressure sensors electronically ratioed		0.05	
			0.2 - 0.7			1.0			0.04					
			0.3 - 0.97			1.0			0.04					
Consolidated Controls Corp.			(Mach No.)			(Mach No.) (units)					Pressure sensors electronically ratioed			a) Altitude limit 10^k to 60^k ft. b) 0.2% F.S. total accuracy of pressure sensors (not including temperature effects) 1.0% F.S./100 F temperature shift. c) Worst-case accuracy @ 60^k ft better accuracy at lower altitudes. d) ΔP range 0-5 psid P range 0-10 psid
			0.3			±0.024 (c)								
			0.5			+0.0166 (c)								
			0.7			+0.0138 (c)								
			1.0			±0.046 (c)								
			1.5			±0.040 (c)								
			1.9			±0.030 (c)								

Table VII. Survey Data, Temperature Sensor, Present Capabilities

MANUFACTURER	MODEL NUMBER	TEMP RANGE (°R)	STEP RESP. (SEC)	AMBIENT ACCY % F.S.	TEMP. DRIFT % F.S./100°F	VIBR. % F.S./g	LIFE	SENSING ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Rosemount Engineering Company	135N	350 - 1500	1.5 (a)	0.2	1.5	0.003	600 hr	Platinum Resist.	AC or DC	0.1	a) at 12 lb/sec/ft^2 Turbojet CDT
	132DY	800 - 2300	4.0 (a)	0.2	1.5	0.003		Platinum Resist.	AC or DC	0.1	Turbojet TIT
	117N	1200 - 2900	2.0 (a)	0.8	0.02	0.001		Platinum Resist.	DCMV	0.3	Saturn S-IC
Aerometrics Division Aerojet-General Corp.	CT-12	1000 - 4500	0.5	±1.0				Thermocouple			
	PT101	Ambient - 4460	0.5	1.0							
Thermowell Inc.	A2-2199	492 - 3660	0.5	±2.0 (a)				Thermocouple	MV		a) % of reading
	A2-2201	492 - 3660	0.5	±2.0 (a)							
	A2-2200	492 - 3710	0.5	±0.75 (a)							
	A2-2202	494 - 2710	0.5	±0.75 (a)							
Thermo-couple Products Company, Inc.	Various	160 - 2860	(a)	±3/8 to ±2 (a)				Thermocouple			a) ISA Specs.
West Inst. Corp.	Various	160 - 3360		±0.5 to ±0.75 ISA				Thermocouple			
Temtech	180A	400 - 960	2.0 (a)	1.0				Platinum Resistance Thermometer			a) 200 ft/sec. b) air to boiling water c) air to water moving at 3 ft/sec. d) air to 180° water moving at 3 ft/sec.
	1830	460 - 1960	2.0 (b)					Resistance Thermometer			
	1139	460 - 2260	1.5 (c)					Resistance Thermometer			
	7108	460 - 2760	1.0 (d)	0.5				Thermocouple	MV		
Zitzewitz Elec. Lab.	55A74	Max. 1840						Platinum- (a) Iridium Wire			a) anemometer probe
Conax	Various	160 - 4860	range (a) 0.2 to 24.0	±0.5 to (b) ±0.75 ISA				Thermocouple and Thermistors	0.03 mv/F 400 Ω/F		a) in water, for air @ 10 ft/sec. multiply by factor 4 b) ISA Specs.
Kulite Semiconductor Products	ST 2000 - 250	360 - 810	0.028 (a)	0.5	N/A	N/A	N/A	Semiconductor	20 mv/°F	Infinite	a) ambient air to hot dynamic air
	BHO 2000 - 130	360 - 810									
Electro-Optical Systems, Inc. (Whittaker Corp.)		210 - 960	0.028(a)	±0.75(b)				Semiconductor	20 mv/°F		a) static ambient air to hot dynamic air b) linearity

Table VII. (Concluded)

MANUFACTURER	MODEL NUMBER	TEMP RANGE (°R)	STEP RESP. (SEC)	AMBIENT ACCY % F.S.	TEMP. DRIFT % F.S./100°F	VIBR. % F.S./g	LIFE	SENSING ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Heat Technology Laboratory Inc.	B802	160 - 2260 660 - 2460	0.1	+3.0, -4.0				Thermocouple			
	B810	160 - 2260	0.5	+3.0, -4.0				Thermocouple			
	B-10000	160 - 2260	0.5	+3.0, -4.0				Thermocouple			
Hy-Cal Engineering	TC-1000	Up to 4960						Thermocouple			a) Used for Engine monitoring, and in Apollo, LEM, Minuteman
	TC-2000							Thermocouple			
	RTS-4000	8 to 672						Platinum Resistance			
	RTS-5000							Platinum Resistance			
Raytek Inc.	R-200 (series)	520-1060 (a)	2.0	±1				Infrared	0-10 MVDC or 0-50 μamp		a) All series have several ranges.
	R-300 (series	720-2660	0.1	±1				Infrared			b) Environment Temperature 500 - 600 R cooling water required above 580 R. for detector
	R-400 (series)	1510-3660	0.1	±1				Infrared			
Omega Engineering Inc.	Various	760 - 2760	0.0004 to [illegible] 3.2					Thermocouple	MV		a) 60 ft/sec air 800 F/100 F
United Sensor & Control Corp.	Various probes	to 2460		(a)				Thermocouple			a) Below 960 R - 1.0° Above 560 R 5.0° b) Aircraft/missile applications.
Rockeldyne Division North American Rockwell Corporation (a)	Radiometer (b)										a) Developmental Work.
	Heat flux	10 BTU/in.^{2} - sec @ 1100 F	0.1					Thermocouple			b) Radiometer to measure combustion chamber gas temperature.

Table VIII. Survey Data, Accelerometer, Present Capabilities

MANUFACTURER	MODEL	TEMP RANGE °F	ACCEL. RANGE g	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	TRANS. ACCEL. g/g	LIFE CYCLES	SENSING ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Consolidated Electrodynamics Corporation	4-205-001	+300/-70	±1.0		90 f_n	±0.75	1.0	1.0	0.01		Unbonded Strain Gage	40 mv	Infinite	
			±2.5		155 f_n	±0.75	1.0	1.0	0.01		Strain Gage	40 mv		
			±5.0		250 f_n	-0.75	1.0	1.0	0.01		Strain Gage	40 mv		
	4203-001	+300/-70	±5.0		300 f_n	+0.75	1.0	1.0	0.01		Strain Gage	40 mv	Infinite	
	4202-001	+300/-70	±5.0		300 f_n	±0.75	1.0	1.0	0.01		Strain Gage	40 mv	Infinite	
Genisco Technology Corporation Components Division	2388	+300/-100	±2.0		10	1.5	Included In Accy		---		LVDT	5 VAC	0.0002 g's	
			±5.0		15	1.5	Included In Accy		---		LVDT	5 VAC	0.0005 g's	
	2387	+250/-100	±5.0		12	1.5	Included In Accy		0.02	10^6	Pot.	DC	0.032 g's	
Statham Instruments, Inc.	A69TC	+250/-65	±5.0		375 f_n	±0.75	1.0	1.0	0.01		Strain Gage	4 mv/v	Infinite	a) Damped 0.7 ±0.1 of critical @ room temp.
	A514TC (b)	+250/-65	±7.5		600 f_n	±0.75	1.0	1.0	0.01		Strain Gage	4 mv/v	Infinite	b) Air damped
	A73TC	+250/-65	±1.0		150 f_n	±0.75	1.0	1.0	0.01		Strain Gage	4 mv/v	Infinite	
			±2.5		230 f_n	±0.75	1.0	1.0	0.01		Strain Gage	4 mv/v	Infinite	
			±4.0		300 f_n	+0.75	1.0	1.0	0.01		Strain Gage	4 mv/v	Infinite	
Schaevitz Engineering	LSB Series	+250/-40	±0.5		50 f_n	±0.05		0.5	0.002		Pendulous Force Balance Closed Loop Type	5 VDC	0.0002	a) Damping 0.3 to 0.8 of critical
			±2.0		90 f_n	±0.05		0.5	0.002			5 VDC	0.0002	
			±5.0		100 f_n	±0.05		0.5	0.002			5 VDC	0.0002	
Genisco Technology Corporation Components Division	2396	+200/-65	±0.5		4	1.5	Included In Accy		0.02	20(10^6)	LVDT	AC	0.00002 g's	
			±5.0		15	1.5	Included In Accy		0.02		LVDT	5 VAC	0.0005 g's	
	2386	+200/-65	±5.0		10	1.5		0.03	0.02		Pot.	DC	0.032 g's	
	2389	+200/-50	±5.0		9	1.5		0.03	0.02		Pot.	DC	0.032 g's	
Fairchild Controls		+200/-65	±0.5		15-200 f_n	±0.2								
			±2.0		15-200 f_n	±0.2								
			±5.0		15-200 f_n	±0.2								

Table VIII. (Cont)

MANUFACTURER	MODEL	TEMP. RANGE °F	ACCEL. RANGE g	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	SENSITIVITY	TRANS. ACCEL. g/g	LIFE CYCLES	SENSING ELEMENT	TYPE OUTPUT	RESOLUTION % F.S	OTHER DATA AND REMARKS
Endevco Corporation	QA-116-15	-200/-65	±15.0		1000 f_n	0.1	0.02	1.0	0.002		Pendulous, Fused Natural Quart	250 mv/g	0.00001g	Developing QA-123 series range -20g
Kistler Instrument Corp	303 B11	+185/-65	±0.5		190	±0.1	3.0	1.0			Capacitance, Closed loop	0 - 5v	5 μg's	
	B13		±2.0		330		1.0	1.0						
	B14		±5.0		390		0.3	1.0						
Genisco Technology Corporation Components Division	2385	+185/-65	±0.5		2	1.0		0.003	0.01	10^6	Pot.	DC	0.002 g's	
			±2.0		4	1.0		0.003	0.01		Pot.	DC	0.008 g's	
			±5.0		5	1.0		0.03	0.01		Pot.	DC	0.02 g's	
U.S. Time Corp.	AP-000	+187/-67	±2.5		25 f_n	±2.0	0.035	0.75			Pendulous, Transformer	14.2 v/g AC	0.0005 g's	a) Damping ratio 0.3 to 4.0
Sanders Associates Inc.	20	+185/-65	±5.0	2nd order (a)	39 f_n	2.3 (c)	0.066	5.0	0.007	1000 hr	Microsyn, Multipole Differential Transformer	AC	0.01	a) Damping ratio 0.4 - 2.0
	30	+185/-65	±0.5	2nd order (b)	25 f_n	2.3 (c)	0.085	5.0	0.0004	1000 hr		AC	0.025	b) Damping ratio 0.3 - 0.9
			±2.0		25 f_n	2.3 (c)	0.085	5.0	0.0016			AC	0.025	c) 0.2% F.S. for 1/2 Scale Range
Statham Instruments, Inc.	A404TC	+165/-65	±1.0		150 f_n	±1.0(b)	2.0	2.0			Unbonded	±2.5 vdc	Continuous	a) Damped 0.7 -0.1 of critical @ room temp.
			±4.0		300 f_n	±1.0(b)	2.0	2.0			Strain Gage	±2.5 vdc		
	A400TC	+165/-65	±5.0		375 f_n	±1.0(b)	2.0	2.0			Strain Gage	±2.5 vdc	Continuous	b) Non-linearity in hysteresis
Humphrey, Inc.	LA37-1507-1	+165/-65	±0.5		10 f_n	2.0	0.5	0.5	0.0005		Seismic mass		0.8	
	LA45-0124-1	+165/-65	±2.0		23 f_n	1.5	0.5	0.5	0.002		Pot.		0.8	
			±5.0		32 f_n	1.5	0.5	0.5	0.005				0.8	
Statham Instruments, Inc.	A402TC	+150/0	±5.0		250 f_n	1.0	2.0	2.0			Unbonded Strain Gage	-2.5 v	Continuous	
Humphrey, Inc.	LA46-0903-1	+140/-30	-0.5 to +2.5		40 f_n	1.5	0.5	0.5	0.01		Transformer	0.01 v/g (a)	0.0001	a) Into a 100k load
Statham Instruments, Inc.	AJ43	+125/-65	±2.5		60 f_n	1.0			0.02		Strain Gage Unbonded	4 mv/v	Continuous	
			±5.0		75 f_n	1.0			0.02		Strain Gage Unbonded	4 mv/v	Continuous	
	A52	Room Temp.	±5.0		250 f_n	2.0	None	None	0.03		Strain Gage Unbonded	4 mv/v	Continuous	
	A6	Room Temp.	±2.5		60 f_n	1.0	None	None	0.02		Strain Gage	4 mv/v	Continuous	
			±5.0		75 f_n	1.0	None	None	0.02		Strain Gage Unbonded	4 mv/v	Continuous	
	A5	Room Temp.	±1.0		70 f_n	1.0	None	None	0.02			4 mv/v	Continuous	
			±2.5		110 f_n	1.0	None	None	0.02			4 mv/v	Continuous	
			±5.0		190 f_n	1.0	None	None	0.02			4 mv/v	Continuous	

Table VIII. (Concluded)

MANUFACTURER	MODEL	TEMP RANGE °F	ACCEL RANGE g	STEP RESP SEC	FREQ RESP HZ	AMBIENT ACCY % F.S.	TEMP EFFECT % F.S./100°F ZERO	TEMP EFFECT % F.S./100°F SENSITIVITY	TRANS ACCEL g/g	LIFE CYCLES	SENSING ELEMENT	TYPE OUTPUT	RESOLUTION % F.S	OTHER DATA AND REMARKS
Conrac Corp. (Giannini Controls)	24991	·250/-65	±0.5	2nd order	to 1k f_n	±0 2	0.5				Piezoresistive		Infinite	a) Damping ratio 0.5 to 0.8 of critical
			±2.0	2nd order										
			±5.0	2nd order										
	24171	±200/-65	±2.0	(a)	· 9 f_n	±0.67	Included in Ambient Accuracy		0.005		Potentiometer		0.25	
			+5.0	(a)	14 f_n	±0.67	Included in Ambient Accuracy		0.005		Potentiometer		0.25	
			±10	(a)	20 f_n	±0.67	Included in Ambient Accuracy		0.005		Potentiometer		0.25	
General Precision Inc., Kearfott Group	C70 2401, Mod H series	+250/-85	to ±100	(a)	60-600 f_n	(b)					Force Balance Closed Loop			a) Damping 0.7 to 200 times critical.
	Mod V series	+250/-85	20	(c)	to 600 f_n	(b)						2.1 ma/g		b) Linearity error $3 \times 10^{-6} g/g^2$
														c) Linearity error $3 \times 10^{-5} g/g^2$
Pace-Wiancko (Whittaker Corp.)	A 18	-165/0	±1		75 f_n	±0.25(a)	1.0	2.0	0.01		Variable Reluctance			a) Hysteresis
			±20		335 f_n	±0.25(a)	1.0	2.0	0.01					b) 3 oz. (A 18) 7 oz. (CA 19)
			+50		530 f_n	+0.25(a)	1.0	2.0	0.01					
	CA 19	-165/0	±1		100 f_n	±0.25(a)	1.0	2.0	0.01		Variable Reluctance	±5vdc		
			±20		450 f_n	±0.25(a)	1.0	2.0	0.01					
			±50		700 f_n	±0.25(a)	1.0	2.0	0.01					

Table IX. Survey Data, Angular Rate Sensor, Present Capabilities

MANUFACTURER	MODEL NO.	TEMP. RANGE °F	$\dot{\theta}$ /SEC	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S/g	LIFE	SENSING ELEMENT	OUTPUT TYPE	RESOLUTION °/SEC	OTHER DATA AND REMARKS
Sanders Associates, Inc.	RGR	+270/−65	2.0	(a)	74 f_n	2.3	0.085	5.0	0.04		Microsyn, Multipole Differential Transformer	AC	0.1	a) Damping ratio 0.3 to 0.9
	RGB, RGG	+212/−65	±40.0	(a)	22 f_n	±5.0				1000 hr.		140 mv/°/sec	0.004	b) Used Missile and Rocket systems
Fairchild Controls	RG101	+200/−65	±2.0		15-200 f_n	±0.3				1000 hr.	Transformer	6 v, 400 Hz	0.01	
			±10.0		15-200 f_n								0.01	
			±30.0		15-200 f_n								0.01	
Sanders Associates, Inc.	RGP	+185/−65	10	(a)	35 fn	2.3	0.066	5.0	0.04		Microsyn, Multipole Differential Transformer	AC 50 mv/°/sec	0.01	a) Damping ratio 0.3 to 0.9
	RGA, RGC	+185/−65	±10	(a)	26 fn	±0.4				1000 hr.		140 mv/°/sec	0.004	b) Used in missile and rocket systems.
U.S. Time Corp	SD-010	+185/−65	±10	2nd order	26 f_n	±0.5	0.12	0.75			Gyro to variable tran	140 mv/°/sec	0.01	a) Damping ratio range approx. 0.3 to 4 depending on temp.
	SD-040		±40	2nd order	26 f_n	±2.0	0.035	0.75			Gyro to variable tran	140 mv/°/sec	0.01	
	CD-010	+185/−65	±10	2nd order	23 f_n	±0.5	0.12	0.75			Gyro to variable tran	140 mv/°/sec	0.01	
	CD-040		±40	2nd order	23 f_n	±2.0	0.035	0.75			Gyro to variable tran	140 mv/°/sec	0.01	
	STCD-060	+185/−65	±60	2nd order		±3.0	0.1	1.9						
Condor Pacific Industries, Inc.	R83	+165/−65	±2	2nd order (a)	2 f_n	1.0	0.25	0.5	0.1	1000 hr	Pot.		0.5% FS	a) Damping ratio 0.3 to 2.0
			±10	2nd order (a)	5 f_n	1.0	0.25	0.5	0.1	1000 hr	Pot.		0.5% FS	b) 1.7 lb
			±30	2nd order (a)	10 f_n	1.0	0.25	0.5	0.1	1000 hr	Pot.		0.5% FS	c) Life is minimum
Humphrey, Inc.	RG28	+165/−65	±2	2nd order (a)	2 (5 f_n)	2.0 to 3.0	0.5	0.5	0.1		Pot.		0.5% FS	a) Damping ratio -0.6 may vary from 0.1 to overdamped.
			±10	2nd order (a)	3 (9 f_n)	2.0 to 3.0	0.5	0.5	0.1		Pot.		0.5% FS	
			±30	2nd order (a)	5 (15 f_n)	1.0 to 2.0	0.5	0.5	0.1		Pot.		0.5% FS	
General Precision, Inc., Kearfott Group	C70-2023	+185/−65	to 400		15 to 150 f_n	(a)			(b)		Closed Loop, Differential Transformer	6 mv/°/sec to 350 mv/°/sec		a) Hysteresis - 0.02°/sec or 0.05% F.S. whichever greater. b) 0.03°/sec/g or 0.05% F.S. whichever greater.
Conrac Corp (Giannini Controls)	36636	+165/−65	±10 ±30		to 48 f_n	(a)	Included in ambient accuracy		0.06 DA/15g @ 20-2K Hz		Microsyn, Multipole Differential Transformer		0.05% FS 0.05% FS	a) Linearity 0.3% hysteresis 0.2%

Table X. Survey Data, Angle of Attack Sensor, Present Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP RANGE °F	ANGLE DEG.	STEP RESP. SEC.	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT F.S./100°F ZERO	TEMP. EFFECT F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING ELEMENT	OUTPUT TYPE	RESOLUTION % F S	OTHER DATA AND REMARKS
Rosemount Engineering Company	858D	(a)	Various[b] to ±40			Various[c]					Differential Pressure Sensors, Ref Model #800E3			a) Withstand 400°C for 48 hours. b) Depends on mach. No. (±15° @ M ≥ 0.7) c) To ±0.1%.
Honeywell, Inc.	LG80		±20											
Teledyne Systems Company, Control Systems Division	CTR-803	-257/-100	±35	0.05	3.5	0.2	0	0	0.0008		Wind Vanes	Pot.	Infinite	
	TR-542	+158/-130	±30	0.05	1.0	0.4	0	0	0.0016		Wind Vanes	Pot.	Infinite	
	TA-107	/-100	±35	0.05	3.5	0.5	0	0	0		Wind Vanes	Synchro and linear transformer	Infinite	
Conrac Corp. (Giannini Controls)	2562	+165/-65	±5	(a)	(a)	±0.25°					Vanes	Synchro	Infinite	a) Per MIL-T-25627.
			±20	(a)	(a)	±0.25°								
			±30	(a)	(a)	±0.25°								
	25623	+165/-65	-45	(b)		-0.2°					Double Vane	Synchro		b) Velocity 40 Knots to Mach 3

Table XI. Survey Data, Absolute Pressure Sensor, Extrapolated Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP. LIMIT °F	PRESS RANGE PSIA	STEP RESP. SEC	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Bytrex, Inc.	Silicon Diaphragm	+1000/-100	10-500	0.0001 to 0.0005 Undamped	2-10 k f_n	±0.5	1.0 (a) 0.5 (b)	1.0 (a) 0.5 (b)	-	100 x 10^6 cycles	Silicon diaphragm/ semiconductor strain gain		Inf.	1.0 Dia. x 4.0 long a) Over complete range b) Over any 200° F range
Conrac Corp (Giannini Controls)	Silicon Diaphragm	1100	0-1 0-5000	<0.001	300 f_n	<0.1	<0.25	<0.25		Inf.	Silicon diaphragm/ Diffused piezoresistive		Inf.	1-1/8 dia x 1.0 long
Kistler Instrument Corp.	Quartz		1.5-100 10-500								Strain-gage			See Table III. Assumed remainder of data unchanged
Sensotec Division Scientific Advances, Inc.	Subminiature Diaphragm	600	0-5000		100k f_n	0.1	0.5	0.5			Diaphragm/ Bonded Strain Gage			0.06 in dia.

*Metal diaphragm unless otherwise indicated

Table XII. Survey Data, Differential Pressure Sensor, Extrapolated Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP LIMIT °F	PRESS. RANGE PSIA	STEP RESP. SEC	FREQ. RESP. HZ	AMBIENT ACCY % F.S.	TEMP. EFFECT ZERO	TEMP. EFFECT SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING* ELEMENT	TYPE OUTPUT	RESOLUTION % F.S.	OTHER DATA AND REMARKS
Bytrex, Inc.	Silicon Diaphragm	+1000/-100	±5-±50	0.002 to 0.005 Undamped	1k to 5k f_n	1.0	1.0	1.0	-	100 x 10^6	Silicon diaphragm/ semiconductor strain gage	-	Inf.	
Sensotec Division Scientific Advances, Inc.	Subminiature Diaphragm	600	±1 ±5000		100 k f_n	0.1	0.5	0.5			Diaphragm/ Bonded Strain Gage			0.06 in. dia.

*Metal diaphragm unless otherwise indicated

Table XIII. Survey Data, Acceleration Sensor, Extrapolated Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP. LIMIT °F	PRESS RANGE PSIA	STEP RESP. SEC	FREQ. RESP. HZ	AMBIENT ACCY. % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING ELEMENT	TYPE OUTPUT	RESOLU-TION % F.S.	OTHER DATA AND REMARKS
Conrac Corp (Giannini Controls)		1100	0.1 to 10,000	0.001	20k f_n	0.1	0.25	0.25		Inf.	Diffused Piezoresistive		Inf.	1 cu. in.
Endevco Corp	Q-Flex Accelerometer	250/-65	±0.5 ±2.0 ±5.0	0.0002	10k f_n	0.001	0.01	0.01		50^k hrs	Force Balance		0.0001	3/4 in x 3/4 in x 3/4 in
Honeywell	GG322	220/-65	±5		100						Strain Gage	28 VAC/DC	0.001 g	
Humphrey, Inc.		160/-65	±0.25	0.012	20	0.1	0.25	0.1			Magnetic Position Transducer/ Seismic Mass		0.05	3 in^3

Table XIV. Survey Data, Angular Rate Sensor, Extrapolated Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP. LIMIT °F	PRESS. RANGE PSIA	STEP RESP. SEC	FREQ. RESP. HZ	AMBIENT ACCY. % F.S.	TEMP. EFFECT % F.S./100°F ZERO	TEMP. EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING ELEMENT	TYPE OUTPUT	RESOLU-TION % F.S.	OTHER DATA AND REMARKS
Honeywell	GG1111	200/-65	±300		61					10,000 MTBF		DC	0.0005	Hysteresis 0.04°/sec Linearity ±0.5% F.S. +1% of Applied Rate
Humphrey, Inc.		160/-65		0.010	25	0.1	0.25	0.1		5000	Magnetic Position Sensor/ Gyroscopic		0.05	11 cubic in.

Table XV. Survey Data, Angle of Attack Sensor, Extrapolated Capabilities

MANUFACTURER	MODEL NO. OR TYPE	TEMP. LIMIT °F	PRESS. RANGE PSIA	STEP RESP. SEC	FREQ. RESP. HZ	AMBIENT ACCY. % F.S.	TEMP EFFECT % F.S./100°F ZERO	TEMP EFFECT % F.S./100°F SENSITIVITY	VIBR. EFFECT % F.S./g	LIFE	SENSING ELEMENT	TYPE OUTPUT	RESOLU-TION % F.S.	OTHER DATA AND REMARKS
Honeywell	PG60	150/-30	0-27 Reg	10°/sec	25 f_n		Drift to ±0.4 deg α		Drift to ±0.4 deg α	5000 hr MTBF	Electrical/ Pneumatic			Hysteresis ±0.25 deg α Drift ±0.25 deg α @ room temp.

APPENDIX B

PRELIMINARY SENSOR SPECIFICATIONS

This appendix contains three preliminary sensor performance specifications:

H-ECS-0 FUNCTIONAL SPECIFICATIONS,

H-ECS-1 PRESSURE MEASUREMENT DEVICES, and

H-ECS-2 TEMPERATURE MEASUREMENT DEVICES

They were not used in conducting the sensor survey and represent only a preliminary statement of requirements.

H-ECS-0 FUNCTIONAL SPECIFICATIONS

1.0 GENERAL

1.1 Scope - These specifications define the environmental conditions surrounding the propulsion control sensors. Also defined are general performance requirements, and definitions of operation media. These requirements are preliminary and subject to change.

1.2 The requirements of this specification are applicable to the following specific sensors unless otherwise noted.

1. H-ECS-1 Pressure Measurement Devices

2. H-ECS-2 Temperature Measurement Devices

2.0 APPLICABLE DOCUMENTS

The documents listed below form a part of the specifications listed in Paragraph 1.2 unless noted otherwise. The requirements of Paragraph 1.2 take precedence in all cases.

2.1 Military Specifications

MIL-E-5007B	Engines, Aircraft, Turbojet, General Specifications for
MIL-E-5009B	Engines, Aircraft, Turbojet, Qualification Tests for
MIL-J-5161F	Jet Fuel, Referee
MIL-T-5624G Amendment 1	Turbine Fuel, Aviation, Grades JP-4 and JP-5
MIL-E-6051C	Electrical - Electronic System Compatibility and Interference Control requirements for Aeronautical Weapon System, Associated Subsystems and Aircraft.
MIL-E-5400C	Electronic Equipment, Aircraft, General Specification for
MIL-S-38130	Safety Engineering of Systems and Associated Subsystems and Equipment; Several Requirements for

2.2 Military Standards

MIL-STD-210A	Climatic Extremes for Military Equipment
MIL-STD-704	Electronic Power, Aircraft, Characteristics and Utilization of
MIL-STD-826	Electromagnetic Interference Test Requirements and Test Methods
MIL-STD-470	Maintainability Program Requirements

3.0 PERFORMANCE REQUIREMENTS

3.1 Environment

3.1.1 Temperature - The continuous and peak temperature conditions are shown in Table XVI. The sensors shall operate within their prescribed tolerances while subjected to the applicable temperature range.

3.1.2 Engine Gases - Portions of the control sensors immersed in or in contact with the combustor or turbine discharge pressure shall be capable of sustaining engine products of combustion, the contamination levels of MIL-E-5009B, Paragraph 4.3.2.3.3.1.1., and the temperature and pressure ranges shown in Table XVII and XVIII. Operating performance shall be as defined in the applicable sensor specification while exposed to these conditions.

Table XVI. Continuous and Peak Temperature Conditions

Parameter	Continuous Duty	Peak Loads (2% or less of operating time)
Ambient Air, System Operating	-65 to 500°F	-65 to 525°F
Fuel (Pump Exit)		
Forward of A/B	395°R or 12 Centistokes Fuel Viscosity if warmer To 780°R	395°R or 12 Centistokes Fuel Viscosity if warmer To 800°R

Table XVII. Internal Temperature Ranges

Parameter	Continuous Duty
Inlet Air	385 to 520°R
Fan Inlet Air	395 to 900°R
Compressor Inlet Air	395 to 1070°R
Compressor Discharge Air	395 to 1570°R
Turbine Discharge Air	395 to 2400°R

Table XVIII. Internal Pressure

Parameter	Continuous Duty
Inlet Air	2 to 15 psia
Fan Inlet Air	2 to 30 psia
Compressor Inlet Air	2 to 75 psia
Compressor Discharge Air	5 to 461 psia
Turbine Discharge Air	5 to 300 psia

3.1.3 Vibration - The control sensors shall be capable of operation within specified limits when subjected to the environmental conditions specified in Paragraph 4.3 of MIL-E-5009B, or the following condition: Continuous vibration in a frequency range from zero to 2,000 cps at any amplitude up to a limit defined by 12 g acceleration or 0.1 inch peak to peak displacement.

3.1.4 Flight Maneuver Loading - Accelerations due to aircraft maneuvers are shown in Figure 31. The sensors shall perform within specified limits when subjected to the conditions shown.

3.1.5 Acoustical Noise - The sensors shall be capable of performance within specified limits when subjected to acoustical noise in the following range: 150 db (above 0.0002 dynes cm^2) white noise between 100 and 5000 cps.

3.1.6 Other Environmental Conditions - The control sensors shall be capable of operating within specified limits when subjected to the environmental conditions specified in Paragraph 4.3 of MIL-E-5009B, and the climatic conditions of MIL-STD-210A.

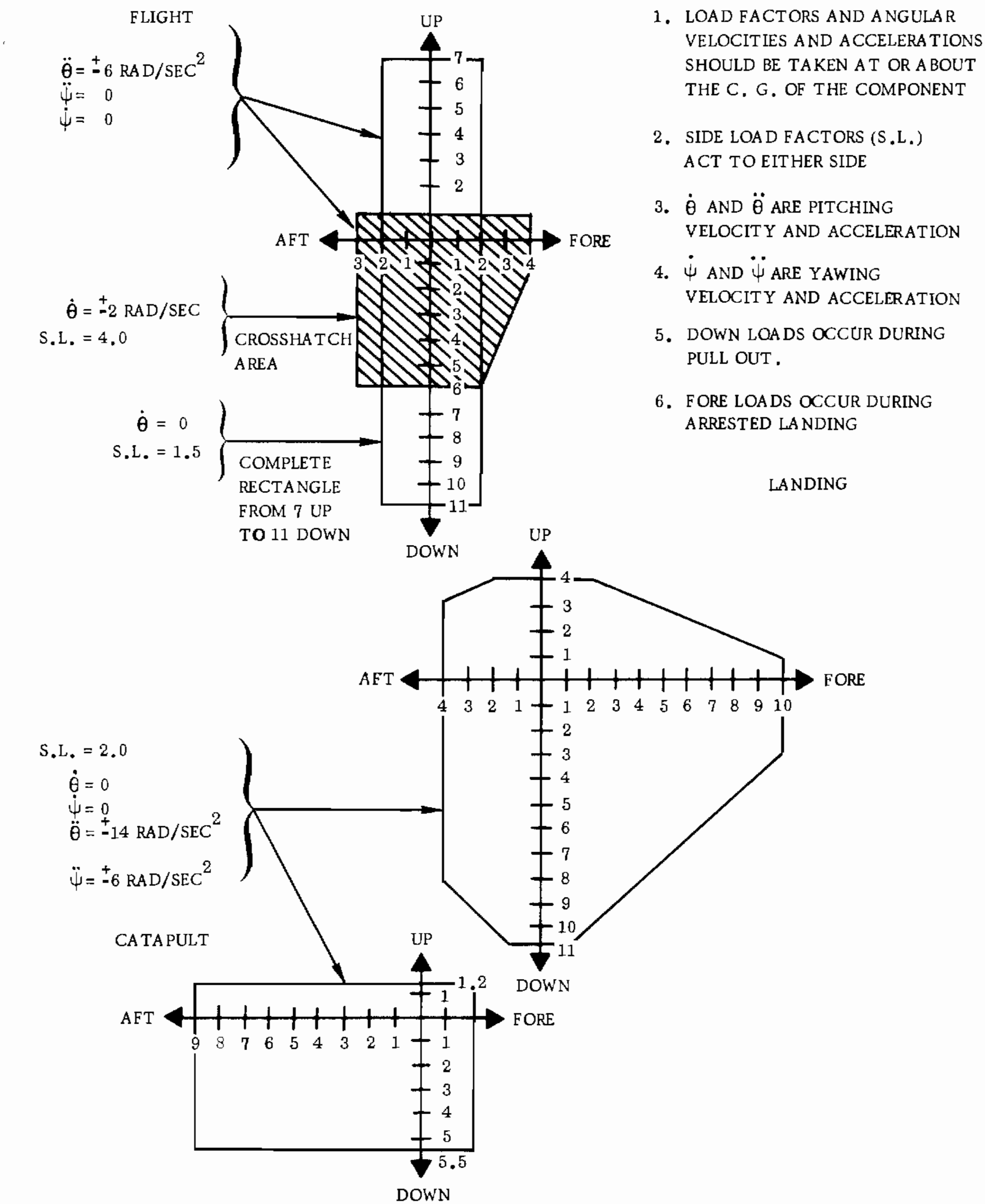


Figure 31. Flight Maneuver Load Diagrams

3.2 Radio Interference - Control sensors shall meet the radio frequency noise and susceptibility requirements of MIL-STD-826 and MIL-E-6051C.

3.3 Cables and Connectors - The cables and connectors, if used, shall satisfy MIL-C-5007B while experiencing the environmental characteristics of this specification.

3.4 Lubrication - The control sensors shall require no external lubricant or internal lubricant.

4.0 EXTERNAL ADJUSTMENTS

Certain external adjustments to limits and schedules are to be provided for in the system mechanization. These adjustments should be capable of being performed without the use of ground test equipment.

5.0 RELIABILITY

5.1 MTBF Requirements - Specific values of MTBF are listed in each sensor specification.

5.2 Failure Definition - A failure is defined as any deviation from the applicable sensor performance specification. Catastrophic failure results in complete shutdown, hardover conditions, or other modes non-responsive to command inputs.

H-ECS-1 PRESSURE MEASUREMENT DEVICES

1.0 GENERAL

1.1 Scope - The pressure measurement devices are used to sense pressure at various stations of the propulsion system and transmit a signal to the control computer. The requirements listed in this specification are preliminary and subject to change.

1.2 Applicable Specifications - The requirement of H-ECS-0, Functional Specification, Engine Control Subsystem shall apply to this specification unless otherwise noted.

2.0 PERFORMANCE REQUIREMENTS

2.1 Subsystem Interfaces - The following preliminary engine station locations will incorporate a pressure measurement device. Other stations may be added.

1. Fan Inlet P_2
2. Main Compressor Inlet P_3
3. Main Compressor Discharge P_4
4. Fan Duct Pressure Ratio $\left.\frac{\Delta P}{P}\right|_F$
5. Inlet Mach Number $\left.\frac{\Delta P}{P}\right|_I$

2.2 Pressure Range Requirements - The pressure measurement devices shall be capable of monitoring the following pressure ranges within specified performance requirements.

$\left.\frac{\Delta P}{P}\right|_F$	0.05 to 0.4 M
P_2	2 to 30 PSIA
P_3	2 to 75 PSIA
$\left.\frac{\Delta P}{P}\right|_I$	0.3 to 2.6 M
P_4	15 to 500 PSIA

2.3 Operating Characteristics

2.3.1 Accuracy

2.3.1.1 General - Accuracy shall be defined as the dynamic thermal error band root-sum-squared with errors due to vibration and acceleration response, humidity and drift. The dynamic thermal error band shall be the maximum deviation of device output from one best straight line fit through all calibration data.

2.3.1.2 Tolerances - The following is applicable to all pressure devices.

Measurement	Required Accuracy
P_2	± 2.0 percent of measurement
P_3	± 2.0 percent of measurement
P_4	± 2.0 percent of measurement
$\left.\frac{\Delta P}{P}\right\|_F$	± 0.5 percent of measurement
$\left.\frac{\Delta P}{P}\right\|_I$	± 0.035 percent of full scale

2.3.1.3 Ambient Operating Temperature Range - Pressure measurement device performance shall conform with 2.3.1.2 over the temperature range specified in Table XVI of H-ECS-0.

2.3.2 Response - The time for the transducer output (P_2, P_3, P_4 only) to reach 63.2 percent of full scale for a step pressure input shall be 0.0005 seconds maximum.

2.3.3 Temperature - The maximum temperature of the media being measured is as follows:

P_2	900 R
P_3	1070 R
P_4	1570 R

The pressure measurement devices shall operate within specified limits while mounting pressures subject to the above maximum temperatures.

3.0 DESIGN REQUIREMENTS

3.1 Operating Media - The measurement device shall be capable of monitoring a gas medium as described in H-ECS-0, Paragraph 3.2.1.4.

3.2 Reliability - The transducer shall have an MTBF of 30,000 hours. A failure is defined as any deviation from the requirements of this specification.

H-ECS-2 TEMPERATURE MEASUREMENT DEVICES

1.0 GENERAL

1.1 Scope - The temperature measurement devices are used to monitor temperature in selected locations of the propulsion system and transmit a signal to the control computer. The requirements listed in this specification are preliminary and subject to change.

1.2 Applicable Specifications - The requirements of Specification H-ECS-0 shall apply to this specification unless otherwise noted.

2.0 PERFORMANCE REQUIREMENTS

2.1 Subsystem Interfaces - The following engine station locations will incorporate a temperature measurement device.

1. Fan Inlet T_2
2. Turbine Inlet T_5
3. Turbine Exit T_6
4. Duct T_3

Each of the above temperatures shall be monitored utilizing a sensing element in each of at least four quadrants which shall be capable of being averaged to yield a single output representative of the temperature at the engine station.

2.2 Temperature Range Requirements - The temperature measurement devices shall be capable of monitoring the following temperature ranges within specified performance requirements.

T_2	385°R to 900°R
T_5	1000°R to 2860°R
T_6	750°R to 2400°R
T_3	385°R to 1100°R

2.3 Operating Characteristics

2.3.1 Accuracy - The device shall provide an indicated temperature accurate to ± 0.3 percent of full scale under any and all combinations of fluid conditions.

2.3.2 Response Time - The time for the device output to reach 63 percent of the final value for a step change in temperature shall not exceed 0.01 seconds for max. air flow conditions.

2.3.3 Pressure - The transducer element of the device shall be capable of performing within specified limits in pressure environments of up to 600 psi maximum.

3.0 DESIGN REQUIREMENTS

3.1 Mounting - The transducer element shall be capable of being mounted flush with the inside diameter of the gas passage.

3.2 Operating Media - The media being sensed shall be turbojet engine combustion gases contaminated as specified in H-ECS-0, Paragraph 3.2.1.4.

3.3 Reliability - The transducer shall have design goal MTBF of 47,600 hours after 500,000 hours engine operating time. A failure is defined as any deviation from the requirements of this specification.

APPENDIX C

CATALOG OF HONEYWELL FLUIDIC SENSOR CHARACTERISTIC SPECIFICATIONS

DISCUSSION

The performance data included in these specification sheets include production and field operational data where possible. The data on fluidic sensors are mostly from laboratory developmental testing, predicted performance from experience on similar type devices, or from engineering estimates and are so marked. These sensors are in the engineering development stage.

GLOSSARY OF TERMS USED

P_T = total pressure

P = static pressure

PR = pressure ratio

PRU = pressure ratio units

T = total temperature

τ = time constant

s = LaPlace operator

ω_n = natural frequency

ζ = damping ratio

D = differential

ΔP = differential pressure

P_α = pressure on one side of angle of attack probe

SF = scale factor

All dimensions are listed in inches unless otherwise noted.

If no temperature or altitude ranges are given, assume low end is standard day conditions.

All performance data listed are from production specifications or experimental test results unless otherwise marked as shown.

* Estimated from tests on similar devices

** Engineering estimates - no test data available

SENSOR CHARACTERISTICS SPECIFICATION	Sheet 1 of 2

Sensor Temperature, Fluidic **Device No.** TG1000A

Description of Device:

A fluidic oscillator whose acoustic frequency is a function of the square root of the absolute temperature of the gas flowing through it. The device is powered by the sample gas flowing through it and needs no other source of energy. Since it is a flow-through device a certain minimum pressure difference (presently 3 psiD) between inlet and exhaust is necessary. For inlet temperature sensing this would require an exhauster or vacuum pump. However at most other locations in the propulsion system sufficient pressures exist to drive the sensor. The frequency of oscillation at a particular temperature is dependent on the size of the sensor, (small sensor-high frequency, large sensor-low frequency). The maximum operating temperature of the device is limited only by the maximum allowable temperature for the material used in the sensor body and sample gas probe.

Characteristic	Present Capability	Extrapolated Capability
A. Dynamic Response	$\frac{0.6}{1+0.01S} + \frac{0.4}{1+10S}$ (less Probe)	$\frac{1}{1+0.01S}$
B. Experimental Response to a Step Input	See Figure 9	
C. Steady State Accuracy		
1. Hysteresis	not detectable	
2. Drift and Repeatability	±0.43% of reading	±0.25% of reading
3. Environment Effects		
a. Altitude	error less than 3% of inlet temperature when a differential pressure across sensor is between 5 and 70 psiD	
b. Vibration	none within limits of F.2	
c. Temperature	No test data available - heat transfer effects not completely understood. Not a factor for sensors immersed in the sample gas stream.	
D. Output		
1. Type	acoustic frequency	
2. Scale Factor	freq = $K\sqrt{T}$ where K is approx. 175 for TG100A1 values of K from 100 to 1100 are possible for different sensors. 0.6°R per Hz at 6000 Hz mid-scale	
3. Sensitivity Threshold	Infinitesimal	
4. Range	to 1700°F (Short term tests to 2400°F)	to 3000°F
E. Power Supply	(None - Sample gas supply only)	
1. Type	pneumatic	
2. Voltage/Pressure	3 to 90 psig	
3. Power/Flow Rate	0.51 lb/min at 50 psig inlet press. room temp.	2-450 psig
F. Environmental Limits		
1. Altitude	none except 3 psi ΔP across sensor must be maintained	
2. Vibration	exceeds MIL-STD 810B curve L	
3. Shock	exceeds MIL-STD 810B procedure I (A and C)	
4. Temperature	1500°F Ambient	3000° Ambient
G. Predicted Failure Rates	57,000 hr MTBF*	

SENSOR CHARACTERISTICS SPECIFICATION

Sheet 2 of 2

Sensor Temperature, Fluidic

Device No TG1000[illegible]

Characteristic	Present Capability	Extrapolated Capability
H. Configuration		
1. Mounting	directly at or in gas temperature source to be measured	
2. Approximate Size	2 x 2 dia	
3. Approximate Weight	5 oz.	

*Engineering estimates - no test data available

SENSOR CHARACTERISTICS SPECIFICATION	Sheet 1 of 2

Sensor Intermediate Pressure Ratio, Fluidic

Device No. ________

Description of Device:

A fluidic oscillator whose acoustic output is a function of the ratio of the inlet to exhaust pressure is being developed for engine pressure ratio sensing. Requires compensation for temperature, compensation was included in present device, along with an acoustic-to-electric transducer Present configuration is for sensing two remote pressures and is not well suited to direct internal propulsion system mounting (see Figure 32). However nothing in the basic design prevents direct engine or air stream mounting.

Characteristic	Present Capability	Extrapolated Capability
A. Dynamic Response	unknow - no test data available	
B. Experimental Response to a Step Input	0.005 sec from 1.3 to 2.5 P.R.	
C. Steady State Accuracy		
1. Hysteresis	±0.02 PRU	±0.005 PRU
2. Drift	±0.02 PRU	±0.005 PRU
3. Environment Effects		
a Altitude	none for supply pressures between 3.75 and 37.5 psiD across sensor beyond this range accuracy becomes poorer	
b. Vibration	none within limits of F.2	
c. Temperature	must be compensated for supply air temp Effect on sensor dynamics is unknown	
D Output		
1. Type	acoustic frequency	
2. Scale Factor	125 Hz/0.10 PRU	
3 Sensitivity Threshold	±0.02 PRU	±0 005 PRU
4 Range	1.5 to 2.3 (high accuracy) 1.3 to 2.5 (operational)	
E Power Supply	none - sample gas only	
1. Type	pneumatic	
2. Voltage/Pressure	3.75 to 37.5 psiD across sensor	
3. Power/Flow Rate	0.1 lb/min Max. *	
F. Environmental Limits		
1. Altitude	depends on supply pressure available see E.2	
2. Vibration	exceeds MIL-STD 810B curve L*	
3. Shock	exceeds MIL-STD 810B Procedure I (A and C)*	
4. Temperature	-65 to 250°F	-65°F to 1200°F
G Predicted Failure Rates	1.4×10^6 hrs**	

SENSOR CHARACTERISTICS SPECIFICATION		Sheet 2 of 2
Sensor Intermediate Pressure Ratio, Fluidic		Device No. ____________
Characteristic	Present Capability	Extrapolated Capability
H. Configuration	includes temp. compensator in pacakge - does not include probe	
1. Mounting	See Figure 32	
2. Approximate Size	3 x 3 x 3	
3. Approximate Weight	12 oz. (less transducer)	

*Estimated from tests on similar devices
**Engineering estimates - no test data available

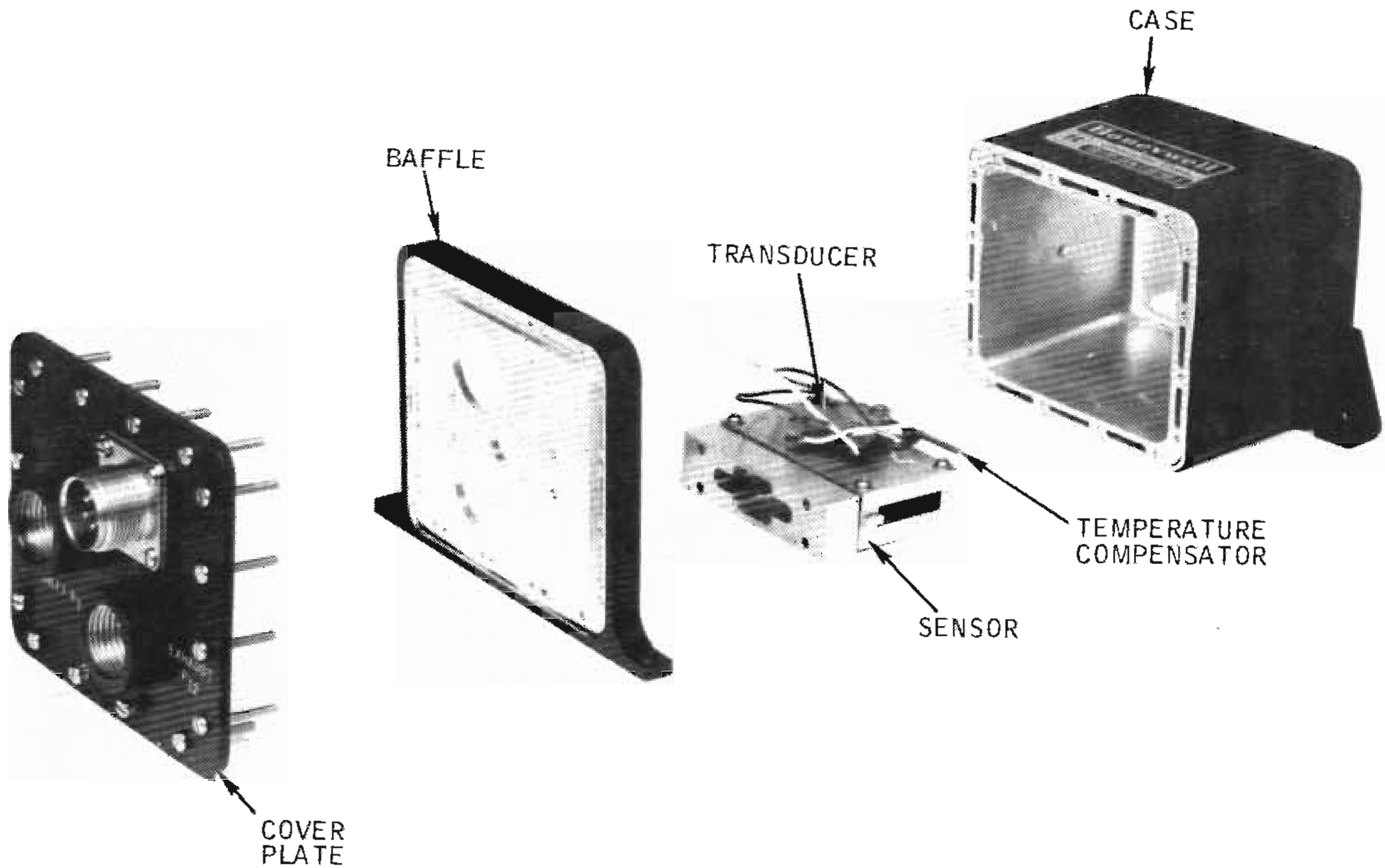


Figure 32. Intermediate Range Fluidic Pressure Ratio Sensor

SENSOR CHARACTERISTICS SPECIFICATION		Sheet 1 of 2

Sensor Low Pressure Ratio, Fluidic Device No. ______

Description of Device:

A fluidic oscillator whose acoustic output is a function of the ratio of the inlet to exhaust pressure. Device is currently being developed for inlet and duct Mach number sensing (M = 0.2 to 0.7) applications. Frequency response should be sufficient for flow distortion sensing and will probably look like a simple first order lag. However, temperature effects may add another first order term. Device is sufficiently rugged to allow direct engine or air frame mounting.

Characteristic	Present Capability	Extrapolated Capability
A Dynamic Response	$\frac{1}{1 + 0.005S}$ *	
B. Experimental Response to a Step Input	0.02 sec from 1.03 to 1.40 PR*	
C. Steady Statey Accuracy		
1. Hysteresis	not available	±0.5% of reading
2. Drift	±1.0% of reading*	±0.5% of reading
3. Environment Effects		
a. Altitude	none for supply pressures between 5 and 30 psiD accuracy should decrease outside this range	
b. Vibration	none within limits of F.2	
c. Temperature	temperature compensation is accomplished with a fluidic amplifier and effects have not been evaluated. Compensation should be near perfect.	0.5% of reading
D. Output		
1. Type	pneumatic ΔP	
2. Scale Factor	1 in HgD/0.01 PRU	
3. Sensitivity Threshold	±0.02 PRU	±0.005 PRU
4. Range	1.03 to 1.40 PR	1.005 to 1.40 PR
E. Power Supply	sample gas plus 5 psig supply press for fluidic amplifier discriminator	
1. Type	pneumatic	
2. Voltage/Pressure	5 to 30 psiD across sensor	1 psiD to 80 psiD
3 Power/Flow Rate	0.015 lb/min sample gas plus 0.2 scfm for fluidic amplifier discriminator	
F. Environmental Limits		
1. Altitude	depends on supply pressure available - see E.2	
2. Vibration	exceeds MIL-STD 810B curve L*	
3. Shock	exceeds MIL-STD 810B procedure I (A and C)*	
4. Temperature	-65 to 750°F*	-65°F to 1200°F
G Predicted Failure Rates	1.4×10^6 hr**	

SENSOR CHARACTERISTICS SPECIFICATION		Sheet 2 of 2
Sensor Low Pressure Ratio, Fluidic		Device No. ____
Characteristic	Present Capability	Extrapolated Capability
H Configuration	probe sensor and discriminator in one package - see Figure 12	
1. Mounting		
2. Approximate Size		
3. Approximate Weight	2 lb including probe and mount	

*Estimated from tests on similar devices
**Engineering estimates - no test data available

F

SENSOR CHARACTERISTICS SPECIFICATION

Sensor Pressure Rate, Fluidic **Device No.** ________

Description of Device:

A pneumatic high-pass unit suitable for sensing or logic and computation functions. Size is a function of the time constant requirement which dictates the size of the capacitance tank or diaphragm. Can be fabricated from many materials but generally electroformed nickel is best for advanced high temperature applications. Figure 33 shows one configuration with input and output curves.

Characteristic	Present Capability	Extrapolated Capability
A. Dynamic Response	$\frac{\tau s}{1 + \tau s}$	
B. Experimental Response to a Step Input	τ variable see Figure 34	
C. Steady State Accuracy	not applicable	
1. Hysteresis	unknown } see pressure difference sensor	
2. Drift	unknown } see pressure difference sensor	
3. Environment Effects		
a. Altitude	compensation or isolation required above 30,000 ft.	to 50,000 ft.
b. Vibration	none to limits in F.2	
c. Temperature	no test data available	
D. Output		
1. Type	pneumatic ΔP	
2. Scale Factor	variable depending on τ	
3. Sensitivity Threshold	0.1 in Hg/sec	
4. Range	τ variable up to five seconds	to 10 sec
E. Power Supply		
1. Type	pneumatic	
2. Voltage/Pressure	5 ± 0.25 psig 10 micron nominal filtration	
3. Power/Flow Rate	0.2 scfm	
F. Environmental Limits		
1. Altitude	see C.3.a	
2. Vibration	exceeds MIL-STD 810B curve L*	
3. Shock	exceeds MIL-STD 810B procedure I (A and C)*	
4. Temperature	1200°F*	
G. Predicted Failure Rates	164×10^6 hr MTBF**	
H. Configuration		
1. Mounting	either in/close to probe or in control system	
2. Approximate Size	1/2 x 1/2 x 1/2 approx.	
3. Approximate Weight	1/2 oz.	

Estimated from tests on similar devices
Engineering Estimates - no test data available

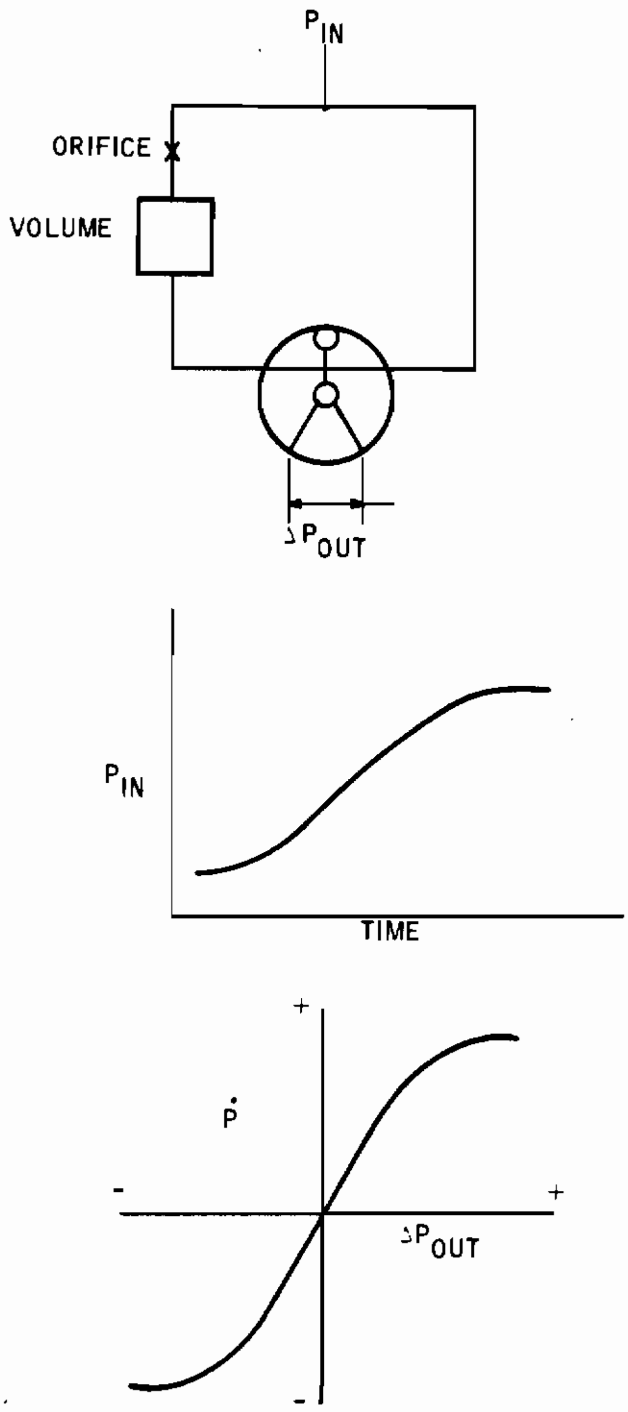


Figure 33. Pressure Ratio Sensor

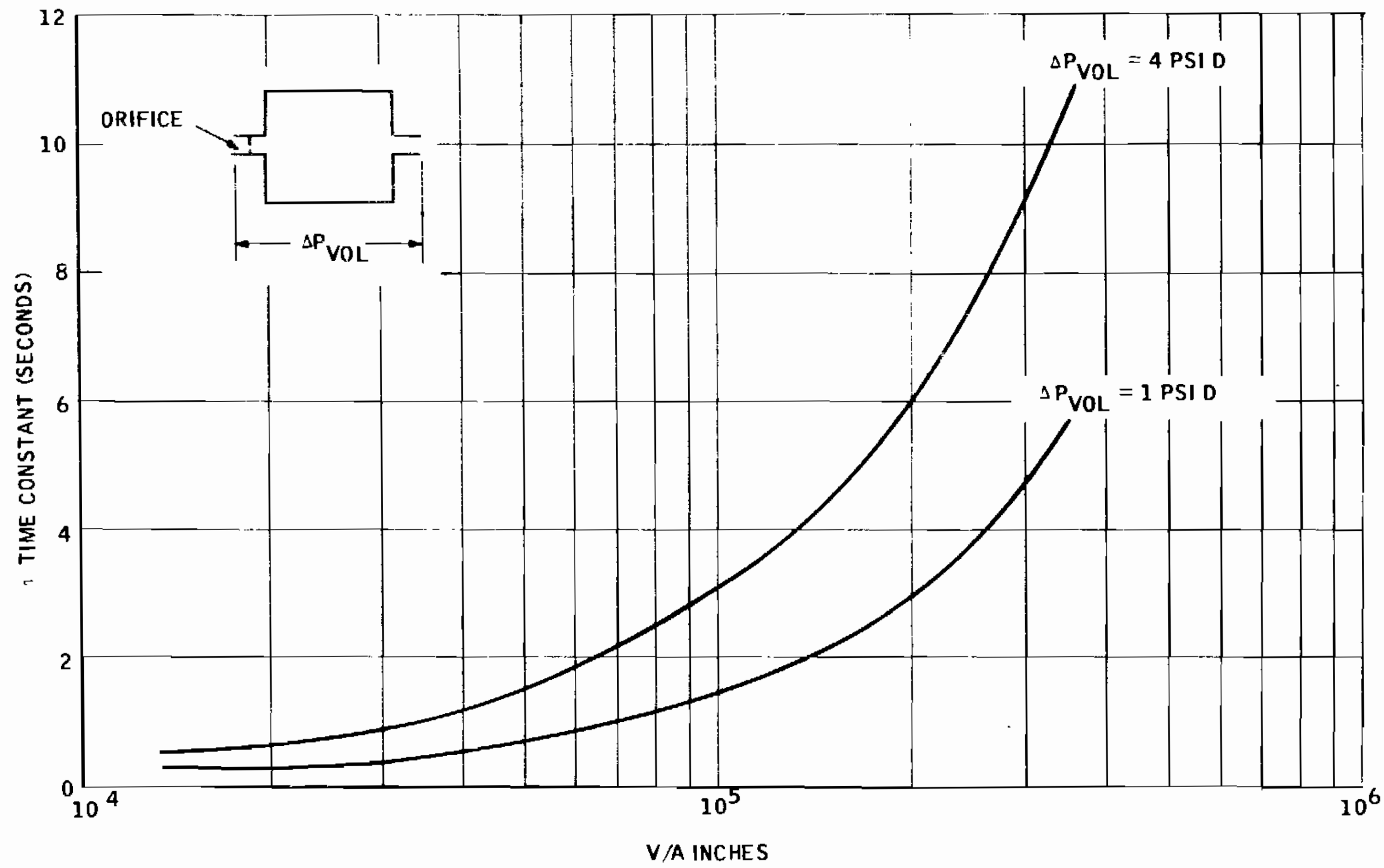


Figure 34. Effect of Volume/Orifice Area on Pneumatic RC Network on Time Constant

SENSOR CHARACTERISTICS SPECIFICATION

Sensor Normal Shock, Fluidic **Device No.** ________

Description of Device:

Device senses the position of the normal shock wave in a supersonic inlet by reacting to the static pressure gradient across it. Sensor consists of a series of bistable fluidic amplifiers which trip and untrip depending on the shock wave position (see Figure 35. Since the position of the normal shock is sensitive to both internally and externally generated disturbances, this sensor can be used in any form of distortion accommodation system Sensor can be mounted directly to the inlet and is capable of withstanding environments well beyond Mach 3. Temperature limit shown is for electroformed nickel sensor and with suitable material could go higher

Characteristic	Present Capability	Extrapolated Capability
A. Dynamic Response	$\frac{e^{-0.002s}}{1+0.01\,s}$ (including 6" line length)	$\frac{e^{-0.001s}}{1+0.005s}$
B. Experimental Response to a Step Input	0.001 to 0.002 sec per amplifier tripped	< 0.001 sec per amplifier tripped
C. Steady State Accuracy		
1. Hysteresis	depends on shock wave definition (boundary layer thickness, etc.)	
2. Drift	none with stable shock wave	
3. Environmental Effects		
a. Altitude	none when constant discharge pressure is maintained above 30,000 ft (Figure 35)	none to 50,000 ft
b. Vibration	none within limits of F.2	
c. Temperature	none to 1200°F*	
D. Output		
1. Type	pneumatic ΔP	pneumatic or electrical
2. Scale Factor	approx. 0.7 in Hg per amplifier tripped	
3. Sensitivity Threshold	depends on tap spacing	
4. Range	not applicable	
E. Power Supply		
1. Type	pneumatic 10 micron nominal filtration	
2. Voltage/Pressure	10 ±1.0 psig	
3. Power/Flow Rate	0.2 scfm/amplifier	0.1 scfm/amplifier
F. Environmental Limits		
1. Altitude	see C.3.a	
2. Vibration	exceeds MIL STD 810B* curve L	
3. Shock	exceeds MIL STD 810B* procedure I (a&c)	
4. Temperature	1200°F*	
G. Predicted Failure Rates	2.86×10^{5} hr**	
H. Configuration		
1. Mounting	as close to throat as possible to reduce line lengths	
2. Approximate Size	7 elements 1.0 x 1.5 x 3.5	
3. Approximate Weight	7 oz.	

* Estimated from tests on similar devices
** Engineering Estimates - no test data available

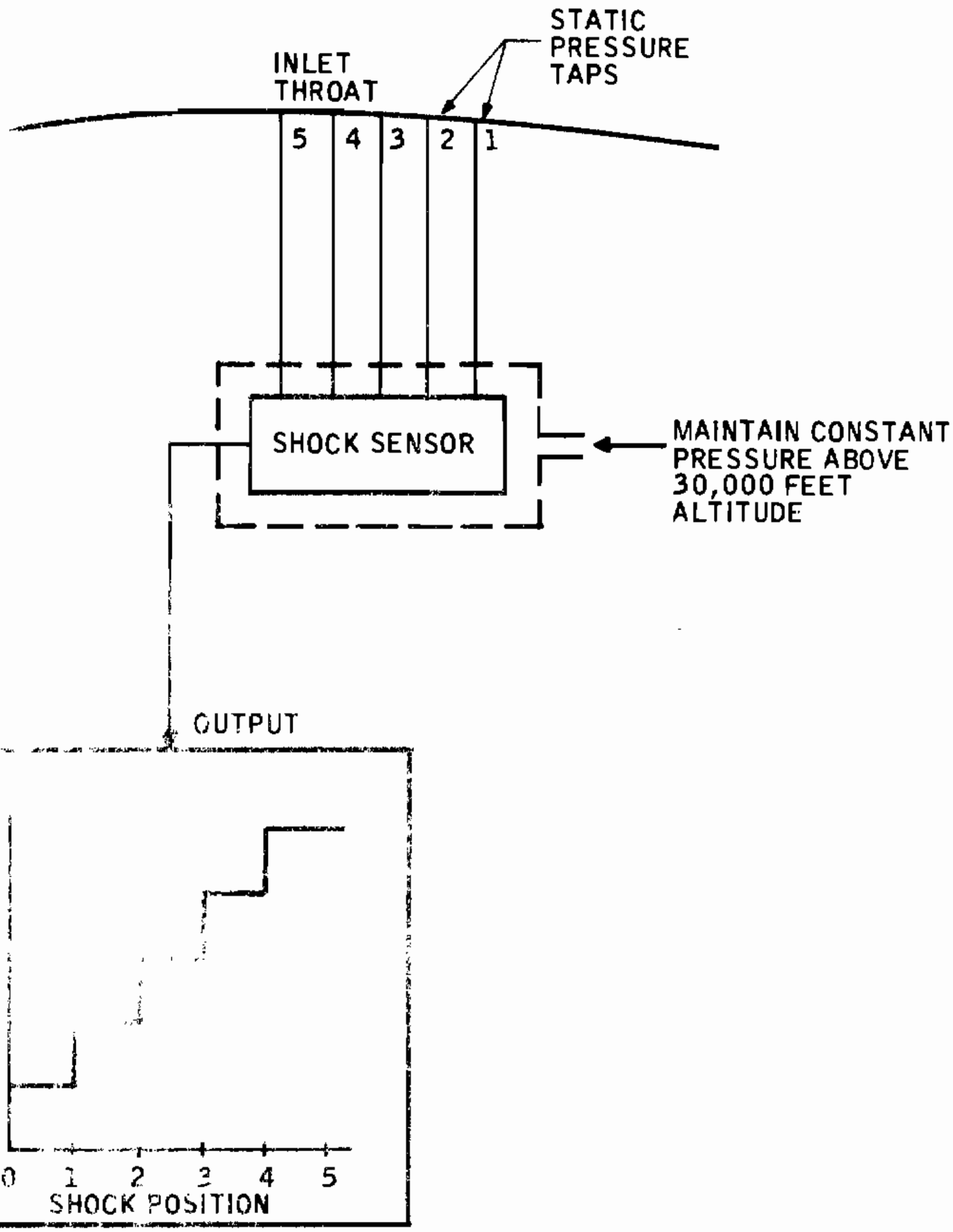


Figure 35. Fluidic Shock Sensor

SENSOR CHARACTERISTICS SPECIFICATION		Sheet 1 of 2

Sensor: Pressure Difference, Fluidic — Device No. ________

Description of Device:

The basic proportional fluidic amplifier is sensitive to the differential pressure applied across it. The output is a differential pressure proportional to the input differential pressure. Supply pressures are nominally less than 10 psig mainly to keep noise at a minimum. The amplifiers are commonly fabricated from electroformed nickel which will operate at 1200°F.

Characteristic	Present Capability	Extrapolated Capability
A. Dynamic Response	$\frac{1}{1 + 0.001\,s}$	
B. Experimental Response to a Step Input	not available	
C. Steady State Accuracy	at recommended supply pressure (See E. 2)	
1. Hysteresis	none — within instrumentation limits (S. G. xducers and x-y plotter)	
2. Drift	none — within instrumentation limits (S. G. xducers and x-y plotter)	
3. Environment Effects		
a. Altitude	gain reduction of about 5%/10,000 ft at over 30,000 ft (See Figure 36). Linear range is approximately constant and noise decreases as shown on Figure 39	To 50,000 ft
b. Vibration	none within limits of F. 2	
c. Temperature	See Figures 37 and 39. Noise varies randomly by ± 25% with increasing temperature	
4. Repeatability	100% within instrumentation limits	
5. Linearity	±1% over total linear range	
6. Signal to Noise Ratio	approximately 200. See Figure 39.	
D. Output		
1. Type	pneumatic ΔP	
2. Scale Factor	pressure gain ~2 is typical	
3. Sensitivity Threshold	infinite resolution	
4. Range	±40% of supply pressure	±60% of supply pressure
E. Power Supply		
1. Type	pneumatic	
2. Voltage/Pressure	5±0.25psig 5 micron nominal filtration. See Figure 38	
3. Power/Flow Rate	0.1 scfm at 5 psig supply	
F. Environmental Limits		
1. Altitude	see C. 3. a	50,000
2. Vibration	exceeds MILSTD 810B* curve L	
3. Shock	exceeds MILSTD 810B* procedure I (A&C)	
4. Temperature	1200°F	

* Estimated from tests on similar devices.

** Engineering estimates - no test data available

SENSOR CHARACTERISTICS SPECIFICATION		Sheet 2 of 2
Sensor Pressure Difference, Fluidic		Device No. ________
Characteristic	**Present Capability**	**Extrapolated Capability**
G. Predicted Failure Rates	2,000,000 hr MTBF**	
H. Configuration		
1. Mounting		
2. Approximate Size	1 x 1 x $^1/_4$	
3. Approximate Weight	1/2 oz.	

**Engineering estimates - no test data available

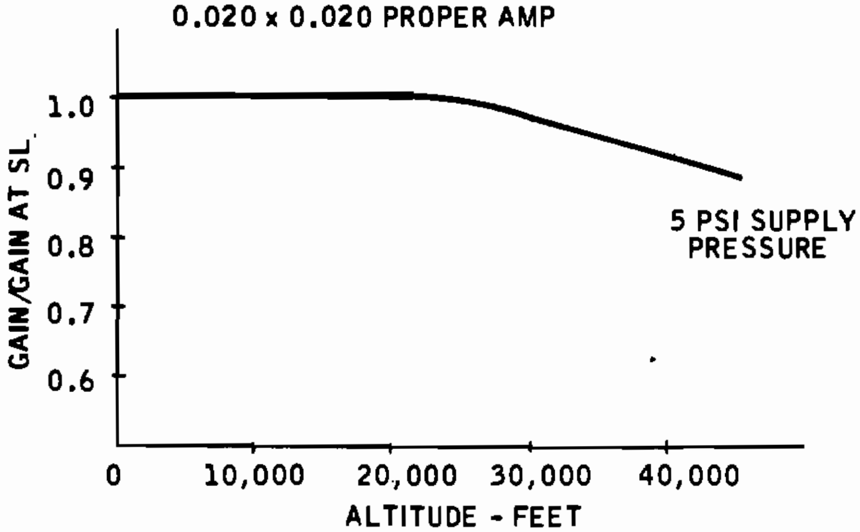


Figure 36. Gain versus Altitude

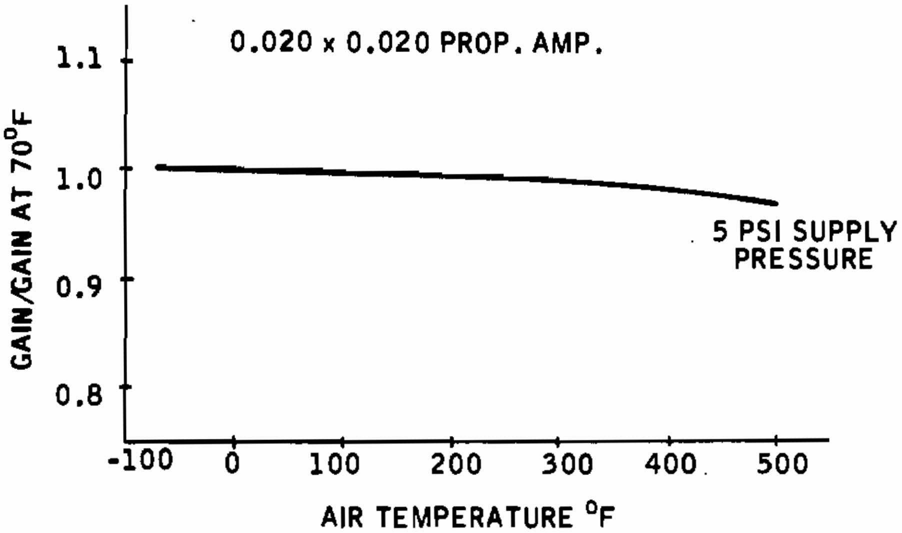


Figure 37. Gain versus Air Temperature

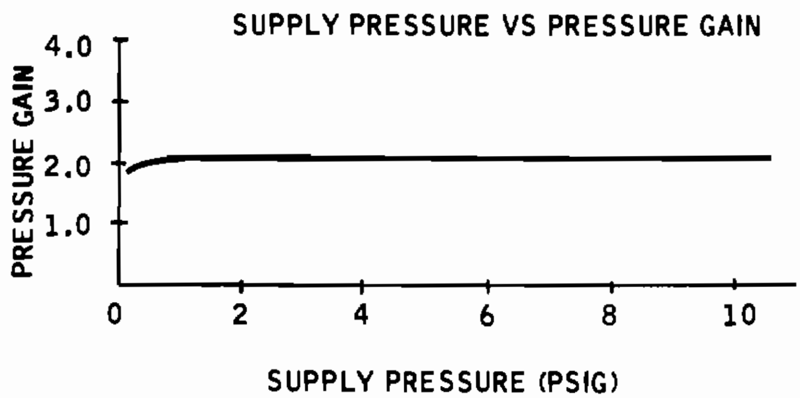
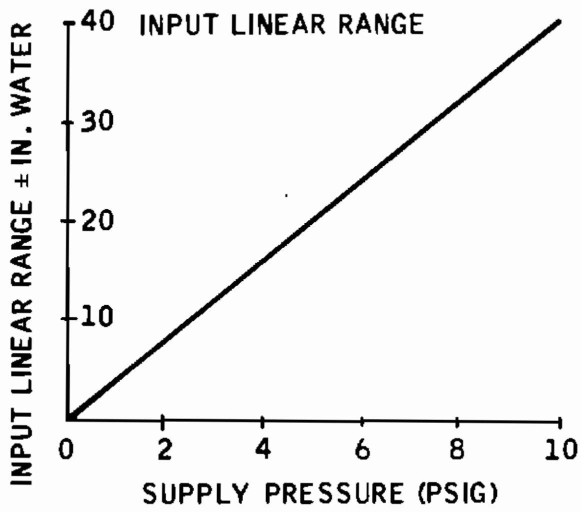


Figure 38. Supply Pressure versus Pressure Gain



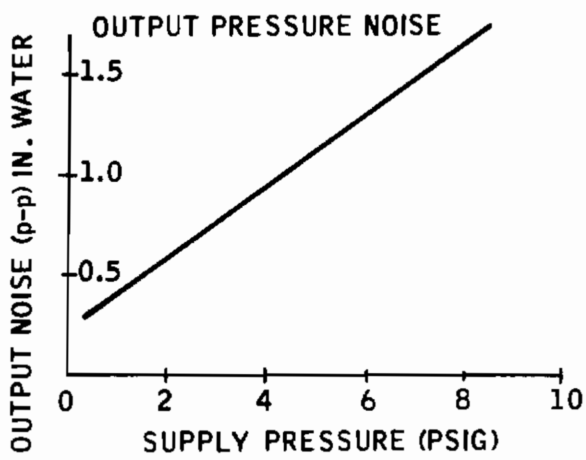


Figure 39. Linear Range and Output Noise for Pressure Difference Sensor

SENSOR CHARACTERISTICS SPECIFICATION	Sheet 1 of 2

Sensor Angular Rate, Fluidic Device No. ______

Description of Device:

The vortex rate-sensor is a pure fluid device that senses angular velocity about its input axis and provides a fluid signal which is proportional to that velocity. There are no moving parts within the device and it employs a pattern of fluid flow to sense angular rotation. It is a developmental device that is being developed for fluidic flight control systems. The performance characteristics are based on laboratory developmental testing. Further development is continuing depending upon the specific application requirements. Output characteristics are for a range of three devices and are presented in order (e.g., ω_n = 5, 15, 25 Hz corresponds to ranges of ±2, ±10, ±30 deg/sec in that order). Where only one value is given it is the same for all devices.

Characteristic	Present Capability	Extrapolated Capability
A. Dynamic Response	2nd order ω_n at 90° phase lag = 5-25 Hz ζ = 1.0	
B. Experimental Response to a Step Input	not available	
C. Steady State Accuracy		
1. Hysteresis	none within instrumentation accuracies. (strain gage transducers and X-Y plotter)	
2. Drift	± 2% *	±0.2% FS
3. Environmental Effects		
a. Altitude	SF decreases with altitude. See Figure 40	
b. Vibration	none within limits of F.2	
c. Temperature	see curve Figure 41 and 42	±2% FS -65 to 160°F
4. Linearity	unknown but is approximately linear over normal operating range	
5. Noise	0.5 deg/sec	
D. Output		
1. Type	pneumatic ΔP	
2. Scale Factor	3.95, 2.25 and 1.75 x 10^{-3} psi/deg/sec	
3. Sensitivity Threshold	0.7 deg/sec	0.2 deg/sec
4. Range	±2.0, ±10.0, and ±30.0 deg/sec	
E. Power Supply		
1. Type	pneumatic	
2. Voltage/Pressure	10 ±0.1 psig — 25 micron nominal filtration. See Figure 43	
3. Power/Flow Rate	1scfm	
F. Environmental Limits		
1. Altitude	must be compensated above 20,000 ft by maintaining a constant discharge pressure	
2. Vibration	10 g sinusoidal 50-2000 Hz 0.05 g^2/Hz random 50-2000 Hz	
3. Shock	15 g 11 ms	
4. Temperature	-65 to +160°F	
G. Predicted Failure Rates	10^6 hrs MTBF **	

** Engineering estimates - no test data available

SENSOR CHARACTERISTICS SPECIFICATION		Sheet 2 of 2
Sensor Angular Rate, Fluidic		Device No.
Characteristic	Present Capability	Extrapolated Capability
H. Configuration		
1. Mounting		
2. Approximate Size	1.5 x 4.0 dia	
3. Approximate Weight	< 1 lb	

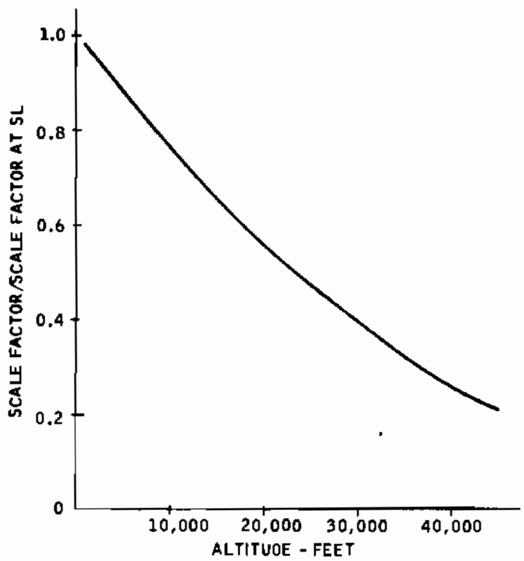


Figure 40. Scale Factor versus Altitude

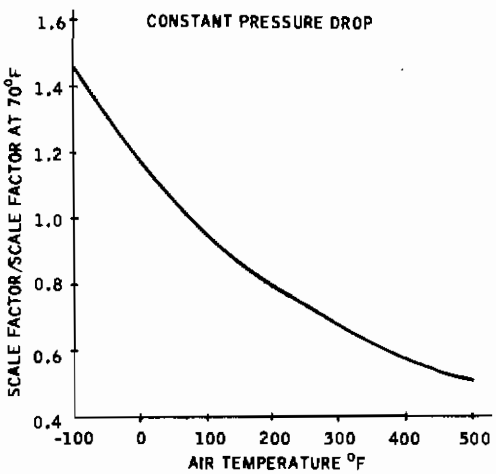


Figure 41. Scale Factor versus Air Temperature

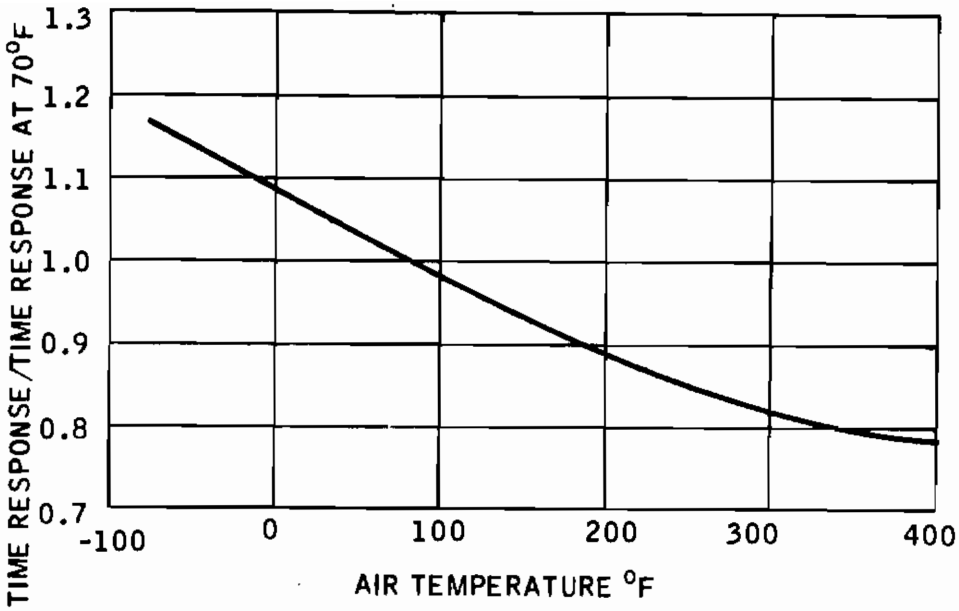


Figure 42. Time Response versus Air Temperature

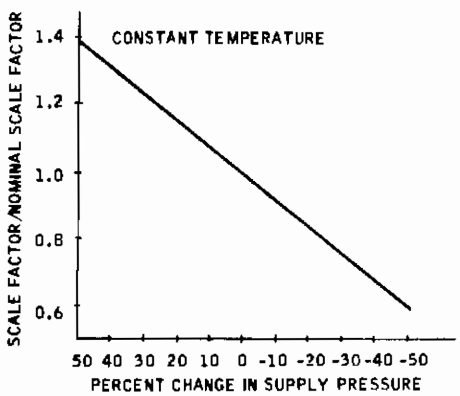


Figure 43. Scale Factor versus Supply Pressure

SENSOR CHARACTERISTICS SPECIFICATION	Sheet 1 of 2

Sensor Accelerometer, Fluidic

Device No. ________

Description of Device:

The fluidic accelerometer has a pneumatically supported inertial mass which operates against pressurized nozzles. The damping is accomplished by the squeeze film method provided by the flanges on the inertial mass. The force developed by an acceleration on the inertial mass, along the sensitive axis, is opposed by the pressure differential created by the closing of a pickoff nozzle and opening of the other pickoff nozzle. The pressure differential is an accurate indication of the applied acceleration. The data shown are from laboratory developmental testing. The ranges available are presented in the same order for the applicable characteristic (e.g., ω_n = 70, 140, 223 Hz corresponds to ranges of ±0.5, ±2.0, and ±5.0 g in that order). Where only value is given it is the same for all devices.

Characteristic	Present Capability	Extrapolated Capability
A. Dynamic Response	2nd order system ω_n = 70, 140 and 223 Hz ζ = in the range of 0.6 to 0.8	
B. Experimental Response to a Step Input		
C. Steady State Accuracy		
1. Hysteresis	± 1.0% FS*	± 0.2% FS
2. Drift	± 1.0% FS	± 0.1% FS
3. Environmental Effects		
a. Altitude	estimated to be greater than 1% at 20,000 ft.	1% to 20,000 ft.
b. Vibration	none within limits of F2	
c. Temperature	SF decreases by approx. 0.04%/°F	
4. Linearity	1% half scale	
5. Repeatability	not tested	
D. Output		
1. Type	pneumatic ΔP	
2. Scale Factor	1.44 psi/g	
3. Sensitivity Threshold	1, 2, and 5 x 10^{-4} g's	1 x 10^{-5} g's
4. Range	± 0.36, ± 1.44, and ± 3.60 psig	
E. Power Supply		
1. Type	pneumatic 25 micron nominal filtration	
2. Voltage/Pressure	5, 10, and 20 ±0.5 psig	
3. Power/Flow Rate	0.17, 0.71 and 1.46 scfm	
F. Environmental Limits		
1. Altitude	not tested	
2. Vibration	10g sinusoidal 50-2000 Hz 0.05 g^2/Hz random 50-2000 Hz	
3. Shock	15 g's lims	
4. Temperature	-65 to 160°F	
G. Predicted Failure Rates	2.5 x 10^5 hr MTBF**	

* Estimated on tests of similar devices

** Engineering Estimates - no test data available

SENSOR CHARACTERISTICS SPECIFICATION		Sheet 2 of 2
Sensor Accelerometer, Fluidic		Device No.
Characteristic	Present Capability	Extrapolated Capability
H. Configuration		
1. Mounting		
2. Approximate Size	3 x 1.5 dia	
3. Approximate Weight	< 1 lb.	

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Aero Propulsion Laboratory (APTA) Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

This part describes the results of a survey conducted to determine the present and the estimated 1970 capabilities of sensors applicable to the control of aircraft propulsion systems. The survey included electromechanical and fluid amplifier (fluidic) sensors for measurement of gas dynamic and static properties as well as for measurement of airframe dynamic parameters.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fluidic Sensors Electro - Mechanical Sensors Propulsion Sensors Sensor Survey						