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FINAL REPORT ON THE TRADE-OFF CHARACTERISTICS OF ACOUSTIC AND PRESSURE SENSORS FOR THE NASP

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INTRODUCTION

This is the final report of a trade study for the development of pressure and acoustic sensors for use on the NASP. Pressure sensors are needed to operate to 100 psia. Acoustic sensors are needed that can give meaningful information about a 200 dB SPL environment. Both sensors will have to operate from a high temperature of 2000°F down to near absolute zero.

At the start of this study, the performance goals and operating environment shown in Table 1 were given as a starting point. At this time in the study, it is known that many of these goals are unattainable, although they have been useful as guidelines in directing this trade study. Revised goals based on the findings of this study for the acoustic sensor are shown in Table 2.

The most significant compromises are: the smallest size attainable is 0.2 inch diameter; the highest frequency response for the microphone is 12 KHz. The temperature range is 70°F to +2000°F operational and absolute zero to +2200°F survival; linearity, resolution, accuracy and thermal performance are as yet unknown, although revised estimates are as shown in Tables 1 and 2.

SURVEY OF GENERAL PRINCIPLES

Sound is an oscillation in pressure, stress, particle displacement, particle velocity, or density that is propagated in an elastic or viscous medium or material. An acoustic sensor or microphone is a device that measures sound and from which information about sound pressure and frequency are obtained.

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Table 1. Design Goals For Pressure/Acoustic Sensors

Performance	Original	Revised Cap	Revised Eddy Cur	Revised Fiber Optic	Units
Freq. Resp.	0 to 20K	0 to 5K	0 to 20K	0 to 20K	Hz
Pressure (max)	100	100	100	100	PSI
Accuracy	±0.5	±1	±0.5	±0.5	% of F.S.
Repeatability	±1	±1	±1	±1	% of F.S.
Size (max dia.)	0.125	0.26*	0.26*	.125	in
Environment					
Temperature (min)	-460	-330**	-330**	-330**	deg-F
Temperature (max)	2500	2000**	2000**	2000**	deg-F
Pressure Range	0 to 100	0 to 100	0 to 100	0 to 100	PSI

Acoustic Noise, Mechanical Shock and Thermal Shock goals unrevised.

*Sensor only--does not include mounting.

**Survival: -460 to 2200°F

Table 2. Revised Design Goals For Acoustic Sensor

Performance	Original	Revised Eddy Cur	Revised Fiber Optic	Units
Freq. Resp.	10 to 50K	10 to 12K	10 to 20K	Hz
Dynamic Range	100-200	100-190	100-190	dB
Linearity	±1	±1****	±1****	dB
Shift of Sensitivity	±1	±2	±1	% of F.S.
Accuracy	1	1****	1****	dB
Size (max dia.)	0.125	0.26*	.125*	in
Environment				
Temperature	-460 to 2500	-330 to 2000**	-330 to 2000**	deg-F
Pressure Range	0 to 100	0 to 100***	0 to 100***	PSI

Duration, Mechanical Shock, and Thermal Shock goals unrevised.

*Sensor only, does not include mounting provisions.

***Must be vented.

**Operating Survival: -460 to 2200°F.

****Except for low press. levels.

Pressure is the force per unit area that one object exerts on another. A pressure sensor measures this force generally by changing the pressure to a physical displacement.

The difference between a pressure sensor and an acoustic sensor then is that the acoustic sensor only measures oscillations in pressure, while a pressure sensor measures both changes as well as static conditions.

Usually a diaphragm is used to convert pressure to a displacement which can be detected by a variety of transduction techniques. At the start of this study, a survey of leading researchers and manufacturers led to the elimination of piezo-electric and piezo-resistive transduction techniques from further consideration. Because of the extreme temperature range of this application, only non-contact transduction techniques are evaluated. These are capacitance, eddy-current and fiber optic.

Under this premise then, pressure acts on a diaphragm which is consequently displaced. This displacement is converted into an electrical signal which is proportional to the pressure. When it is required that this device operate over a wide temperature range, the relationship between pressure, diaphragm displacement and electrical signal becomes a variable influenced by temperature and pressure. Minimizing the temperature effect, or at least identifying and quantifying it, is the objective of good extreme environment pressure/acoustic sensor design.

Accounting for temperature transients and gradients along the sensor further complicates the design task. Also, compatibility of materials as well as stability or at least accountability of the changing material properties over a very wide temperature range must be inherent in the well designed pressure/acoustic sensor.

DIAPHRAGMS

A plain circular diaphragm was selected for this study because of its high natural frequency relative to other pressure sensing devices of equivalent size (Bourdon tube, bellows, convoluted diaphragm). Furthermore, the plain diaphragm is well suited (manufacturable) to small sized sensors (less than 0.25" diameter).

The design formulae for flat circular diaphragms that were used in this trade study are as follows:

$$\text{(T)} \quad T_{MAX.} = \frac{3\, a^2\, P}{4\, t^2}$$

$$\text{(Z)} \quad Z_{MAX.} = \frac{3\,(1-V^2)\, a^4\, P}{16\, E\, t^3}$$

$$\text{(F)} \quad F = \frac{2.56\, t}{\pi\, a^2} \sqrt{\frac{g\, E}{3\, M\,(1-V^2)}}$$

T = MAX. STRESS
a = DIAPHRAGM RADIUS
P = FULL SCALE PRESSURE
t = DIAPHRAGM THICKNESS
Z = MAX. DIAPHRAGM DEFLECTION AT FULL SCALE PRESSURE
V = POISSON'S RATIO
E = YOUNG'S MODULUS
F = RESONANT FREQUENCY
M = SPECIFIC WEIGHT
g = GRAVITATIONAL CONSTANT

The first requirement, or the one that is not compromised, is the pressure range (100 psi pressure sensor, 15 psi acoustic sensor). Then the maximum diaphragm stress for a range of diaphragm diameters and thicknesses is calculated. A graph of stress versus radius for a 0.005" and 0.003" thick diaphragm is shown in figures 1 and 2.

Using the results of the material survey, a practical design limit of 20 KSI at 2000°F is established. This limit means that for a 0.003" thickness, the diaphragm can be no larger than 0.25" diameter, and for a 0.005" thickness, it can be no larger than 0.42" diameter.

Diaphragm center deflection is calculated for the same diaphragm thicknesses over a range of diameters and temperatures for MA 6000. These graphs are shown as Figures 3 and 4. From these graphs, the full scale diaphragm center deflection is determined by adding the maximum diameter requirement of the previous paragraph. The maximum deflection for a 0.003" and 0.005" thick diaphragm is 0.0011" and 0.0002" respectively.

For the three types of transduction techniques discussed, a minimum full scale diaphragm deflection of 0.0003", 0.001" and 0.003" is required for fiber optic, eddy-current and capacitance, respectively. These minimum deflections are based on system level signal to noise ratio and the desired resolution (1 part in 1,000).

A region of feasibility can now be determined as that area bounded by the maximum sensor diameter, the minimum required diaphragm deflection for a particular transduction technique and the deflection versus diameter curve. This region of feasibility for the eddy-current and fiber optic transduction techniques is shown in figures 5 and 6. Because the capacitance technique requires 0.003" deflection, it is not feasible at the diameters and thicknesses considered (up to 0.5" diameter, down to 0.003" thickness).

The resonant frequency for an eddy-current microphone is calculated to be 15 KHz and for the smallest fiber optic sensor, it would be 35 KHz. If the diaphragm is undamped, the useful portion of this frequency range is one third of the resonant frequency. This is approximately 5 KHz for the eddy-current probe and 12 KHz for a fiber optic probe.

COMPARISON OF TRANSDUCTION TECHNIQUES

Fiber Optic Sensors

Transduction Techniques

Many fiber optic based techniques have been used to sense pressure and acoustic signals. Fiber optic based sensors can offer a number of advantages over other techniques. These include: excellent sensitivity, small size, immunity to EMI, ease of multiplexing, and use in some extreme environments. Not all advantages are available in each of the various techniques. Disadvantages of some fiber optic sensors include: sensitivity to other environmental factors such as temperature and strain, complexity, sensitivity to light from other sources, and fragility.

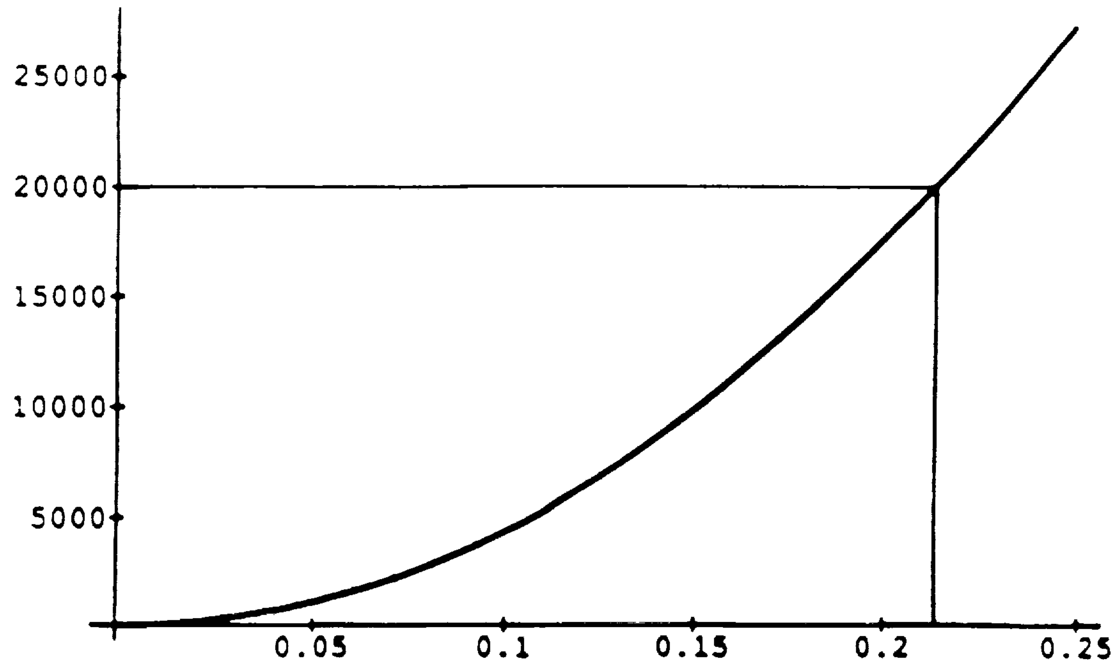

Figure 1. Stress (KSI) vs radius (inches) for 0.005" thickness.

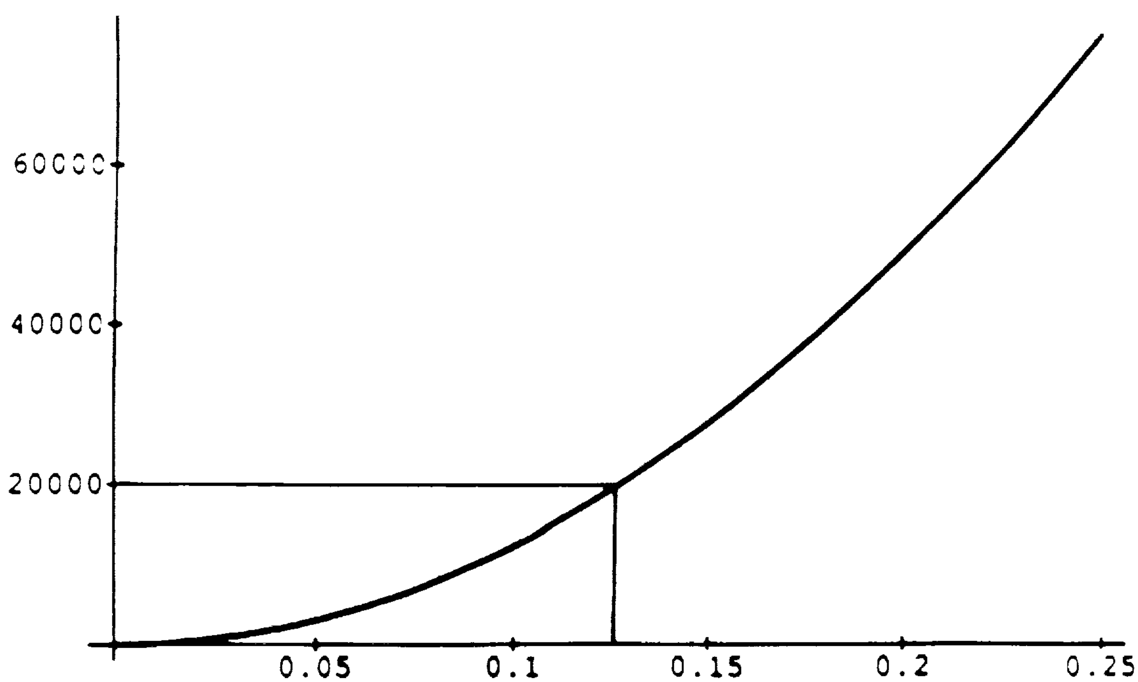

Figure 2. Stress (KSI) vs radius (inches) for 0.003" thickness.

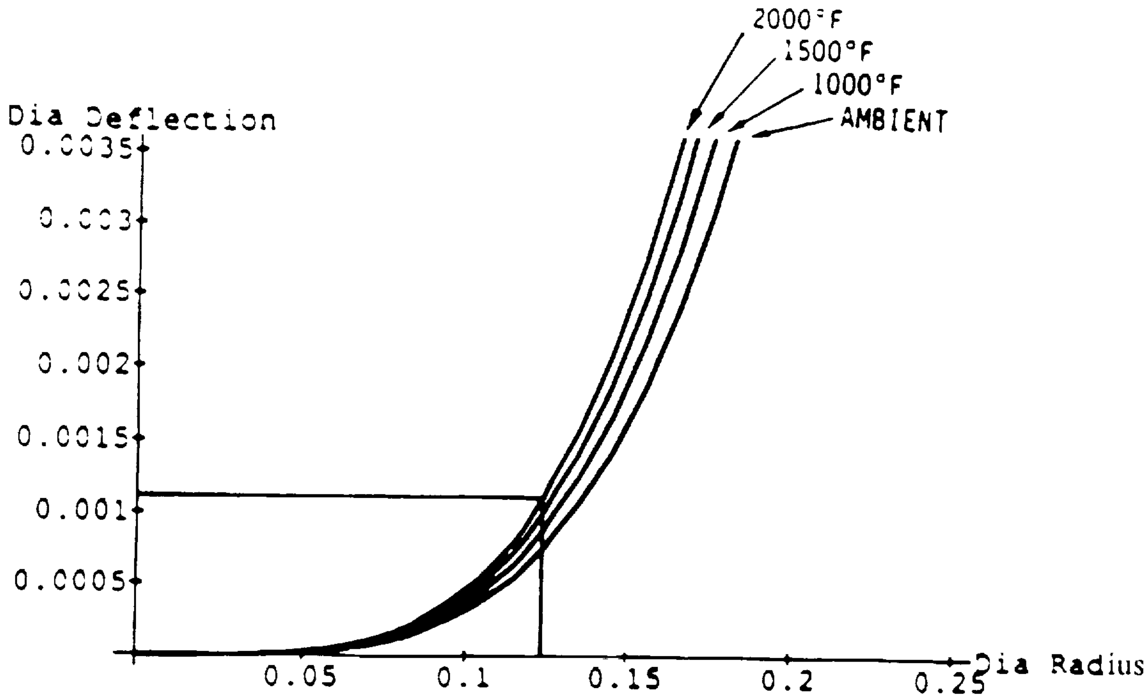

Figure 3. MA 6000 for 0.003" thickness.

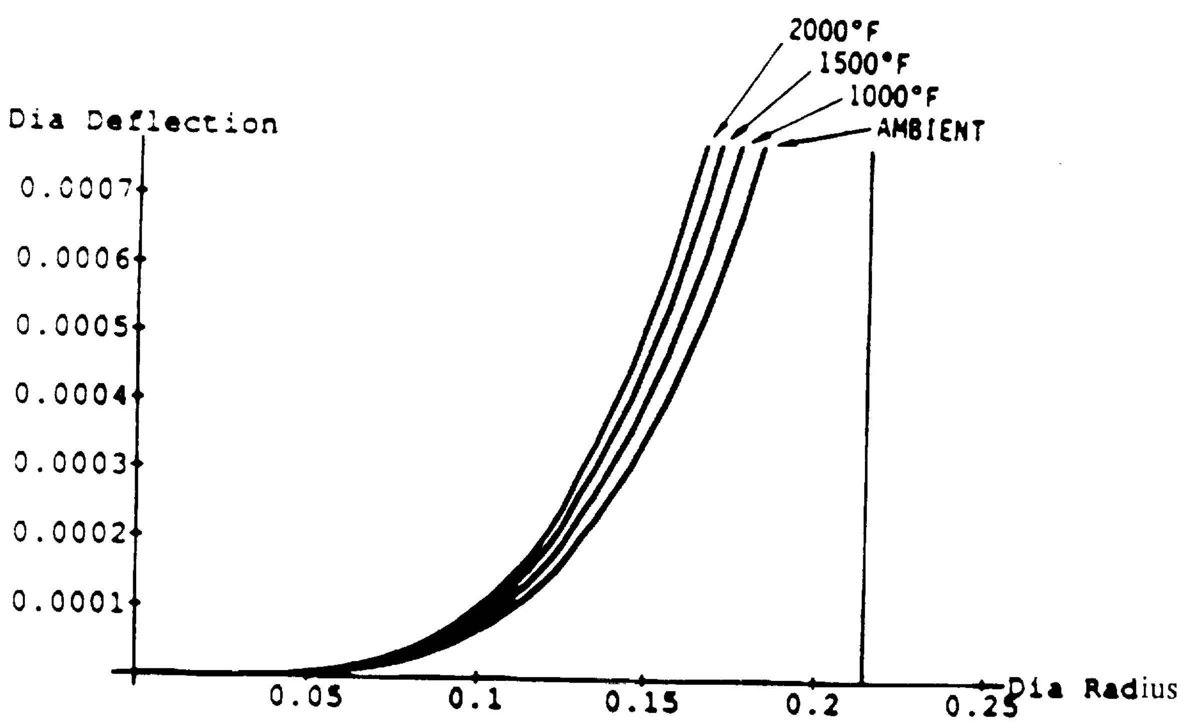

Figure 4. MA 6000 for 0.005" thickness.

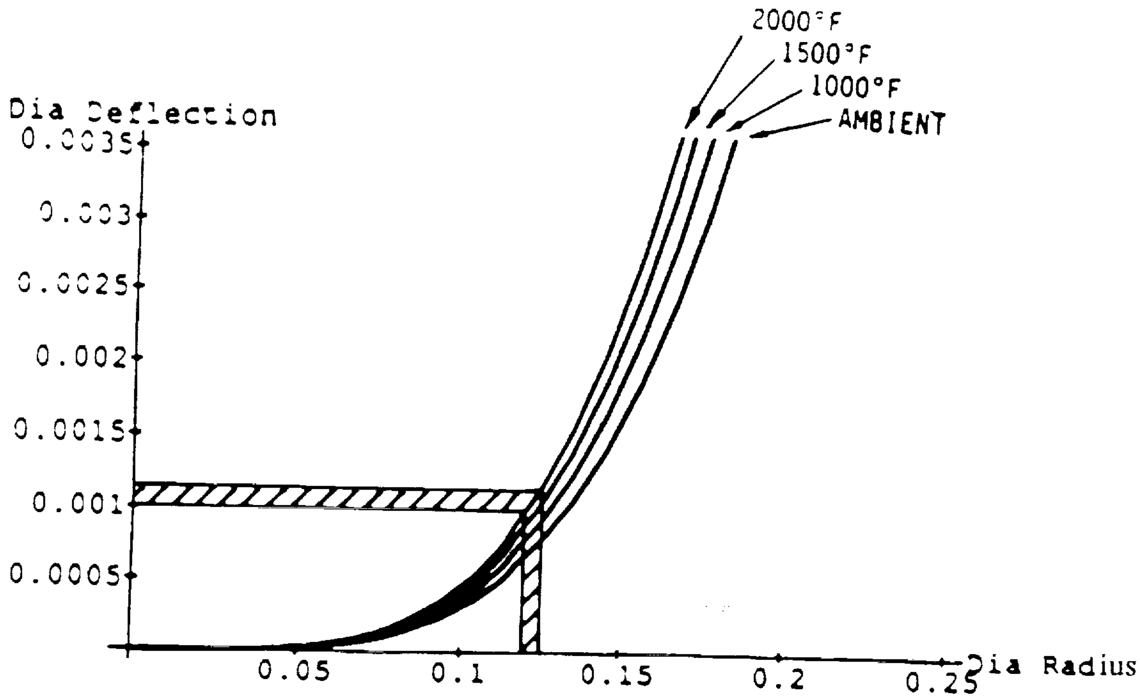

Figure 5. Eddy current feasible region.

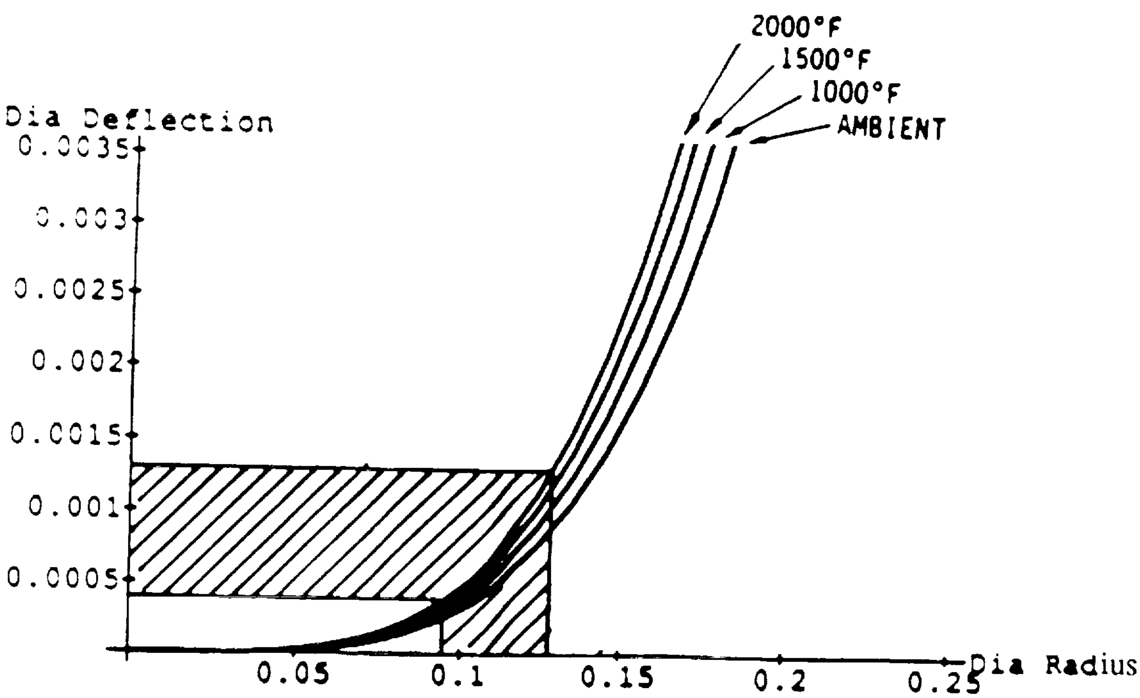

Figure 6. Fiber optic feasibility region.

Fiber optic sensors usually are divided into intrinsic, where the sensing occurs in the optical fiber, or extrinsic, where the sensing is external to the fiber and the fiber serves only to transport the light from the source to the sensor and then to the detector. Amplitude, phase, wavelength, and polarization are parameters that are affected by external stimuli and have been used as the basis for optical sensors. Pressure and acoustic sensors generally utilize amplitude, phase, or wavelength changes. Polarization generally is not used for these types of sensors and will not be discussed.

In amplitude sensors, the intensity of the light is modulated by the variable being measured. Amplitude sensors tend to be relatively simple, inexpensive, and easy to apply. Amplitude sensors include those that modulate the transmission of light across a gap (extrinsic) and microbend sensors (intrinsic). In gap sensors, the light exits a fiber, travels through a gap, may be reflected, and is received by the same fiber or a different one. The intensity of the light received is modulated by the size, or some other parameter, of the gap which varies with the quantity being measured. Microbend sensors make use of the fact that light is lost from an optical fiber when it is bent in a particular fashion. In this sensor, the fiber is placed between two ridged plates. When squeezed in response to some external variable, the fiber exhibits losses in a predictable manner. Microbend sensors tend to be much more sensitive than gap sensors, but have the disadvantage of being fairly large in order to accommodate the ridged plates.

Phase (or interferometric) sensors rely on a shift in phase of the optical signal relative to a reference signal and measure the interference that occurs when these signals combine. Phase sensors are more complicated than amplitude sensors, but usually offer greater sensitivity. Phase sensors have been built utilizing Mach-Zehnder, Fabry-Perot, Michelson, and Sagnac interferometers. These interferometers have many similarities. Generally, a source of coherent light is coupled into an optical fiber (usually single-mode) split into two paths (one a reference and the other the sensor), recombined such that interference occurs, and detected.

In a Mach-Zehnder interferometer, changes in characteristics of the sensor fiber (i.e., length or index of refraction) result in a change in phase relative to the reference path which is detected by the interferometer. Fabry-Perot interferometers generally consist of a single fiber with a sensor cavity at the end which has partially reflective surfaces at both ends. The amount of interference depends on the length of the cavity relative to the wavelength of the light. This type of sensor is generally insensitive to changes in the fiber characteristics. Michelson interferometers can be built similar to the Mach-Zehnder with a reference fiber and a sensor fiber. Displacements of a reflective mirror at the end of the sensor fiber cause phase differences relative to the signal reflected from a mirror at the end of the reference fiber. Michelson interferometers can also be constructed similar to Fabry-Perot interferometers utilizing only one fiber. In this case, half of the end of the fiber is coated with a reflective surface. The reference signal reflects off this surface, while the sensor signal exits the fiber and reflects off the sensor surface. The interference in the cable depends on the length from the end of the cable to the sensor surface relative to the wavelength of the light. As with the Fabry-Perot, this type of Michelson interferometer is generally insensitive to changes in the fiber characteristics. Sagnac interferometers inject light into both ends of a fiber coil and are sensitive to rotations about the axis of the coil. They are not generally used to sense pressure or acoustic signals.

Wavelength sensitive transducers tend to be the most complex, but can offer advantages in multiplexing more than one sensor on a single fiber. Sensors that make use of changes in wavelength include Bragg gratings and wavelength division multiplexing. Bragg grating sensors can be made by producing periodic variations in the index of refraction along a short section in the core of an optical fiber. These gratings cause light corresponding to a wavelength of double the spacing of the index variations to be reflected. Spectrum analysis can be performed on the reflected or transmitted signal to determine the spacing of the index variations. In a sensor, the spacing of the index variations is made to vary as a function of the measured variable. Bragg gratings can easily be multiplexed by placing many sensors along one fiber, each sensitive to a different wavelength. Wavelength division multiplexing (WDM) sensors chromatically disperse the light from a broadband source and focus it on reflective/nonreflective code tracks. The presence or absence of reflection at different wavelengths is sensed by the detector and a digital output is formed which corresponds to the reflective code illuminated. The reflective code that is illuminated is made to vary as a function of the variable being sensed.

Due to the flexibility of fiber optics, there seems to be an infinite variety of fiber optic sensors. Those listed above are some of the more common types. Many others do exist, however, and could be the basis for an extreme environment sensor.

Survey of Fiber Optic Capabilities

Numerous organizations have developed or are developing pressure and/or acoustic sensors using fiber optic techniques. It isn't possible within the constraints of this project to contact each of these organizations to ascertain their capabilities. A literature survey was conducted in order to identify those organizations most likely to be involved in the development of extreme environment pressure and acoustic sensors. These and several other companies were contacted. In addition to determining present capabilities, an attempt was made to determine what the possibilities and limitations are.

The survey indicated the following:

1) Presently available commercial fiber optic pressure and/or acoustic sensors are limited to approximately 450°C (840°F).

2) Silica optical fiber sensors have been developed in a research environment for temperatures of 900-1000°C (1650-1800°F). This appears to be the upper limit for silica sensors.

3) Several fiber optic manufacturers are willing to develop fiber optic sensors rated to approximately 1000°C (1800°F) on a "best effort" basis.

4) One researcher reports success measuring displacement using a sapphire sensor attached to a silica optical fiber up to 1600°C (2900°F). This technique could possibly be applied to pressure and/or acoustic sensors.

5) Interferometric methods are the most favored for small high temperature fiber optic pressure and/or acoustic sensors.

Fiber Optic Sensor Considerations

In considering fiber optic sensors for the NASP application, it must be determined whether or not an accurate measurement can be made consistently with a sensor meeting the physical constraints over the range of environments expected. Of the common fiber optic sensor types, the size constraints and accuracy requirements appear to limit the choice to interferometers, especially Fabry-Perot or Michelson types, measuring displacement to a diaphragm. These provide the greatest accuracy with the smallest size. They also provide relative immunity to changes in fiber characteristics with changes in temperature. Typically with interferometers, fringes are counted and interpolation is performed between fringes to increase resolution. Difficulties exist in determining diaphragm displacements using this technique due to ambiguities. Peaks in the output signal can be due to fringes or peaks in displacement. Usually a second sensor operating in quadrature and some sort of signal processing are required in order to remove the ambiguities. Also, determining absolute displacement can be a problem if the signal is temporarily lost or the sensor turned off. Changes in optical attenuation, due to changes in temperature, may cause intensity variations that could be interpreted as displacements.

Researchers at one organization report success measuring displacement with an unclad sapphire rod attached to a silica single-mode optical fiber up to approximately 1600°C (2900°F). They believe this to be the first successful silica to sapphire splice. The sensor is an interferometer which counts fringes and interpolates between them. A signal-to-noise ratio of 20 (13 dB) was achieved. This technique possibly could be applied to pressure and/or acoustic sensors measuring displacement to a diaphragm. No other researchers have been identified that have progressed this far in the development of high temperature fiber optic pressure and/or acoustic sensors.

Questions that must be asked when considering an extreme environment pressure and/or acoustic sensor include:

- Can adequate range and sensitivity be achieved?
- Can adequate resolution be achieved?
- Can changes in diaphragm characteristics over the temperature range be compensated?
- What is the frequency response?
- Can a sensor be built to withstand the expected environment?
- What is the minimum size?

The answers we can give to some of these questions will be more vague for fiber optic sensors than for capacitive or eddy current sensors due to the experimental nature of high temperature fiber optic sensors.

Range and Sensitivity

Excellent range and sensitivity are characteristics of fiber optic interferometers. Because of the excellent sensitivity, the diaphragm can be designed for a smaller displacement, which leads directly to a smaller diameter sensor. Fiber optic interferometers may be the only way to achieve the NASP requirements for small size and high sensitivity. The maximum range is limited by how much light is captured by the sapphire rod after reflecting from the diaphragm. Because of the relatively large size of the sapphire, it appears that for the diaphragm diameters and displacements of interest, the range is more than adequate.

Resolution

Experimental high temperature sapphire displacement sensors have not exhibited good resolution due to poor signal-to-noise ratio. There are several possible explanations for this. It appears that these sapphire sensors may not be limited by the same factors that limit typical lower temperature fiber optic sensors. Instead, they appear to be limited by factors related to the high temperature and the need to attach a sapphire rod on the end of a silica fiber.

Figure 7 shows a typical sapphire fiber optic interferometer. Interference occurs between the light that is reflected from the end of the sapphire and that which exits the sapphire, reflects from the diaphragm, and re-enters the sapphire. The intensity of the light in the sapphire after the interference occurs is dependent on the distance from the end of the sapphire to the diaphragm relative to the wavelength of the light.

Resolution is determined by noise and error levels compared to signal level. Normal low temperature sensors are limited by spectral purity of the light source, detector dark current, and detector and amplifier noise. High temperature sapphire sensors have additional noise and errors due to optical noise caused by the glowing diaphragm, reflections at the silica-to-sapphire transition, and loss of light at the sapphire-to-silica transition due to the large difference in diameters.

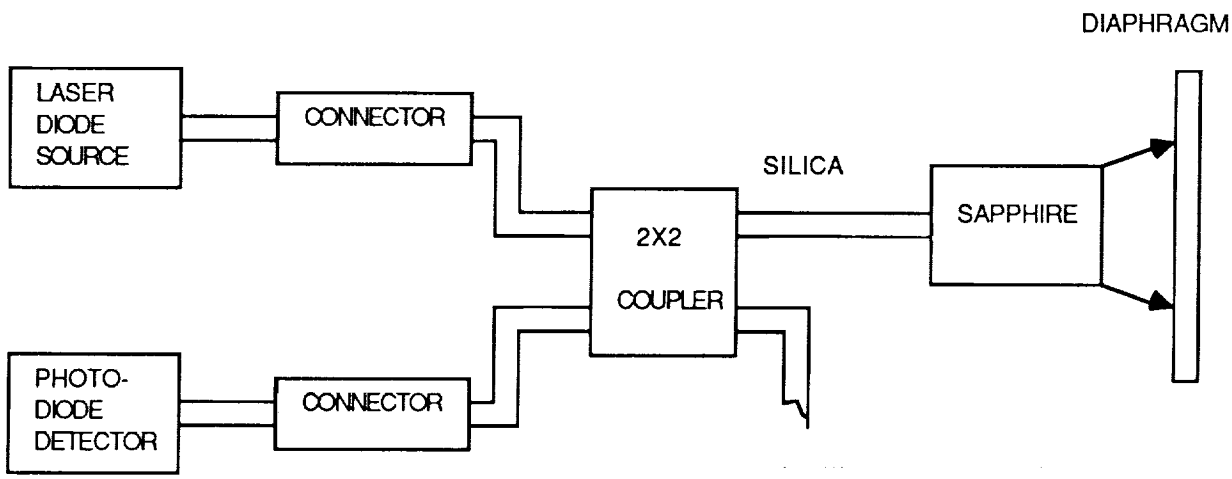

FIGURE 7. TYPICAL HIGH TEMPERATURE FIBER OPTIC PRESSURE/ACOUSTIC SENSOR

Signal Level

Signal level at any point in the system is estimated by first estimating the power level coupled into the silica fiber by the laser diode source and then calculating the loss budget due to the various connectors, couplers, and the sensor. The electrical signal in the detector/amplifier is estimated by assuming a value for its responsivity at the wavelength of the source. Loss values for commercial connectors and couplers are specified by the manufacturer. A loss value due to reflection at the silica-to-sapphire transition can be calculated using the Fresnel reflectance coefficient (later we will discuss the unwanted interference that occurs here). Losses incurred at the end of the sapphire and the diaphragm can be estimated if some simplifying assumptions are made. Coupling loss at the sapphire-to-silica transition depends highly on the nature of the splice. Due to the large difference in diameter of the two fibers, considerable light loss is possible. Also, some light will be reflected. Instead of estimating a value for this loss, calculations have been performed assuming 100 percent coupling efficiency and assuming a minimum efficiency determined by the ratio of the fiber diameters.

Typical laser diode modules will couple 2 mW of optical power into the source fiber. This value will be assumed in the following calculations. Loss values assumed for various components and associated power levels are given in Table 3. The sapphire-to-silica losses are based on a 50 micron sapphire fiber (which is the smallest available and results in the lowest losses). Because the sapphire is so much larger than the silica fiber, it is

Table 3. Optical Signal Levels

COMPONENT	LOSS dB	MAX. SIGNAL LEVEL (uW)
Laser Diode Module	----	2000
Connector	0.5	1780
2X2 Coupler	3.5	801
Silica Fiber	1.0	633
Silica/Sapphire	.04	626
Sensor	2.4	363
Sapphire/Silica	.04-15.9	9-360
2X2 Coupler	3.5	4-162
Connector	0.5	4-144

difficult to couple all of the light in the sapphire into the silica, and also difficult to estimate what efficiency is possible. Therefore, a range of losses is given for this transition.

If perfect reflection from the diaphragm is assumed, and the maximum possible angle of the light exiting the sapphire is assumed to be dependent on the numerical aperture of the silica fiber, and the exit angle is assumed to be uniformly distributed, calculations indicate that more light is coupled back into the sapphire than what is reflected from the sapphire/air interface (for distances of 17.5 to 32.5 microns). This is not ideal for a good interferometer. For these calculations, it is assumed that the sapphire can be coated to increase the reflection and create an ideal interferometer (even though this may be very difficult in practice). If this is not the case, losses will be higher, resulting in lower signal levels.

Table 3 indicates that the power level in the fiber just prior to the detector is estimated to be between 4 and 144 microwatts, depending on the efficiency of the sapphire-to-silica splice. This table points out the importance of achieving an efficient splice. Please note that these calculations are meant to be rough estimates in order to identify general trends and not to be accurate design calculations.

Noise Levels

One of the advantages of using silica single-mode fiber to transport the light signal is the low loss of this fiber. Because the loss is low and an interferometer is insensitive to changes in characteristics of the silica fiber, the sensor can be located a significant distance from the support electronics, allowing the electronics to be located in a controlled environment. This permits the use of standard laser diode sources and photodetectors. It is assumed since standard sources can be used that spectral purity of the light source is not a limit to the resolution of a sapphire interferometric sensor. This source of noise will be ignored in the following calculations.

Detector and amplifier noise can be estimated from the specifications of typical commercial hardware. A typical value for the noise equivalent power of a detector and amplifier is 0.044 microwatts. The noise equivalent power is the optical power in the fiber just prior to the detector that would result in equivalent electrical noise. This number allows comparison of the electrical noise of the detector and amplifier with the optical signal level. Compared to a signal level of 4 to 144 microwatts, we see that this noise can be quite significant (1%) if a poor sapphire-to-silica splice is made. Of course, if a lower noise detector/amplifier can be used, these numbers can be reduced.

A unique problem associated with high temperature fiber optic pressure/acoustic sensors is optical noise caused by glowing of the pressure diaphragm. The radiation from the diaphragm can be estimated using Plank's Radiation Law. Figure 8 shows the spectral exitance calculated for 1370°C (2500°F) for a black body. As can be seen from this figure, most of the energy is above 1000 nm in wavelength. Using typical responsivity curves for silicon and germanium detectors and assuming a spectral emittance for the diaphragm, the noise can be estimated. If the spectral responsivity curves are normalized to the signal wavelength (assumed to be 850 nm for silicon and 1330 nm for germanium), multiplied by the spectral exitance at 2500°F, integrated over wavelength and multiplied by the assumed spectral emittance of 0.65, the equivalent noise power can be calculated and compared to the signal power. Using this method, the noise in the sapphire is estimated to be 5 microwatts for the silicon detector and 90 microwatts for the germanium detector compared to an estimated signal level of 363 microwatts. This rough calculation indicates that the noise from the glowing diaphragm is significant, and from this standpoint it is better to use a shorter wavelength for the source and detector. A modulator/demodulator scheme may be necessary to minimize the effects of this noise.

Error Sources

Typical photodiode dark currents are on the order of a few nanoamps. When compared to other error and noise sources, this is insignificant.

Less than 1% of the optical power is reflected at the silica-to-sapphire transition. This would appear to be insignificant. However, the electric field of the reflected signal is approximately 9% of the incident field. This reflected signal will interfere with the signal returning from the diaphragm after it has passed through the sapphire-to-silica transition. Even if no light is lost at the sapphire-to-silica transition, with the losses at the diaphragm, this interference will be significant. With significant losses at the sapphire-to-silica transition, this interference will swamp the sensor signal. The actual interference that occurs will depend on the relative phases of the two signals, which among other things depends on the length of the sapphire, which depends on temperature (a 1 cm piece of sapphire changes by over 100 wavelengths from 0 to 1370°C).

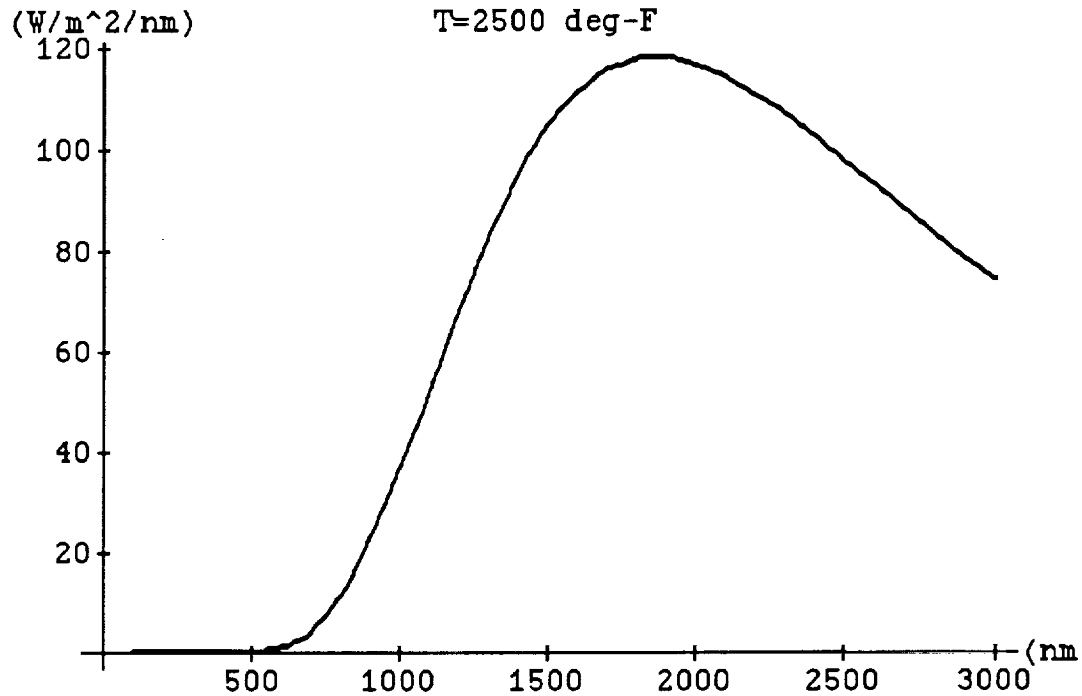

FIGURE 8. SPECTRAL EXITANCE FOR 2500°F

In summary, several noise and error sources limit resolution. Significant error can result when the reflected signal from the silica-to-sapphire transition interferes with the returning light, particularly if losses are high at the sapphire-to-silica transition. Also, optical noise due to the glowing diaphragm and detector/amplifier noise may possibly be significant.

Temperature Compensation

A concept has been developed using a reference sensor near the edge of the diaphragm to compensate for temperature induced variations in displacement. This appears to be a viable approach and may provide other advantages, including compensation for changes in intensity due to temperature changes and a measurement of noise due to radiation.

It most likely will be necessary to measure temperature in order to compensate for changes in diaphragm characteristics. This possibly can be done with a fiber optic sensor.

Frequency Response

Frequency response of fiber optic systems generally is well beyond that required for NASP. Frequency response in a high temperature sensor will be determined by diaphragm characteristics (see section on diaphragms).

Environmental/Materials

Sapphire is an excellent high temperature material. It is mechanically strong and hard and can withstand high temperature gradients. A disadvantage is that it is difficult to bond to other materials, such as silica fibers, claddings, and other sensor parts. Also, it is produced using single crystal growth, a process that is slow and expensive. Impurities can be a problem. Presently, only rods and large diameter fibers (minimum size is 50 microns) are available for sensors. No single-mode fiber is produced. Because of this, high temperature sapphire interferometric sensors normally use silica single-mode fiber to transport the light signal from the source to the sensor and from the sensor to the detector. A splice is required to connect the silica fiber to the sapphire. Sapphire can easily withstand the temperatures required for NASP. Whether or not a practical sensor can be constructed using sapphire combined with other materials which can survive the expected environment is the question that is yet to be answered.

Size

Present experimental high temperature fiber optic displacement sensors do not exhibit the small size required by NASP. However, the potential exists for a probe using fiber optic techniques to be smaller than those using other techniques if resolution can be improved so that a smaller diaphragm can be used.

Other

As stated earlier, due to the low losses of silica optical fiber, the sensors most likely can be located a significant distance from the support electronics.

Capacitive Sensors

Transduction Techniques

Capacitive sensors have been used for many years to measure displacement in a non-contact manner. Pressure and acoustic sensors are constructed by measuring displacement to a pressure diaphragm, which deflects in a known manner as a function of pressure. Capacitive sensors can be divided into those that use parallel plate capacitors as sensing elements and those that depend on fringing capacitance. Measurement techniques vary widely. Most use a high frequency carrier to drive the sensor and demodulate the output.

The capacitance of an ideal parallel plate capacitor is equal to a constant times the area of the plates divided by the distance between the plates ($C = kA/d$). This is the basis for most capacitive sensors. As the distance between the plates varies, the capacitance changes in an inverse relationship. Some capacitance sensors make use of the changing effective area of the plates as they move relative to each other in a transverse manner (not usually done in pressure/acoustic sensors). Generally in a parallel plate sensor, one plate is grounded and the other driven by an AC excitation signal.

Capacitances of actual sensors typically are 1 pF or less. Because of this, these sensors are sensitive to other capacitances between the sensor electrode (and anything connected to it) and ground. These include cable capacitances, capacitances in the electronics, and other stray capacitances. In order to minimize the effect of these capacitances, many sensors make use of a guard electrode. The guard electrode surrounds the sensor electrode and shields it from any grounds except the "target". The guard electrode is connected to the shield of a coax cable (near 100% shielding is necessary) and driven at the same potential as the sensor electrode, which is connected to the cable center conductor. The effect of the guard is to minimize currents flowing in the sensor circuit to charge and discharge extraneous capacitances. The guard also has the effect of reducing nonlinearities introduced by fringing fields at the edges of the sensor electrode.

Some capacitive sensors make use of fringe fields to sense displacement. These sensors typically use side by side plates and can measure the effect of grounded or ungrounded metal targets or even dielectrics introduced into the fringing field. In some cases, neither capacitor plate is grounded and a three terminal arrangement is used. In this arrangement, cable effects often can be minimized or eliminated.

Many different techniques are used to convert changes in capacitance to an electrical signal. These include bridge circuits, transformer ratio bridges, resonant circuits, and constant current sources used to measure capacitive reactance.

Bridge circuits use the sensor capacitance as one arm of a bridge. Changes in capacitance from a null position generate an output. Frequently, two sensor capacitors are used in a differential mode to improve linearity and provide some temperature compensation, at the expense of increased complexity.

Transformer ratio bridges use a transformer with multiple taps controlled by a microprocessor to balance the unknown sensor capacitance with a known reference capacitance. Three terminal techniques minimize the effects of cable capacitances. This method can provide very accurate results, but tends to be slow.

In a resonant circuit, the sensor capacitance is combined with an inductor to create a high Q resonance. The response at the carrier frequency varies as the frequency of resonance varies due to capacitance changes. Either amplitude or phase changes can be detected. This method tends to be very sensitive, but is also sensitive to changes in parameters of other circuit elements.

One method measures capacitive reactance (X_C) instead of capacitance. Because reactance is inversely related to capacitance and capacitance is inversely related to displacement, capacitive reactance is directly related to displacement. This method uses an AC constant current source to drive the sensor, and the output voltage is directly related to displacement. Synchronous detection removes out of phase components due to resistive losses. A guard is required to minimize cable effects.

Survey of Capacitive Sensor Capabilities

Many companies have developed and market capacitive based sensors. Because this is a more mature market than fiber optics, the tendency is for fewer organizations to be involved. Several were contacted in order to ascertain the state-of-the-art and to determine what might be possible. The survey indicated:

1) The highest temperature rating identified for a capacitive displacement sensor is 1000°C (1800°F). This sensor was operated accidently to 1100°C (2000°F), but not in a calibrated fashion.

2) Other capacitive displacement sensors have been operated to 650-750°C (1200-1400°F).

3) Two manufacturers believe a 1200°C (2200°F) sensor is feasible, but would require a development effort.

4) One organization is presently working on a program to develop a 1650°C (3000°F) sensor.

5) A capacitive reactance type sensor driven by a constant current source and using a guard electrode appears to be the favored technology for a small, high temperature pressure and/or acoustic sensor.

Capacitive Sensor Considerations

The technique using a constant current source to measure capacitive reactance is what has been used to construct the highest temperature capacitive sensors to date. Since this technique has resulted in the best results, appears to have many advantages, and is the most promising to extend to higher temperatures, it will be considered here. One of the advantages of this technique is that as the capacitance is reduced the signal level is increased. This supports the use of smaller electrodes with greater separation to some extent. However, as the capacitance is reduced, the necessary output impedance for a constant current source and the input impedance for the amplifier both increase. Also, as the distance from the sensor to the diaphragm increases, so do thermal variations.

Range and Sensitivity

Range and sensitivity estimates are based on information obtained from a leading supplier of capacitive measurement systems. In the past, the highest temperature displacement systems have used a transducer with a sensor electrode of 0.060 inch. Transducers with electrodes as small as 0.040 inch are available but not for high temperature applications. The 0.060 inch electrode is what is recommended for an extended temperature range sensor. The maximum range for this electrode is approximately 0.030 inch, which is much larger than the diaphragm design will allow. Therefore, the range of this sensor is more than adequate.

In order to achieve adequate sensitivity, the supplier mentioned above estimates a full scale diaphragm deflection of at least 0.003 to 0.004 inch.

Resolution

Resolution in capacitive sensors is generally limited by noise. Because of this, there is a trade-off between resolution and frequency response. Noise sources include thermal (Johnson) noise, amplifier voltage and current noises, cable noise and carrier noise. The impedance of a capacitive sensor tends to be very high due to the low value of capacitance. This reduces the current drive necessary to provide a reasonable output voltage, but adversely affects noise. The high impedance of the sensor necessitates a constant current source with an extremely high output impedance and an amplifier with an extremely high input impedance (to the extent that manufacturers patent their particular circuit). These extremely high impedances can result in high noise levels.

Typical resolution for a capacitive sensor of this type is 3 mVrms for a 5V maximum output and a frequency response of 200 Hz (at room temperature). With a frequency response of 3500 Hz, the resolution increases to 25 mVrms (at room temperature). Some of this is due to the carrier, which typically is at 15 KHz. The maximum carrier frequency is limited by available drive amplifier technology. With new driver technology and a new demodulation scheme, it is estimated that a 2000 Hz bandwidth can be achieved with a resolution of 10 mVrms (at room temperature).

Noise in high fidelity systems is usually a function of temperature. If it is assumed, due to the high impedance of the circuit, that the dominant noise is resistor thermal (Johnson) noise, the noise at high temperature can be estimated by multiplying the room temperature noise by the square root of the ratio of the absolute temperatures. This results in a multiplier of 2.3 which leads us to estimate the noise at 2500°F to be 23 mVrms for a bandwidth of 2000 Hz and a maximum output of 2000 Hz and a maximum output of 5V. This is 0.7% of full scale.

Temperature Compensation

Changes in the capacitive sensor output will occur due to changes in dielectric properties with temperatures even though every effort is made to eliminate this effect. If the temperature effects are repeatable and of the right polarity and magnitude, it may be possible to compensate changes in diaphragm characteristics as a function of temperature. The possibility for this type of compensation is not considered very likely.

For temperature compensation of diaphragm characteristics, a leading capacitive supplier believes a second capacitive sensor and/or temperature transducer will be required in each probe.

Frequency Response

See discussion on resolution.

Environmental/Materials

Capacitive sensors require conductive materials for the various electrodes and connections, insulating materials to separate the conductors, and materials to hold things together.

Because of the high impedance of the capacitive reactance, series impedances tend to be insignificant. These include conductor and electrode resistances and inductances. No special requirements are placed on the conductive materials, and any somewhat conductive material that meets the environmental and other requirements will do.

Also, because of the high impedance of the capacitive reactance, parallel impedances tend to be significant. These include cable and extraneous sensor capacitances and leakage in dielectric materials. In particular, in the constant current source system being discussed, whereas the impedance between the sensor electrode and guard can be quite low, the impedance between the guard and ground must be kept above one megohm. Several good high temperature ceramic materials are available. Unfortunately, due to the high capacitive reactance at the high temperatures to be encountered, even those have non-negligible conductances. To some degree, synchronous detection can eliminate the effects of leakage, but large leakage currents can load drivers and swamp the output signal. The design of a capacitive sensor will require careful attention to the selection of the dielectric material and the design of the insulators.

The selection of materials to hold things together possibly will be simplified by the lack of constraint on the conductive materials and complicated by the limited choice of dielectric materials.

Size

The use of a 0.060 inch sensor electrode, as discussed in the section on range and sensitivity, and the need for a second sensor and/or temperature transducer result in a minimum probe size of approximately 1/4 inch. This does not include any additional room which may be required to increase the thickness of dielectrics in order to increase their electrical resistance at temperature.

The requirement to have a diaphragm displacement of 0.003 to 0.004 inch results in a minimum diaphragm diameter of approximately 3/4 inch (see the section on diaphragms for further discussion of this requirement). This requirement then is the driving one.

Other

Capacitive based sensors are sensitive to cable length. Most systems (including the one discussed here) are limited to cable lengths of 20 feet, with 5 to 10 feet being the preferred maximum length.

Eddy Current Sensors

Eddy Current Transduction Techniques

Eddy current techniques have been used for non-contact displacement sensors for quite some time and the basic principles are well understood. This transduction technique can be used in pressure and/or acoustic sensors in a similar fashion to the other techniques discussed - measuring displacement to a pressure diaphragm.

In an eddy current sensor, an AC current flowing in a coil generates a magnetic field in the area near the coil. Placing the coil near a metal target induces a current flow in the target. Because the current flows in a circular pattern, it is called an "eddy current". The induced current produces a secondary magnetic field that opposes and reduces the intensity of the original field. This changes the effective impedance of the exciting coil. The impedance change depends on the distance of the target from the coil. It can be detected and provides the basis for a non-contact displacement sensor.

Typically, a balanced bridge network is used to detect impedance changes in the sensor coil. The bridge is driven by a high frequency (approximately 1 Mhz) carrier, and its output is amplified, demodulated, and converted to a linear output proportional to the target displacement.

Survey of Eddy Current Capabilities

The highest temperature eddy current sensor developed to date is an 1100°C (2000°F) microphone developed for the Air Force Dynamics Laboratory. This sensor had a dynamic range from less than 90 dB SPL to greater than 190 dB SPL (relative to 20 micropascals). Resolution was limited by noise, which was measured to be 0.195 mVrms with full scale (the worst case) output and a 10 KHz bandwidth (at room temperature).

Eddy Current Sensor Considerations

Eddy current sensors differ from capacitive sensors in that they are low impedance devices and they use magnetic fields versus electric fields. While some of the same considerations must be made, for the most part, they tend to be quite different.

Range & Sensitivity

Range of the sensor is limited by the size and inductance of the coil. For coils that can be built with available materials, more than adequate range is available for practical diaphragm displacements. Sensitivity of the eddy current sensor is determined by a number of factors, including the coil inductance and target resistivity. Sensitivity is an important factor in determining necessary diaphragm displacement, which determines diameter. See the discussions on diaphragm design.

Resolution

As with capacitive sensors, resolution is limited by noise. However, eddy current sensors have two properties which tend to greatly reduce noise levels. First, a much higher carrier frequency is used - about 1 MHz versus 15 KHz. This allows much higher bandwidths without introducing carrier noise. Also, any carrier present is usually beyond the frequency range of interest. Second, the low impedance of eddy current sensors results in much less noise being generated and greater attenuation of noise from other sources. The impedance of eddy current sensors is measured in hundreds of ohms versus tens or hundreds of megohms (or greater) for capacitive sensors. Signals from eddy current sensors do require higher levels of amplification, so some of the advantage is lost. Noise in eddy current systems mainly is generated in the amplifier and other electronics and, therefore, is not dependent on the sensor temperature. A noise level of 0.195 mVrms has been measured for a 1/2 inch diameter high temperature microphone with a bandwidth of 10 KHz and maximum signal level of 2.5V. This noise level is 0.01% of full scale. It is expected that the resolution of a 0.3 inch sensor will not be this good. Resolution of better than 1 part in 1000 is expected.

Temperature Compensation

Due to the fact that eddy current sensors are low impedance devices, they are sensitive to changes in conductivity of the sensor coil and, to a lesser extent, target materials. Also, they are sensitive to inductance changes caused by thermal expansion (or contraction) of the sensor coils. Because changes in conductivity and thermal expansion are well behaved physical properties, in the past it has been possible to use these changes to compensate for changes in diaphragm characteristics with temperature. The ability to do this depends on the particular materials and geometry used.

In extreme environment applications, generally two coils are used in opposite legs of the bridge to provide a signal that is much less sensitive to extraneous environmental factors (such as temperature). Stimuli that act on both coils equally are effectively cancelled out.

Frequency Response

As stated in the section on resolution, good resolution has been achieved in systems with 10 KHz bandwidth. Higher bandwidths are possible with lower resolution. However, it is likely that for an eddy current sensor, diaphragm characteristics will be the limit on frequency response (see the discussion on diaphragms).

Environmental/Materials

The requirements for materials are quite different for eddy current sensors when compared to capacitive sensors, mainly due to the difference in impedance of the sensors. With eddy current sensors, the impedances of the conductors are significant and careful attention must be paid to the selection of conductor materials, including the diaphragm (which is the target). The properties of these materials must be well understood over the operating temperature range. As discussed in the section on temperature compensation, temperature-induced changes in different properties are often used to compensate each other. Dominant effects are due to changes in mechanical properties of the diaphragm, such as thermal expansion and change in modulus.

Due to the low impedance of the sensor, dielectric properties of the insulators are relatively unimportant and almost any good high temperature insulating material will do.

The selection of materials to hold things together possibly will be simplified by the lack of constraint on the dielectric materials and complicated by the choice of conductive materials.

Size

The minimum size for an eddy current sensor is determined by the smallest coil that can be wound with high temperature wire and have adequate inductance, coil side clearances, minimum diaphragm deflection, and sensor side wall thickness. See the section on diaphragms for further discussion. The minimum outside diameter for an eddy current sensor is estimated to be 0.3 inch.

Other

Maximum cable length is determined by the cable capacitance. The amount of cable capacitance that can be tolerated depends on the characteristics of a particular sensor. With extreme environment sensors built in the past, cable lengths have been limited to approximately 42 feet. This is likely to be different for a new sensor, and could be longer or shorter. If lower capacitance cable were used, it may be possible to extend this range.

Summary Of Transduction Techniques

No transduction technique is available to meet the NASP requirements with existing technology.

Capacitive sensors are large relative to the NASP requirement and suffer from poor resolution and frequency response and the need for the sensor to be within 20 feet of the electronics. The poor resolution and frequency response are fundamental problems due to noise caused by the high impedance of the capacitive sensors. With further development, it might be possible to reduce the size or increase cable length, but not without adversely affecting resolution and frequency response.

Eddy current sensors are also large relative to the NASP requirement and also have limited cable lengths (typically 42 feet in the past). Although eddy current sensors have proven performance in extreme environments, due to the constraints in designing them, it is believed the size of an extreme environment sensor could be no smaller than 0.3 inch in diameter. With some work, cable lengths possibly could be extended.

Fiber optic sensors provide the possibility for a small sensor to meet the NASP requirement, even though present developments don't exhibit this characteristic. The need to use sapphire at high temperature complicates the design and introduces errors and uncertainties not present in low temperature silica sensors. Present research sensors suffer from poor resolution. A significant development effort will be required to realize the potential of fiber optic sensors.

Short-term development seems to favor eddy current techniques with the penalty of larger size. Long-term development may favor fiber optics with the penalties of cost, schedule and uncertainty.

MATERIALS

For the development of an acoustic/pressure sensor that operates from -460 to 2000°F (and possibly higher) materials are the key limitation to performance. For the three sensor types considered in this development (capacitance, eddy-current, fiber optic), some of the basic material requirements are shown in Table 4.

Numerous materials are available in the above categories that will maintain useful properties up to 1500°F and some even up to 1800°F. However, very few choices remain when the requirement goes up to 2000°F. Platinum, molybdenum and rhodium are some of the choices for the conductors and magnet wire. Alumina, magnesia, hafnia, berylia and boron nitride are available as insulators. Cotronics and other manufacturers make ceramic cements with a range of properties that are useable to 3000°F and higher.

But when it comes to choosing a material for mechanical support and specifically the diaphragm, few materials have anything left to offer. For this study, the materials shown in Table 5 were reviewed for the diaphragm application.

The most promising material for use as a diaphragm at 2000°F and higher is the mechanically alloyed nickel base oxide dispersion strengthened and precipitation hardened series of metals. Two of these alloys are Inco Alloy's MA 6000 and MA 754. Samples of both these materials have been purchased for this study.

Both these alloys are machinable to the requirements of this study. Weldability has yet to be fully characterized but appears promising so far (two samples have been machined and hermetically welded). Compatibility with other materials has yet to be tested. High temperature properties have yet to be verified. Investigation of other materials necessary for these sensors is continuing.

Table 4. Types Of Materials Required

- Electrical Insulators - To isolate conductors
- Electrical Conductors - To transmit signals
- Mechanical Support - For insulators, conductors, and other components
- Diaphragm - To transduce pressure into displacement
- Hermetic Seal - To isolate sensor components from environment
- Magnet Wire - To make an efficient inductor (eddy current only)
- Sapphire and Silica Fiber - To transmit optical signals (fiber optic only)
- Silica or Sapphire to Metal or Ceramic Seal - To isolate components from environment (fiber optic only)
- Reflective Coatings - To improve signal to noise ratio (fiber optic only)
- Ceramic Cements - To assemble components
- Springs - To accommodate differential expansion of various materials
- Ceramic Fibers or Wool - To use as electrical insulators
- Transition Materials - For spanning different material properties

Table 5. Diaphragm Material Candidates

- Titanium Silicon Carbide Composite - SiC fibers 3 to 5 mils, too large for a 3 mil diaphragm
- Titanium Aluminide Composites - Same as Ti-SiC, fibers too large
- Nickel Aluminide - Shows promise
- Iron Aluminide - Shows promise
- Niobium Beryllides - Still under consideration
- Ceramic Matrix Composites - Non-conductive, may be suitable for fiber optic sensor
- Carbon-Carbon Composites - Non-conductive, may be suitable for fiber optic sensor
- INCO 718 - Insufficient strength at 2000 deg-F, useable to 1500 to 1800 deg-F.
- INCO MA 6000 - Shows promise, oxidizes rapidly above 2000 deg-F.

CONCLUSIONS

- Diaphragm materials limit minimum size and maximum frequency responsible attainable.
- No transduction is available to meet all the NASP requirements with existing technology.
- Capacitive sensors are large relative to the requirement, have limited resolution and frequency response due to noise, and cable length is limited to approximately 20 feet.
- Eddy current sensors are large relative to the requirement and have limited cable lengths (typically 42 feet in the past).
- Fiber optic sensors provide the possibility for a small sensor, even though present developments don't exhibit that characteristic. The need to use sapphire at high temperature complicates the design. Present high temperature research sensors suffer from poor resolution. A significant development effort will be required to realize the potential of fiber optics.
- Short-term development seems to favor eddy current techniques with the penalty of larger size, and reduced dynamic range for acoustic sensors.
- Long-term development may favor fiber optics with the penalties of cost, schedule, and uncertainty.