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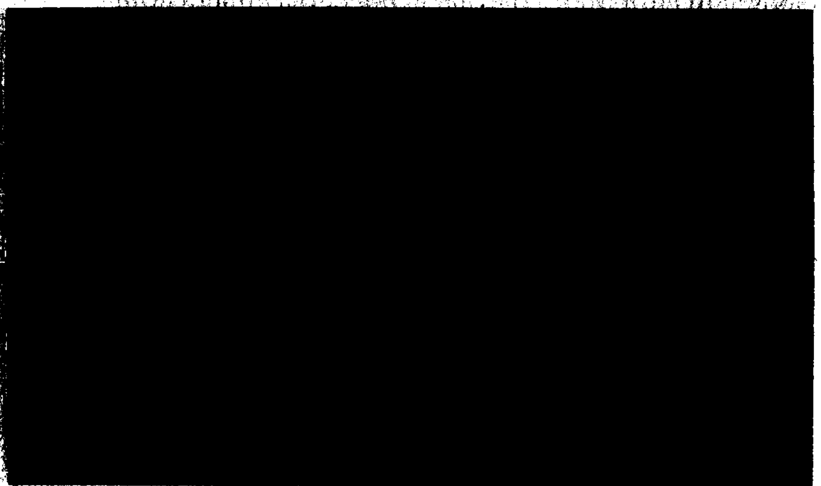

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SECOND QUARTERLY REPORT

on

NONCONTACTING MEASURING DEVICE TO INDICATE DEFLECTION OF TURBOPUMP INTERNAL ROTATING PARTS

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

by

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NONCONTACTING MEASURING DEVICE TO INDICATE
DEFLECTION OF TURBOPUMP INTERNAL ROTATING PARTS
(Contract NAS8-26903)

by

D. B. Hamilton, D. R. Grieser, A. M. Plummer,
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SUMMARY

This is the second quarterly report on the program to develop noncontacting, nondestructive techniques to measure vibrations and deflections of parts in future LOX and LH_2 multistage turbopump prototypes. The measurements of interest include shaft vibration, vibration of turbine wheel and blades, blade clearance, vibration of impellers, valve component flutter, and vibration of face seal components. This report summarizes the results of Phase I (Feasibility Study).

With the exception of a new idea for a fast-neutron detection technique, evaluation of the various techniques was concluded. As a result of a meeting between MSFC and BCL (Battelle's Columbus Laboratories) personnel, three techniques were selected for Phase II (Development). These are

(1) Ultrasonic Doppler devices

(2) Flash X-ray

(3) Light-pipe reflectance.

An old J-2 turbopump will, if possible, be made available to assist the development of the three techniques. The results of the evaluations conducted during the second quarter are as follows.

Examination of drawings of several turbopumps has indicated that the ultrasonic Doppler approach is feasible for the pump sections where a solid acoustical path is available from pump case to the part being measured. It is likely that solid paths cannot be found in the turbine section; so this approach may be unsuccessful for measuring vibrations of turbine blades or wheels. Ultrasonic Doppler devices are not expected to require substantial pump modification.

Our studies have indicated that neutron radiography cannot provide real time measurements. Thermal neutron sources are too large to provide sufficient resolution for the turbopump application. Fast-neutron radiography would suffer from excessive scattering, reducing contrast. A new fast-neutron detection device has been conceived which may allow displacement measurements to be made at a single point. It is recommended that Phase I be continued to evaluate feasibility of the idea.

Experiments with a flash X-ray unit have demonstrated that neither motion nor a 1-inch-thick piece of interposed aluminum appear to reduce resolution significantly. Further, repetitive pulsing of the unit does not deteriorate the resolution of the radiograph produced. Our evaluations indicate that flash X-rays are feasible for the application. The ability to penetrate very thick sections is questionable. Flash X-rays may be appropriate only for the turbine sections; however, this judgement can only be made after experimentation with an actual turbopump.

A light-pipe-reflectance device was purchased and evaluated. If the required turbopump modification is possible, this technique appears feasible for the pump sections and the turbine wheel. The high temperature of the turbine blades may preclude its use in that area, although turbine wheel measurements appear feasible.

The evaluation of Mössbauer analysis of gamma rays was concluded. The use of frequency modulation of a carrier wave by Doppler-shifted gamma rays was judged not feasible. The magnitude of vibrational displacement encountered in turbopumps is sufficient to spread the vibrational information over numerous FM side bands.

Evaluation of inductance, eddy-current, and capacitance techniques failed to produce an approach which appeared substantially better than the Bentley inductance probes currently in use. Signal transmitters appear to be a feasible way to replace contact-type slip rings.

INTRODUCTION

The purpose of this program is to develop noncontacting, nondestructive devices to measure vibrations and deflections of internal parts in future LOX and LH_2 multistate turbopump prototypes. The program is a three-phase effort in which Phase I is a feasibility study resulting in approximately three candidate approaches, Phase II is a development study, and Phase III involves experimental verification.

This second quarterly report summarizes the results of Phase I (Feasibility Study). As a result of a meeting held at MSFC on August 24, 1971, between BCL and MSFC project personnel, three approaches were selected for development in Phase II. Shortly after the meeting, a new idea was conceived to permit application of fast neutrons to the application. Since the idea appears worthwhile, BCL has recommended that Phase I be continued for another quarter (concurrent with Phase II) to evaluate the feasibility of the new idea.

During the meeting held at MSFC, it was agreed that an old J-2 turbopump in running condition would be made available to BCL to assist us in our development of the three approaches. After receiving the pump, we plan to mount it in such a way that it can be driven at partial speed by an external drive. This will enable us to evaluate and develop each technique with respect to realistic conditions.

During the first quarter of the program, literature searches were conducted and interviews held with manufacturers representatives to uncover potential measurement techniques. Evaluations were begun of techniques which appeared applicable. Both paper studies and experiments were conducted. During the second quarter, the experimental and theoretical feasibility evaluations were concluded (with the exception of a fast-neutron technique) and three approaches were recommended for advancement into Phase II.

Progress in each technical category is summarized briefly below, followed by a brief discussion of the relative merits of each of the three recommended approaches.

ULTRASONIC TECHNIQUES

Ultrasonic waves are capable of penetrating most engineering materials to considerable depths and they do this at low energy levels. In addition, they are capable of being guided through curved paths. They are sensitive to abrupt changes in acoustic impedance and for this reason they have been used to measure thickness of materials, to measure distances to target areas, and to locate defects in materials.

Methods of generating, detecting, and processing ultrasonic data are numerous. Several of these have been evaluated as possible means of measuring the deflection of turbopump internal rotating parts such as shafts.

During the first quarter, we concluded that ultrasonic Doppler devices appeared feasible, but were dependent on the actual geometry of the turbopump involved. During the second quarter, examination of drawings representative of a variety of turbopump designs have convinced us that ultrasonic Doppler techniques are definitely applicable to turbopumps; however, not all of the desired measurements are likely to be possible. In general, since a solid path is required from ultrasonic source to the part measured, measurements in the turbine sections will be difficult, if not impossible. In particular, measurements of turbine blade vibration or clearance, turbine wheel vibration, or turbine shaft movement may not be feasible. On the other hand, impeller or diffuser vibration or other movement in the pump sections would definitely appear to be feasible. The attractive feature of ultrasonic Doppler measurements, of course, is that if the source and receiver are ridgidly fixed to the pump case, very little modification of the pump is needed.

A summary of the techniques evaluated is given below.

Methods of Measuring Thickness

Two basic principles are used conventionally to measure thicknesses. These are (1) time of travel of a pulse of energy between two reflecting surfaces, and (2) resonance frequencies of standing waves between two reflecting surfaces.

Methods Based on Pulse Travel Time. These methods are useful for measuring thicknesses or distances between static reflecting surfaces at any depth which does not exceed the penetrable depth of the ultrasonic energy. Electronic gating can be employed to restrict measurements to a specified distance.

Dynamic measurements can be made by recording the travel times between the two reflecting surfaces and the difference between them.

Basis for Rejection. There is much in favor of pulse travel time methods for measuring displacements in the turbopump system. In fact, the method recommended incorporates some of the favorable aspects of the pulse methods. Three weaknesses of the pulse travel time methods that the recommended method is expected to correct are (1) need for extremely short pulse within the measurement region, (2) sensitivity to spurious echoes occurring between the echoes from the two reflecting surfaces, and (3) poor accuracies of present methods in measuring very small displacements.

Methods Based on Resonance Frequencies of Standing Waves Between Two Reflecting Surfaces. Two methods of measuring thicknesses by resonance are in common use. Both require frequency modulation. The methods used are (1) continuous wave and (2) pulse interference. The continuous wave resonance method is used to measure thicknesses of materials, such as plates, in which one surface is in direct contact with the ultrasonic probe or is separated from it by a liquid path. The pulse interference method of measurement of thicknesses is based upon the differences in transmission through a material at resonance and at antiresonance. The pulse may be monochromatic with the frequency swept through a range or it may be broadband and the received pulse subjected to frequency analysis.

Basis for Rejection. These methods cannot be applied easily to the turbopump displacement measurement. The continuous wave measurement requires parallel surfaces of fairly large areas and high frequencies of operation. Distances to the vibrating surfaces are excessive compared with the amplitudes of vibration to be detected.

Methods of Measuring Vibration Amplitudes

Methods Based on Beam Interference or Deflection. Beam-interference refers to the interference of the propagation of a beam of ultrasonic energy by an obstacle. If a beam of energy is directed between two members which are vibrating relative to each other, the total energy transmitted through the gap is modulated by the relative motion. By sensing the total energy change, it is possible to determine the relative displacement between the vibrating surfaces.

Beam deflection can be used to measure displacements of vibrating bodies by shifts in positions of reflected beams.

Basis for Rejection. Beam interference and beam deflection methods cannot be used in the turbopump to measure deflections. The problem is one of appropriately locating the transducers in the turbopump to obtain the desired beam directions.

Methods Based Upon Doppler Shifts. Doppler shifts are changes in frequency observed by a receiver due to changing the distance traveled by waves between a transmitter of the waves and the receiver. A moving target can produce the changes in frequency even with the transmitter and receiver fixed in position. The change in frequency depends upon the velocity of the target and the direction of its motion.

The Doppler method is recommended for use in measuring the displacements in the rotating parts of the turbopump.

Basis for Recommendation. The Doppler method can be designed to combine the desirable characteristics of pulse methods. For instance, it can be pulsed (using pulse-sampling techniques) and gated, thus eliminating effects from vibrating surfaces that are more remote than those of interest. The received signal can be filtered over a narrow band corresponding to the maximum frequency shifts to be expected due to the target amplitudes of vibration. This filtering eliminates most vibrational noises. A further noise reduction occurs by filtering after the Doppler signal has been extracted.

Pulses for Doppler measurements can be guided to an area of interest through wave guides which may be a normal part of the structure being monitored or, if necessary, additional members conveniently located. The path should not be too complicated. Complicated paths may result in spurious indications.

The major problem with ultrasonic techniques is that of transferring energy from one medium to the next. Transfer from liquid to solid in the absence of cavitation can be accomplished effectively. Transfer from gas to solid or vice versa requires special treatment. The measurements in the turbopump will be restricted to solid and liquid paths.

Published values of the ultrasonic characteristics of cryogenic materials are favorable to the ultrasonic approach to the measurement of the vibration of the rotating parts in the turbopump.

The detector used for measuring displacements by the ultrasonic Doppler method also can be used to detect anomalous sounds (sonic analysis). Sonic analysis is often an inexpensive method of detecting incipient failures of machine parts before they become catastrophic.

RADIOISOTOPE AND GAMMA-RAY DEVICES

Our evaluations have been concerned with Mössbauer analysis of gamma rays from a source attached to the moving part to be measured. Previously, we showed that a simple Mössbauer detection scheme was not feasible for the relatively large vibrational velocities associated with vibrating turbopump components. During the second quarter we evaluated the possibility of moving the absorber to sense the gamma radiation from the source.

There would appear to be at least two possible detection schemes associated with moving the absorber. The first would involve synchronizing the absorber with the source vibration. The fact that the source may vibrate at several frequencies characteristic of critical frequencies of, say, the turbine wheel, would appear to make the synchronizing system prohibitively complex. The second possibility involves vibrating the absorber at a high frequency and allowing the Doppler-shifted signal from the source to, in effect, frequency-modulate it. Our calculations show, however, that the range of Doppler velocities to be anticipated will result in numerous side bands, spreading the vibration information over such a wide range of frequencies that the inference of vibration magnitudes and frequencies may be impossible. Simply stated, Mössbauer analysis is a much too sensitive measuring technique for something as large as a turbopump.

No other detection scheme was conceived which offered a good possibility of using radioisotopes or gamma rays.

X-RADIOGRAPHY

During the first quarter, evaluation of pulsed, or flash, X-radiography was begun. Commercial flash X-ray apparatuses can be pulsed a few milliseconds apart with a pulse duration of about 20 nanoseconds. These parameters are consistent with 35,000 rpm pump operation. During the second quarter, a series of experiments designed to assess penetration and resolution was completed. The results of the experiments indicate that resolution is expected to be sufficient to detect movement of perhaps 0.02 mm or less. Penetration, however, is questionable. It is likely that turbine blade movement or clearance can be measured, since very little metal mass surrounds the turbine section. It may not be possible to sense vibrations in the pump section, because of the relatively thick pump case surrounding that section.

The experiments performed involved the use of a 3.8-cm diameter mild steel shaft with abrupt reductions in radius of 0.12 mm (5 mils), 0.25 mm (10 mils), and 0.5 mm (20 mils). First a flash X-ray was taken with the source and film about four centimeters from the shaft. Resolution was excellent; the 0.12 mm step was readily apparent on the film negative.

Next, a 2.5-cm-thick aluminum plate was interposed between the source and shaft to simulate scattering by the pump case. Resolution was not reduced significantly.

The final experiment with the stepped shaft involved evaluation of focal point migration with pulse repetition. The shaft (with interposed aluminum plate) was exposed twice at half intensity. No difference was observable with the negative from the previous experiment. The result of this experiment shows that focal point migration in the X-ray tube is insufficient to cause a significant loss of resolution. In addition, it suggests that repetitive pulsing may be a means to increase intensity. Flash X-ray units are available with up to ten heads for repetitive pulsing.

An additional experiment with a small (15-cm-diameter) electric motor was performed. Radiographs were taken with the motor stationary and running at 1200 rpm. It is not possible to distinguish between the two radiographs without identification. Good definition of wires and components within the motor is apparent. Definition of bearings and components behind thick metal sections is not good, however, suggesting that penetration may be inadequate for the pump section of turbopumps.

The fact that a 0.12-mm step can be detected by the naked eye in the shaft experiments indicates that much smaller variations could be detected by photographic processing and densitometry. The fact that excessive scattering was not observed in the motor photographs suggests that flash X-rays are appropriate for complicated structures. The big question, however, is whether flash X-rays will penetrate sufficiently to be used for components (such as impellers) which are inside relatively thick sections of metal. This question can only be resolved by attempting radiographs of actual turbopumps. There is no question that flash X-rays are appropriate for components such as turbine blades where the thickness of metal separating them from the film would not be great.

OPTICAL TECHNIQUES

During the first quarter, a large number of optical techniques were evaluated. We concluded that the most promising was a commercially available light-pipe-reflectance system. Table 1 summarizes our evaluation of various optical techniques. We purchased a light-pipe-reflectance unit ("Fotonic") and conducted a series of experimental evaluations.

Evaluations of the performance of the Fotonic sensor under ordinary laboratory conditions have confirmed the manufacturer's claims. A high-speed grinding attachment was mounted on the crossfeed of a small lathe. A small rotor was chucked in the grinder collet. Each fiber-optic-sensor probe was mounted, in turn, into the stationary lathe chuck. The average separation between the probe end and the rotor was adjusted by using the fool-feed micrometer drive. A solid state voltage control was used to select rotor speeds up to 4500 rpm. Six small flats located around the rotor periphery served to yield distinct displacement pulses at rates up to 27,000 pulses per minute. Surface roughness contributed less distinct and less uniform pulses at rates roughly 10 times higher (or the equivalent of 200,000 pulses per minute). The manufacturer's data indicate a flat response for the instrument out to 6×10^6 pulses per minute with an attenuation of 5 percent at 10^7 pulses per minute. The experiments showed that the instrument was quite stable and it should be capable of a precision of several percent of the linear range, as claimed.

A second experiment was performed in which the signal output from the sensor was fed into a tunable frequency detector. As anticipated, a band of frequencies was generated by surface imperfections whose center frequency was linearly proportional to the rotor surface velocity. The band width at half maximum was about 10 percent of the center frequency. It is estimated

TABLE 1. SUMMARY OF OPTICAL TECHNIQUES EVALUATED

Type of Technique	Parameter Measured	Brief Critique
Intensity of gap transmission	Displacement	Required straight-line path through pump for each measurement site is difficult to provide. Requires two optical quality windows. No surface preparation necessary.
Edge gradient locator	"	Same as above
Surface triangulation	Beam area	One large window or two small windows of high optical quality at each measurement side are difficult to provide along with the straight line optical path to the pump exterior.
Interferometer	Displacement	Capable of very high accuracy but high quality optical window is a problem. Straight-line path to pump exterior is needed. Optical flatness needed on surface to be measured.
Light pipe/reflectance	"	No surface preparation needed. Torturous optical path capability is inherent. "Window" is provided by the light pipe itself. Source and detector exterior to pump.
Diffraction by a gap	"	Same as for gap transmission
(Specific operating principle not known)	"	Insufficient information available to evaluate beyond the necessity for optical quality windows.
Laser/speckle	Speed	Indirect method of measuring vibration although perhaps providing valuable information about non-rotating surfaces.
Mirrors on twisted shaft	Torque	Developed for cryogenic pump torque measurement but not a method for measuring vibration.

that one could determine dynamic changes in surface speed to within several percent using an FM detection scheme. He-Ne laser illumination was used in some of the experiments; however, there was no improvement in operation. The sensor gain could be turned down considerably since the laser provided more irradiance of the surface, but this technique is not sensitive to signal amplitude. . .it is sensitive to frequency only. The laser might be of more value in creating a more distinctive frequency spectrum in cases where the surface is much smoother than was the test rotor used here.

Some consideration has been given to the problem of sealing the sensor end where it will be subjected to hostile environments. The manufacturer of the Fotonic sensor has used this type of sensor at liquid-nitrogen temperatures. They have also operated others at pressures of 1500 psi. The fibers in the standard probes are of the clad type, and this type is necessary to keep down the optical cross talk. A quick experiment with a rigid fiber-optical pipe containing unclad fibers showed that a second section of the fiber pipe could be used as a "window". However, the experiment also showed that the cross talk from the 5-cm length of unclad fibers lowered the sensitivity by an order of magnitude. The use of clad fibers or of a much shorter length of unclad fibers could result in nearly full regaining of sensitivity. The interest in this involves the possibility of using a rigid section of fiber bundles as a high pressure window and the normal flexible section as a lead out. This has good promise for solving the problem at cryogenic temperatures. The elevated temperatures in the turbine section are a more difficult matter. We have been unable to locate clad fiber components having promise of an usefulness above 1022 F, and there is no guarantee of extended life above 842 F. Consequently, we hold out very little hope of measuring using optical means in the vicinity of the 1700 F regions in the turbine. On the other hand, we believe that there is reasonable promise that small transparent gaps can be measured with high precision in the cryogenic pump system using the fiber optic/reflectance approach. The major impediment appears to be the possibility of cavitation in the measurement gap which would render the signal meaningless insofar as displacement is concerned. (The cavitation itself might be revealed by a strong output signal whose central frequency corresponds to one-half the relative lateral velocity between the probe and the surface being measured.) There are optical methods for carrying signals to and from the shaft of the pump. Therefore, sensors might be mounted in the rotating member if desired without the necessity for any electrical or mechanical connection to the shaft.

NEUTRON RADIOGRAPHY

Neutron radiography makes use of neutrons instead of X-rays usually used in radiographic techniques. Although neutron sources produce fast neutrons, conventional neutron radiography uses thermal neutrons to take advantage of the higher cross sections displayed by most materials for thermal-neutron capture. Neutron radiography is inherently attractive for the turbopump application, since neutrons can be expected to pass through relatively thick sections of metal.

A feasibility study has been conducted on the basis of simple calculation for a simple pump configuration. The results of this study indicate the following.

(1) Real-time radiographic examination of an operating turbopump is a practical impossibility. The time segments available to form images of components vibrating at the frequencies corresponding to typical operating speeds would require a neutron beam intensity that is not available with any existing type of neutron source.

(2) Pulsed neutron sources--reactor and accelerator--can provide time segments short enough to image components vibrating at typical frequencies, but such sources have other limitations that preclude their application to this problem. A pulsed reactor source could provide an intensity high enough to produce an image within the time of a single pulse, but the pulse rate is very low (typically several pulses per hour) so only extremely stable vibrations could be imaged. The

situation with accelerator sources is similar; in this case, however, the source is intensity limited and a large number of pulses would have to be integrated to form an image, thus restricting its application to extremely stable situations.

(3) The application of thermal neutron radiography to this problem is limited by the geometrical nature of the source itself. The finite size and diffuse nature of the source, and the imaging geometry imposed by the shape and size of the turbopump produce a situation in which the geometrical unsharpness is greater than the features of interest. Our analysis indicates that further investigation of thermal neutron radiography is unwarranted.

(4) Several fast neutron sources (californium-252 in particular) provide beam geometries that are equal to or better than those attainable from X-ray sources, and thus have the best potential for this application. From the standpoint of the pump itself, attenuation coefficients are high enough to produce sufficient contrast for imaging. The conventional means of fast neutron imaging are much too insensitive to be used for this application, but a recently conceived electronic fast neutron imaging system appears to offer sufficient sensitivity and resolution to meet some of the requirements of this program. We recommend that additional analytical and experimental efforts be directed to the development of this imaging system.

(5) Turbopump materials are an important factor, but are secondary in importance to source and imaging

factors, particularly in the case of fast neutron radiography. Although certain materials exhibit unusually high attenuation coefficients for thermal neutrons, the incorporation of these materials in turbopump components for the purpose of enhancing contrast does not appear to offer sufficient improvement to offset the inherent disadvantages of thermal neutron radiography in this application.

In consideration of the factors summarized above, the investigation indicates that this application of neutron radiography is marginal with currently available sources and imaging methods, but that the investigation should be extended to include the evaluation and possible development of an advanced concept in fast neutron imaging. Details of the analyses leading to this conclusion are summarized below.

Turbopump Model

The turbopump model used in this analysis is shown in Figure 1; the pump was assumed to consist of solid concentric cylinders. The analysis was focused on the annulus between the two components, and in particular comprised the calculation of neutron transmission through the region of the annulus with (1) the cylinders concentric and (2) with the inner cylinder displaced. The contrast difference between these two conditions is indicative of the capability to detect radial vibration of the inner cylinder with respect to the outer (or vice versa). Only two-dimensional aspects were included. In the case considered for thermal neutron transmission the source was assumed to be a line source of 1-inch length, positioned perpendicular to the tangent through the center of the annulus; for the case of fast neutrons, a point source on the same line was assumed.

In the early work using this model, the material was assumed to be titanium. Although this assumption was later found to be incorrect, the conclusions that were drawn from this work would not be altered significantly by the presence of other materials, so the work was not repeated.

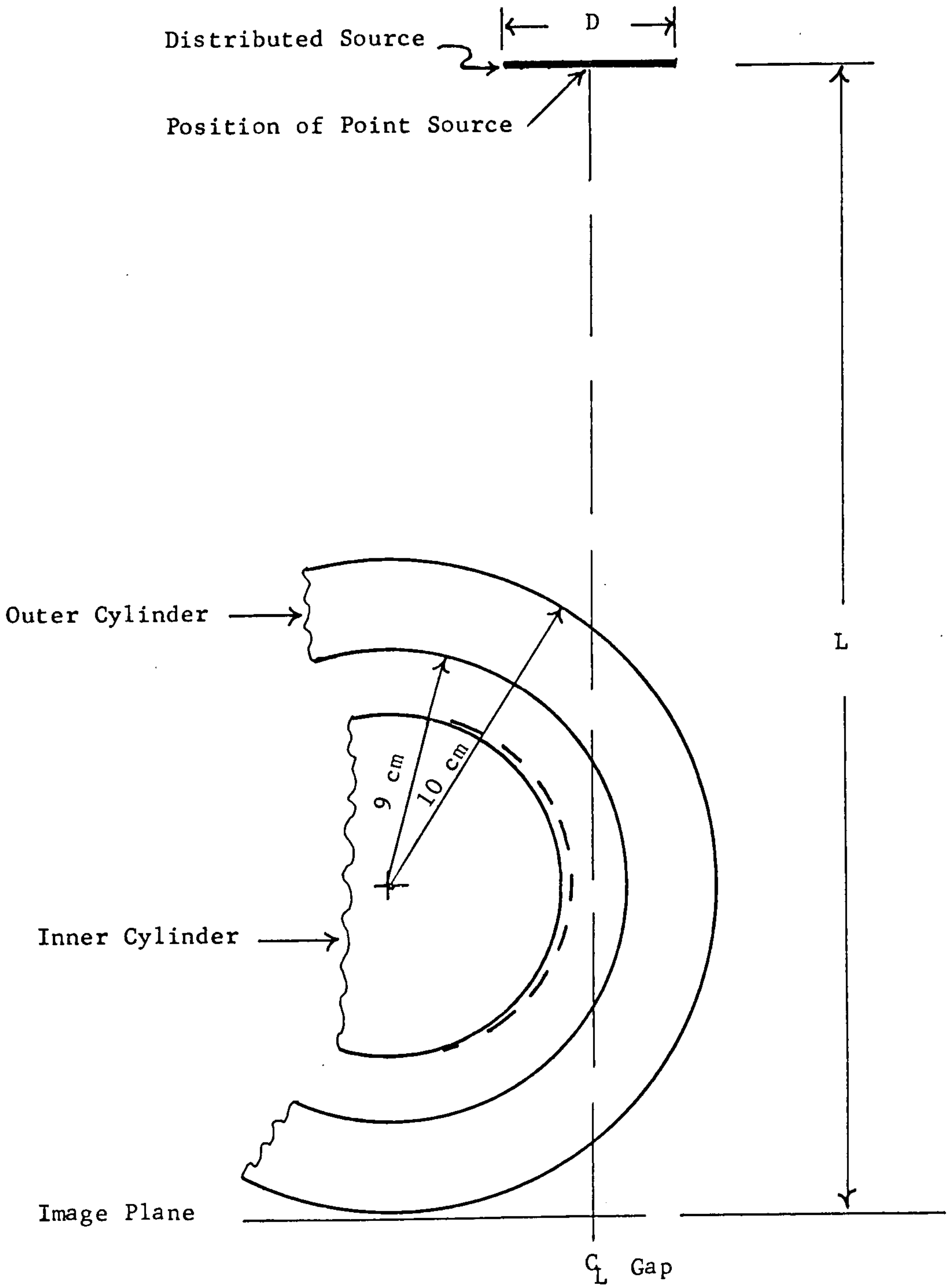

FIGURE 1. PUMP MODEL AND SOURCE LOCATION USED IN ANALYSIS (NOT TO SCALE)

Real-Time Imaging

The most desirable method to observe vibrating components is of course to record the motion of a component in real time; this approach eliminates the possibility of overlooking transients and of introducing ambiguities by sampling processes. The feasibility of applying real-time imaging was examined on the basis of the neutron transmission through the pump model and the signal-to-noise ratio required to produce a discernible image of the gap between the inner and outer cylinders. The signal-to-noise ratio is defined as

$$R = \frac{N_1 - N_2}{\sqrt{N_1}} \quad , \qquad (1)$$

where N_1 is the number of neutrons transmitted in the region of the gap, and N_2 those neutrons transmitted through the inner wall of the outer cylinder just adjacent to the gap. The minimum value of R for photographic imaging is 3. The contrast is defined as

$$C = 1 - \frac{N_2}{N_1} \quad . \qquad (2)$$

For titanium in the configuration shown in Figure 1, the calculated value of C is 0.384. Combining Equations (1) and (2) and solving for N_1 for the given values of R and C gives

$$N_1 = \frac{R^2}{C^2} = 61.2 \quad .$$

Considering the diameter of a resolution element to be half the gap width and assuming this to be 0.01 inch for the sake of this argument, the required neutron fluence is 1.2×10^5 neutrons/cm^2. For a rotational speed of 36,000 rpm and assuming that the time segment allowable for a single image frame is 1/10 revolution, the frame time is 1.67×10^{-4} seconds and the required transmitted flux is 7.3×10^8 n/cm^2-sec. Furthermore the neutron transmission through the region of the gap is 0.013, so the required flux incident on the pump is 5.4×10^{10} n/cm^2-sec. This flux is considerably higher than the flux available from any collimated thermal neutron source, with the possible exception of a pulsed reactor. Since pulse repetition rates for such reactors are quite low (several pulses per hour) they would be of little value in real-time imaging. For the reasons presented, real-time imaging in this application is considered to be a practical impossibility.

Thermal Neutron Radiography

The alternative to real-time imaging is image formation by time integration of the transmitted neutron beam. One approach to this integrating process is the conventional process of continuous integration that is commonly employed in neutron radiography. The successful application of this approach depends on the ability of the image-forming system to record the time-averaged neutron transmission through a vibrating component with sufficient contrast and resolution to distinguish the difference between this image and one produced under static or stable conditions.

This situation was investigated by the use of the model described above; the neutron transmission profile in the region of the annular gap was calculated for two positions of the inner cylinder. To allow for the effects of the distributed nature of thermal neutron sources, a finite sized source was assumed, and the effects of its distance drom the pump were included. The image plane in all cases was assumed to be tangent to the outer cylinder and perpendicular to a line through the center of the source and the center of the gap.

The results of these calculations are summarized in Figure 2, which shows the relative thermal neutron transmission in the region of the gap for the two positions of the inner cylinder. The normal gap was taken to be 0.5 mm (20 mils), and the displacement of the inner cylinder 0.12 mm (5 mils) inch. The contrast obtained between these two cases is plotted in Figure 4 (with the corresponding fast neutron contrast).

This analysis shows that under the best conditions, thermal neutron radiography does not produce a sufficiently sharp image to show the location of a displaced component (the situation would of course be much less favorable under real conditions where the image would be produced by the time-averaged position of a vibrating component). Figure 4 shows that even though the displacement of the inner cylinder produces a discernable contrast, this

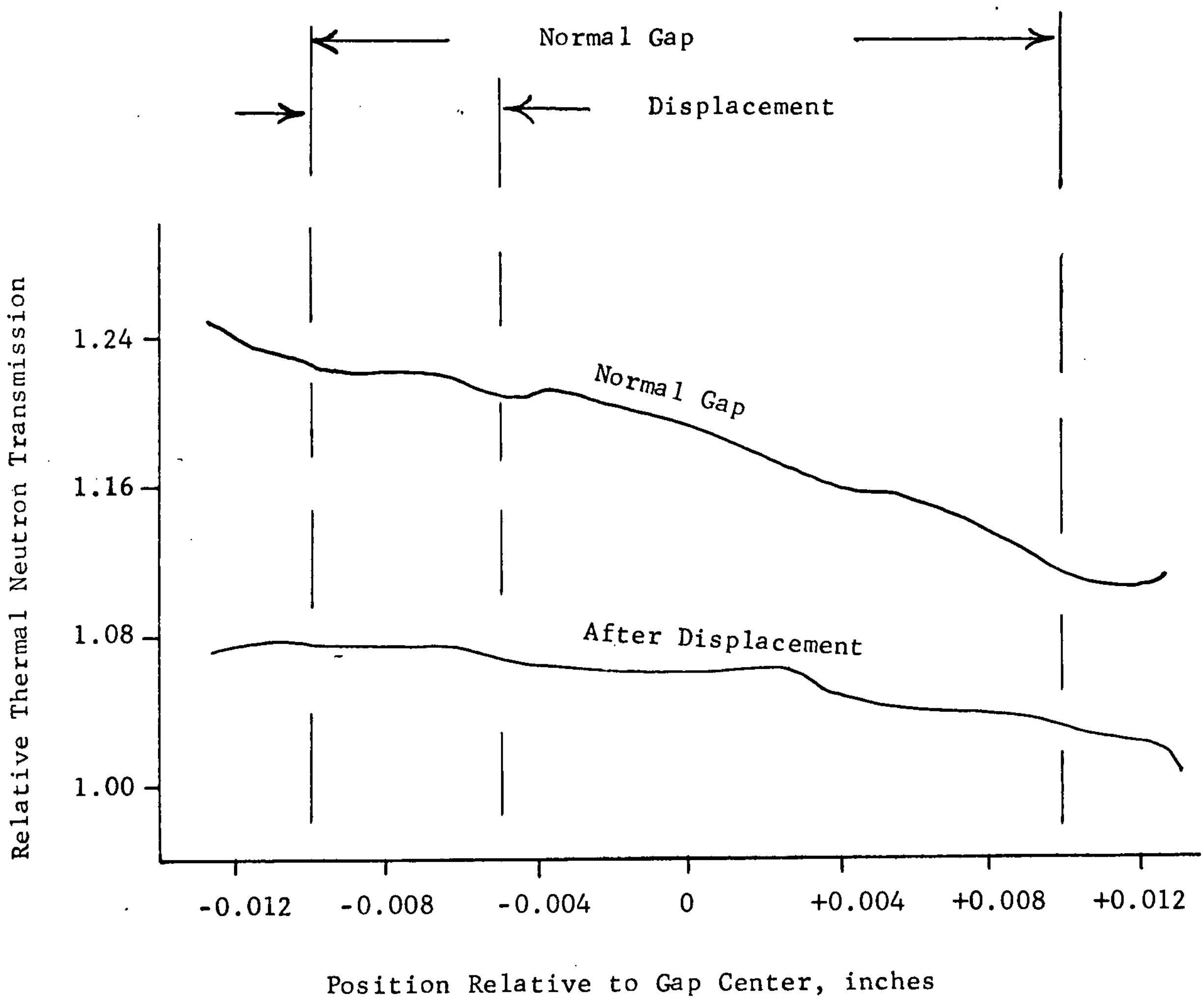

FIGURE 2. THERMAL NEUTRON TRANSMISSION PROFILE

contrast is not associated geometrically with the displaced component. The source geometry is responsible for this image unsharpness, and since this is an inherent feature of thermal neutron sources, it is clear that thermal neutron radiography is not suitable for this application.

Fast Neutron Imaging

The fact that source geometry and not the neutron absorption properties of the components is responsible for the unsuitability of thermal neutron radiography suggests that the use of fast neutrons might yield the required sharpness, since fast neutron sources of extremely samll size are available. Fast neutrons would also have the possible advantage of a somewhat higher transmission through the pump since cross sections are lower at the higher energy. Simply substituting fast neutrons for thermal neutrons, however, does not improve the situation, because the efficiency of conventional detecting and imaging methods is too low for fast neutrons. Further, the ratio of scattering to capture cross sections is high enough for most materials to substantially reduce contrast. A new detector concept, described below, has been generated which holds promise to overcome these difficulties with fast neutrons.

To assess the suitability of using fast neutrons to detect component displacements, the calculations described above were repeated for a point source of neutrons and with appropriate changes in neutron absorption coefficients. The results of these calculations are shown in Figures 3 and 4. The calculations clearly show that fast neutrons would yield significantly more information than thermal neutrons and it appears that they would yield sufficient information to image displacements somewhat smaller than the 0.12 mm (5 mil) displacement used in the calculations.

The detector concept mentioned above consists simply of a long thin tube of an organic scintillator material; the length provides the thickness necessary to achieve a high collection efficiency, the diameter determines the resolution, and the use of an organic material supplies the required sensitivity to fast neutrons. Readout would be in digital form and would be achieved by appropriate coupling of the scintillator to a light-sensitive device. An array

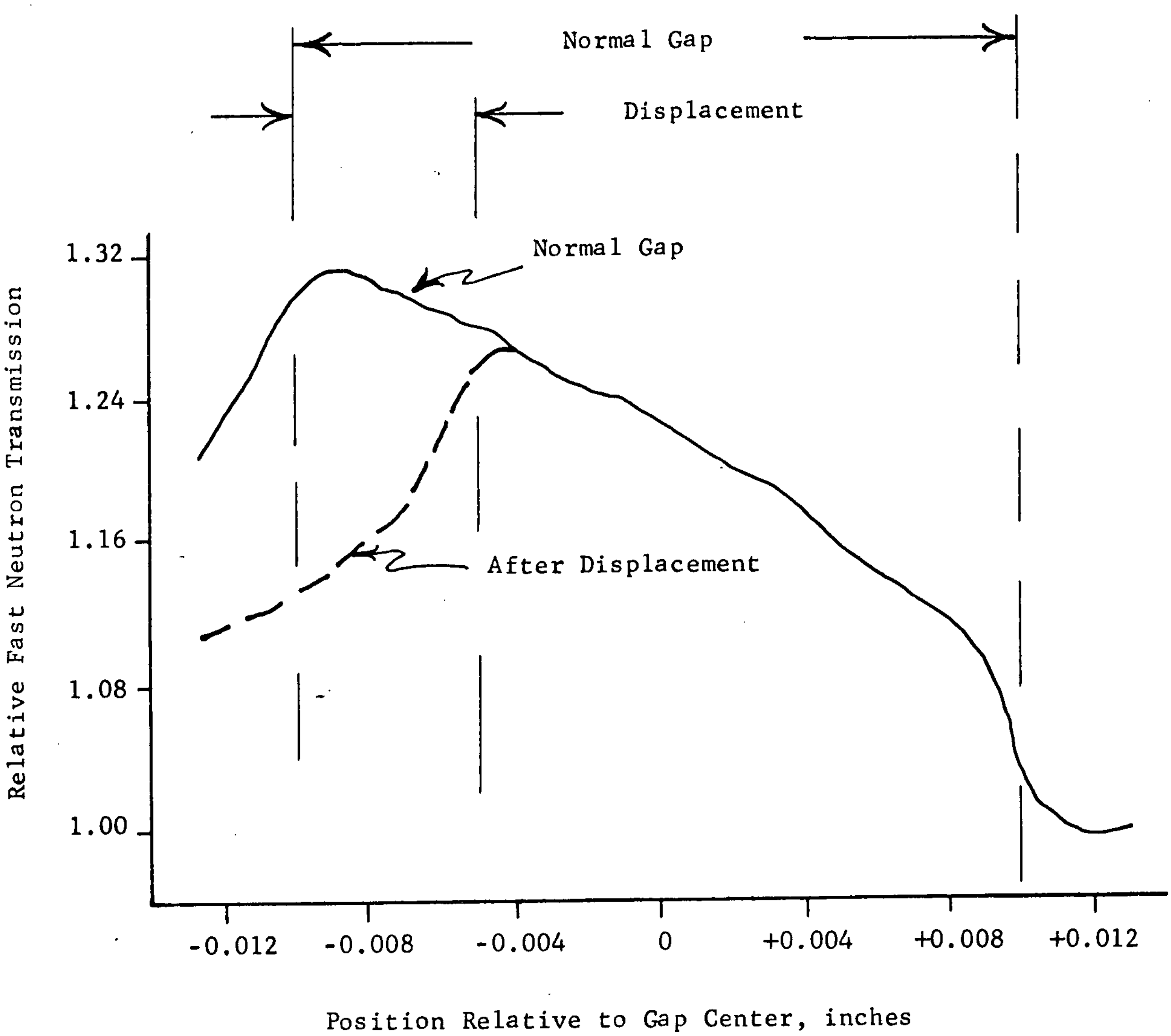

FIGURE 3. FAST NEUTRON TRANSMISSION PROFILE

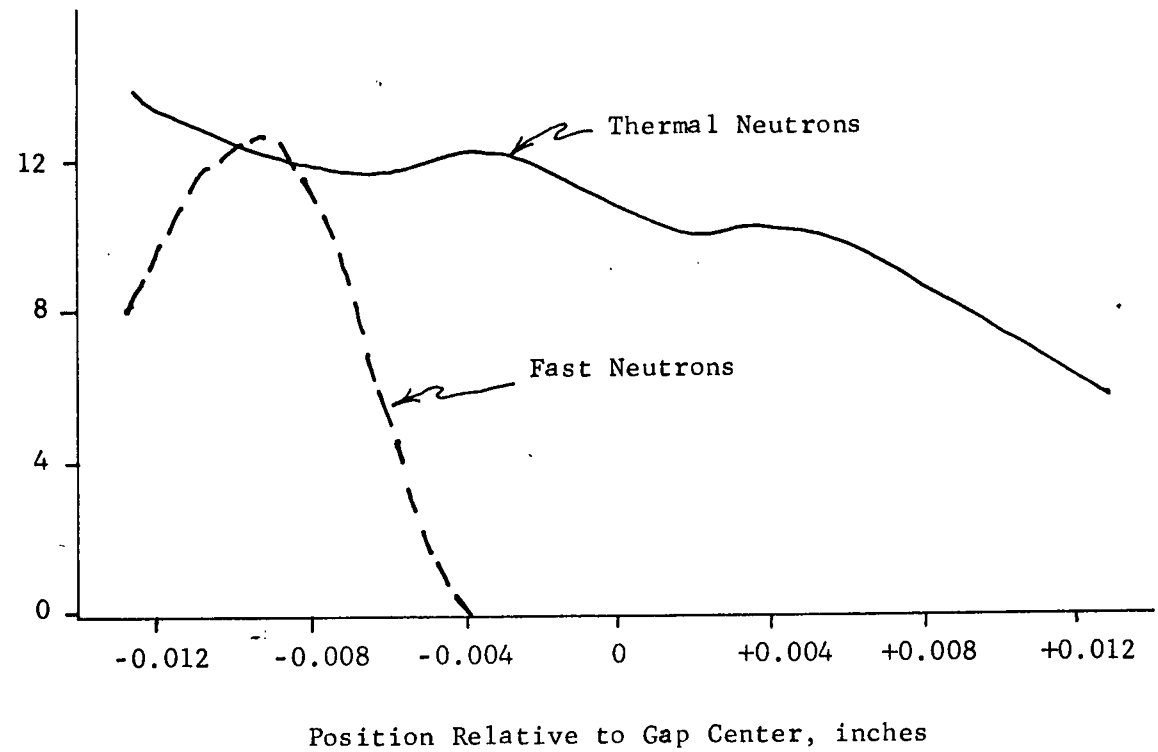

FIGURE 4. THERMAL AND FAST NEUTRON CONTRAST IN REGION OF GAP FOR 5 MIL DISPLACEMENT OF INNER CYLINDER

of such devices could be used to yield sufficient information to synthesize an image, but for this particular application one or two detectors properly positioned could probably provide the needed information. The fact that the measurement of transmitted intensity is made with a point source and a detector with a small area would also appear to overcome the problem of scattering.

Since the output of this device is electronic, the collection of data could be gated and synchronized with the rotation of a turbopump and thus provide information over selected segments of rotation. With available sources, integration over a number of revolutions would undoubtedly be necessary; integration over 10 seconds of pump operation is estimated to be the order of magnitude of the time required to collect sufficient information with available sources. A portable californium-252 source would be required. At this time, we think that a 10-milligram source costing perhaps $10,000 would be sufficient. Both source and detector would have to be fixed rigidly to the pump case.

The new detection technique appears to offer the advantages of a point source of radiation, the ability to penetrate relatively thick metal sections, and virtually no variation of neutron cross sections with temperature.

The major disadvantage, of course, is the necessity for time-integration to achieve a sufficiently strong signal. It may also prove difficult to align the source and detector when applied to an actual turbopump. Of course, neutron radiography cannot be used to sense position of parts in the presence of liquid hydrogen. In any case, we believe the technique is of sufficient promise to warrant further feasibility studies. If approved by MSFC project personnel, we will continue our evaluation of neutron radiography by fabricating a liquid-organic-scintillator detector and experimentally determining sensitivity using, perhaps, a stationary shaft whose position can be adjusted with a micrometer.

If general sensitivity is as expected, then experiments will be conducted to determine whether it is necessary to discriminate between gamma rays and neutrons (both will activate the scintillator material). The next step in the feasibility will be to evaluate the effect of material interposed between source and detector. Subsequently, application to an actual turbopump could then be made. The final step in the feasibility analysis would then be to evaluate the use of a multichannel analyzer to look at dynamic shaft position.

CONVENTIONAL DISPLACEMENT SENSORS

Basically, three kinds of techniques were evaluated in this category: magnetic sensors, capacitance sensors, and signal transmitters which do not use slip rings. Magnetic techniques evaluated have included sensors measuring changes in inductance, and eddy-current sensors using either coils or Hall elements for detection. The Bentley inductance probe is currently used to measure deflections of turbopump components and, as such, can be considered as the state of the art. Application of Bentley probes requires substantial modification of a turbopump to locate the probes near the parts to be measured.

During the literature search and interviews with manufacturers, emphasis was placed on attempting to discover techniques which could be applied without substantial modification of the turbopumps. With the possible exception of FM signal transmitters, no such techniques were uncovered. The Bentley probes currently in use are, in our opinion, representative of the state of the art of magnetic and capacitance probes as applied to turbopump measurements.

Magnetic and Capacitance Techniques

Two kinds of magnetic sensing devices are available commercially. Inductive probes measure the change of inductance in a coil as the gap between the coil and the moving part changes. These require a high-conductivity material on the moving part. Eddy-current probes measure the impedance of a coil as influenced by eddy currents set up in the moving part. In some eddy-current devices, a Hall element is used in place of a coil. Capacitive devices essentially sense the change in electrical capacitance of the separating gap between a probe and the component being measured.

Both magnetic and capacitive techniques share one advantage. There are probes in each category which are highly developed and have been applied to a wide range of applications with a wide range of environmental conditions. One commercial capacitance probe made by Dynamic Data Corporation has actually been in successful service at temperatures above 2000 F. Also one type, F. W. Bell Inc.'s Hall-Pak Generators (inductive), have demonstrated successful operation at cryogenic temperatures. Several of Dynamic Data's high-temperature capacitance probes were recently operated at liquid nitrogen temperatures and apparently performed well and also did not suffer any permanent damage. It must be borne in mind, however, that the capacitance method is only feasible if no changes in the dielectric occur in the gap. This could be a limitation if the gap contains alternately liquid and gas or a mixture of these. This could pertain if cavitation occurs. A capacitive transducer face consists of concentric electrodes separated by an insulating material; because these materials are of different hardnesses there is the likelihood of differential wear in the event of cavitation or simply the erosive action of the high-velocity fluid. Such wear would be likely to change the contour of the probe face, and to some extent alter the calibration of the system. In addition, any roughening of the surface would be apt to increase the tendency for turbulence and more violent cavitation. Such a situation is self-aggravating and must lead to premature, and possibly rapid failure of the transducer. Overcoming this difficulty would involve a judicious selection of materials for probe components and/or coating the sensing face with a durable dielectric film--e.g., a sprayed-on ceramic. Another problem would be sealing of the probe and its concentric electrodes against leakage of the 7000 psi cryo-fluid. This also requires proper materials selection plus possible design improvements to produce an adequate strength as well as a minimum elastic deformation under pressure.

The inductive techniques are inherently more attractive because measurements are not affected by changes, such as cavitation, in the gap region being measured. Even the presence of a medium of low conductivity in the gap can be tolerated. One manufacturer, F. W. Bell, produces Hall effect magnetic field sensors which can be used to - 269 C; apparently other manufacturers have not yet attacked the cryogenic applications. In any event the selection of materials having low coefficients of conductivity and of permeability at cryo temperatures appears quite feasible. The other problem--differential thermal expansion effects--should prove somewhat less difficult to overcome than was the case for development of transudcers capable of operation at high temperatures. The Hall-effect type of pickup cannot be exposed to temperatures in excess of ~ 150 C; in fact, they begin to lose calibration above ~ 105 C. Other conventional types of inductive transducers have been applied in ambient temperature fields up to ~ 1500 F.

Mechanical Technology Inc. have designed and successfully operated transducers using ceramic insulated gold wire wound on a ceramic form. These coils have been subjected to many temperature cycles to 1500 F with no detectable degradation in the coil electrical properties. The subsequently manufactured transducer was fully encapsulated with all welded joints. This points up an inherent advantage to employing inductive transducers, the sensing function can be accomplished through a metallic sheating or bulkhead. Thus, no roughening or differential wear or erosion rates need to be anticipated (the situation described above for the capacitative types). This construction feasture also protects the internal transducer parts from the high-pressure environment. The presence of pressure-produced mechanical deflections which would change transducer calibration might pose a problem for the hermetically sealed capsule design. Application over a broad temperature range could also be expected to produce calibration changes, but optimization should be feasible.

Nonslip-Ring Signal Transmission

Consideration heretofore has been with respect to sensing techniques which do not require contact with the moving part under surveillance. A more common approach, used in the past, is the application of accelerometers, strain gages, and thermocouples to the moving part. Transmission of the low power output signals from these sensors through slip-ring contacts however, has been unsatisfactory for high-speed rotating machinery because of wear and unreliable performance. Recently telemetry hardware has been developed for application to high-speed rotating equipment. An example of the refinement attained for such equipment is evidenced in the Aerotherm Corporation telemetry systems. Tiny transmitters potted to withstand 30,000 g at 125 C, are fitted into compartments in a hollow shaft or rotating support ring. The transmitters are powered by a transformer or batteries, and communicate via a modulated carrier wave to a stationary (and circular) antenna mounted about one-eighth inch away. These low-level signals are carried via co-ax cable to the receiver-amplifier and hence to a data readout or recording device. At present, transmitters are cylindrical, 5/8 inch x 1-1/8 inches in diameter; or rectangular, 9/16 inch square x 1-3/8 inch long. One transmitter is used for each signal; however, the manufacturer is currently developing a multiplexing system which will handle eight signals simultaneously.

The use of a signal transmitter appears to us to be an attractive way to do away with the disadvantages of contact-type slip rings. For best results, however, the use of a system in which the rotating and stationary components are very close together would be required. In the case of a turbopump, this would imply that the turbopump design should allow a stationary pickup to fit inside a hollow pump shaft. Such a requirement might be a severe restriction on pump design. In any case, the use of a signal transmitter solves only half the problem. Sensors must still be located at the points of interest.

DISCUSSION

With the exception of the new fast-neutron detection technique which remains to be evaluated, the feasibility study of Phase I has resulted in three techniques which appear feasible for the turbopump applications.

(1) Ultrasonic Doppler

(2) Flash X-ray

(3) Light-pipe reflectance.

These three techniques, by mutual agreement between BCL and NASA-MSFC project personnel, have been advanced into Phase II.

It is clear that none of the three techniques will be able to make all the measurements of interest. An ultrasonic Doppler device will be limited to applications where a solid or liquid path can be devised into the part to be measured from the source. This appears to remove the turbine section from its capability, because of cooling channels around the blades. On the other hand, the flash X-ray appears capable of measurements in the turbine section where metal sections are thin, and appears questionable in the pump section where heavy metal sections exist. If the fast-neutron technique proves feasible, it should be able to sense motions in the pump section. The light-pipe-reflectance device appears somewhat limited in high-temperature capability, so it is not expected to be applicable to the turbine blades (although probably applicable at turbine-wheel temperatures).

It is possible, therefore, that a combination of the various techniques may be desirable. For instance, a flash X-radiograph might be taken first to obtain diagnostic information regarding several turbopump components. Subsequently, one or more ultrasonic or optical sensors might be fitted on the pump to measure only the most critical components.

Obviously, the specific advantages and disadvantages of the three feasible techniques cannot be determined accurately until Phase II has been concluded. The feasibility study has, however, illuminated some of the characteristics of each. These are listed below.

<u>Ultrasonic Doppler Devices</u>

Advantages

(1) Only minor pump modification needed
(2) Ability to sense motion of parts far inside the pump
(3) Apparent capability of sensing the entire range of motions anticipated: displacements from 2.5 microns (0.1 mils) to 0.5 mm (20 mils), frequencies to 100,000 cpm
(4) Capability of sonic analysis
(5) Real-time, instant readout.

Disadvantages

(1) Requirement of "solid" acoustical path
(2) Need for complex instrumentation to permit vibrational amplitude and frequency to be inferred from Doppler velocity

(3) Need for direct calibration for some components

(4) Sensitivity of acoustical properties of materials to rapid temperature changes (not a problem for gradual temperature changes).

Flash X-Ray

Advantages

(1) Noncontacting; very little pump modification required

(2) Diagnostic capability; can view several components at once

(3) Can be pulsed to detect motions as rapid as 35,000 cpm.

Disadvantages

(1) Cannot penetrate extremely dense sections

(2) Is not instant reading

(3) May not be able to detect displacements smaller than 25 microns (1 mil)

(4) Line of sight may be limited by pump support structure.

Light-Pipe-Reflectance

Advantages

(1) Basic unit is already developed

(2) Light fibers can be bent to make installation easier

(3) Can sense both small displacements on the order of tenths of microns and large displacements on the order of millimeters

(4) Probable temperature capability from -400 F to 1200 F

(5) Frequency response up to 2 x 10^6 cpm.

Disadvantages

(1) Requires modification of turbopump.

FUTURE WORK

The first step in Phase II will be to set up the J-2 turbopump at BCL and to make it capable of being externally driven at moderate speeds. Subsequently, each of the three techniques will be applied to various components to determine the specific problems posed by an actual turbopump. with this information available, experimental work will be undertaken to develop each technique with respect to the turbopump requirements.

Future plans to evaluate the fast-neutron detector are detailed in the section dealing with neutron radiography.

COST DATA

Contract value less fee - $87,752

Approximate actual expenditures as of August 1, 1971 - $22,210

Estimated expenditures for August - $3650

Estimated funds to completion - $61,892

Anticipated over/under run - none

Changes - none.

No schedule problems are foreseen at this time.

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