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DIGITAL TRANSDUCERS

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DIGITAL TRANSDUCERS

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ABSTRACT

This paper outlines the major advantages of digital transducers and describes the principles and features of (1) direct digital transducers, (2) indirect digital transducers, (3) quasi-digital transducers, and (4) A to D transducers.

The mutual effect of transducers and systems will be discussed briefly, and some trends of transducer research and development will be presented.

INTRODUCTION

During the past years the need for and use of digital transducers increased considerably with the rapid advance in technology, which generated very sophisticated computers, automation, data handling, etc. The major advantages of digital transducers are:

1. Increased precision and accuracy of measurements.

2. Improved accuracy, reliability, and practicability in data handling and storing.

3. Reduced noise effect in transmission systems.

4. Direct compatibility with digital computers and control systems.

These advantages apply in varying degrees to the many different digital transducers and data acquisition systems. The individual situations require individual considerations, and digital transducers are not necessarily superior for all systems and applications.

Increased accuracy and reliability of switch or pulse type measurements were recognized long before computers came into being. Nearly 30 years ago, discrete liquid-level gages increased the accuracy of fuel consumption measurements for rocket development more than an order of magnitude at test stands and about 50 times for flight measurements. The telemeter had only 5 percent accuracy for analog values but 0.1 percent accuracy for time pulses; therefore, we also developed a pulse rate transducer, which was probably the first digital pressure transducer.

This early digital pressure transducer is shown in Figure 1. Bellows convert the pressure into force, a helical spring balances the force, and the displacement is picked up by commutator brushes as a pulse rate signal. A friction clutch converts the constant speed of a synchronous motor into varying speed proportional to the pressure.

Since then, numerous digital transducers have been developed and many reports have been written about their advantages, concepts, principles, and techniques. Some of these reports are referenced in this paper, thus providing a fairly adequate reference list, even though it appears to be rather limited. Some statements in these reports will be used in this paper, but the majority cannot be discussed because of space allowances.

In publications and discussions among different groups, there is no uniform terminology and classification for digital transducers. This paper does not propose a solution or standardization; however, every sensor, providing a quantized output signal, is called here a digital transducer and the following classification applies:

1. Direct Digital Transducers

2. Indirect Digital Transducers

3. Quasi-Digital Transducers

4. A to D Transducers

The categories of this classification are defined for the different groups and the principles, features, and future trends are discussed.

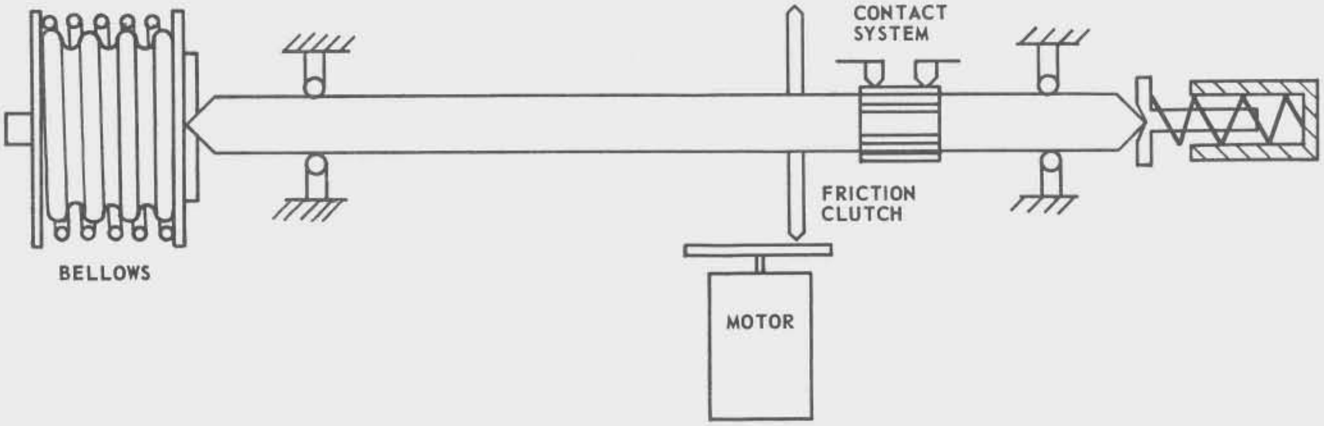

FIGURE 1. FRICTION CLUTCH-PULSE RATE DIGITAL PRESSURE TRANSDUCER

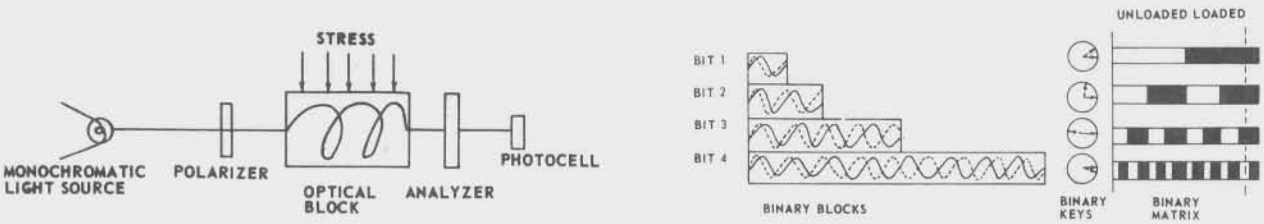

FIGURE 2. DIRECT DIGITAL PRESSURE TRANSDUCER

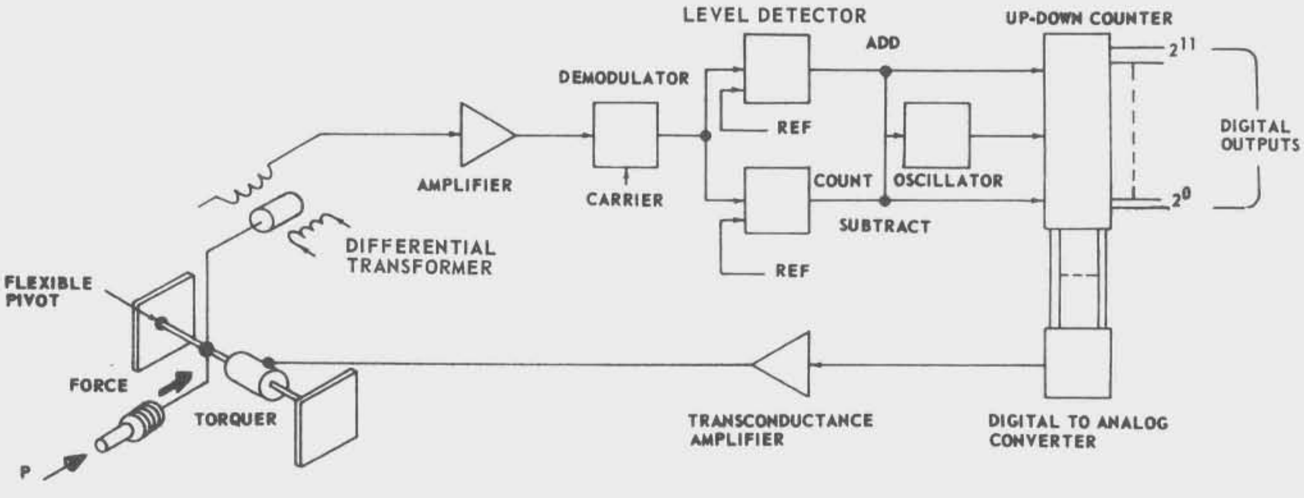

FIGURE 3. BLOCK DIAGRAM OF A DIGITAL FORCE BALANCE PRESSURE TRANSDUCER

DIRECT DIGITAL TRANSDUCER

The direct digital transducer senses the basic parameter direct without displacement, force balance, or any other analog phenomenon; it provides an instant discrete coded output without counting or similar data processing over a period of time.

These specifications appear to be unrealistic, and no such transducer is known to be performing satisfactorily now. However, such transducers will be developed, because each analog element before A to D transformation contributes to the total error and the present trend in designing an integrated system is to provide and use signal-to-digital pulse codes right at the source. Direct digital transducers can be developed if we take a microscopic view where the energy absorption is quantized. Attention must be given to naturally occurring digital phenomena such as molecular motions, changes in nuclear state of matter, and similar phenomena. In due time, advances in basic physics and technology will probably make this as easy and routine as integrated circuits.

About 10 years ago, an ISA Conference and Exhibit had "Analog to Digital Conversion" as its slogan and the Keynote Speaker from MIT said, "The instrument developers should try to measure direct digital like the motion of molecules as measure of temperature, instead of sensing with thermocouples and then convert the EMF back to digits." Considerable research has been and still is being performed on this subject, and solutions might be near or already available. In preparing this paper, many inquiries were made and sometimes data were withheld because of their proprietary nature.

In 1961, General Electric Corporation conducted a research program for development of a direct digital transducer using photoelastic properties of certain materials, as described in Reference 1, but no practical transducer became available. In 1967, Marshall Space Flight Center requested proposals for such a research program and all but two of the proposals recommended a quasi-digital principle. The most promising proposal, by Dynamics Research Corporation, suggested the rotation of polarized light in photoelastic material under stress similar to the General Electric version. Again no practical transducer has evolved from this program. Figure 2 illustrates the principle for four of the eleven bits planned. Four photoelastic blocks, each being twice as long as the previous one, rotate the planes of polarized light counterclockwise in binary coded amounts as indicated by the dotted arrows. At each 90 degree rotation, analyzers behind the blocks extinguish the light that comes from the blocks, and with photocells and a binary matrix, the digital output is established. The program planned an eleven bit transducer with eight blocks and three retarding plates behind the longest block, causing $1/4\ \lambda$, $1/2\ \lambda$, and $3/4\ \lambda$ shifts with 90 degree, 180 degree, and 270 degree rotation.

Dynamics Research Corporation had a working breadboard model in which organic photoelastic materials had good sensitivity but also had creep effects. Several inorganic materials were tried but none had enough sensitivity. The program was discontinued until more favorable materials, light sources, and detectors become available.

NASA's Manned Space Center in Houston has a study contract about this subject with the University of Texas. References 2 and 3 report on their work which also has not yet produced hardware.

INDIRECT DIGITAL TRANSDUCERS

The indirect digital transducers use displacement, servobalanced force, or any other analog phenomenon for sensing and convert them to a digital output. This group includes shaft encoders, optical or nuclear radiation masking techniques, capacitance or reluctance techniques, and others, mostly called true digital transducers.

Giannini (now Conrac) Corporation developed for MSFC a force balance digital pressure transducer which is shown in Figure 3. Bellows convert the pressure into force that tends to rotate a shaft, and an electromagnetic rotary torquer counterbalances this torque. Any imbalance in torque is detected by a differential transformer. After amplification and demodulation, a level detector gives adding or subtracting signals to an up-down counter that gives a digital output in binary form at any time. A digital to analog converter drives the torquer to rebalance the forces, thus zeroing the differential transformer output. After the prototype demonstrated an accuracy of one count in 2048, Conrac improved the packaging to a 4 inch long by 3 inch diameter unit utilizing monolithic, microelectric circuits and produced a group of 20 digital pressure transducers for MSFC. In the meantime, even more advanced force balance transducers with 13 bits have been built by Conrac for the Boeing 747 turbojet, and an accuracy of 0.025 percent is claimed.

Other research and development work in this field is continuing, but there is a strong tendency to avoid moving parts as much as possible.

QUASI-DIGITAL TRANSDUCERS

Quasi-digital transducers are sensors with frequency, pulse rate, or pulse duration outputs. This group includes vibrating wire transducers, turbine flowmeters, quartz crystal thermometers, ultrasonic transducers, discrete liquid-level gages, and many others. Recent additions just for flow measurements are ring laser flowmeters, laser Doppler flowmeters, nuclear magnetic resonance flowmeters, and the Swirlmeter from Fisher and Porter. Figure 4 shows how the swirl producing blades create a vortex of the flowing medium and a Venturi type enlargement in the housing will cause a precession or the center of the vortex to rotate. A thermistor senses the frequency of this rotation in the range of 10 to 1000 Hz.

MSFC has a contract with Trans-Sonics to develop a nuclear resonance thermometer for cryogenic liquids. Figure 5 shows a simplified block diagram of the measuring system but shows no details of the detector or probe. For the nuclear resonance techniques, a material such as chromium tribromide or potassium chloride is placed in the field of a high frequency oscillator. The nuclei of the material will start to resonate, reorient themselves, and absorb energy from the oscillator when the frequency of the oscillator reaches the nuclear resonance frequency of the material. A servosystem changes the oscillator frequency to the nuclear resonance frequency which is a function of temperature. The calibration factor depends only on the chemical structure of the sample and not on its dimensions, which is a big advantage of this thermometer. The soundness of this principle has been established, and a prototype will be delivered in the near future. The block diagram shows the oscillator outside the probe. Perfect operation was demonstrated at liquid hydrogen temperatures. It is expected that the nuclear resonance thermometer does work or can be made to work at liquid helium temperatures of 4° K, which may provide a new standard for low temperature measurements since the present platinum resistance thermometer flattens out badly at these low temperatures.

Honeywell has developed a quasi-digital pressure transducer using solid-state techniques. Figure 6 shows a functional block diagram of this "next generation airborne sensor" which is mentioned in "Transducers: On to Solid State" in the February 1969 issue of Space/ Aeronautics, Reference 4. Piezoresistive elements are diffused into a single-crystal silicon diaphragm that senses and sums the pressure. These sensing elements are distributed RC networks that are changing the frequency of two oscillators, as indicated in the diagram. Honeywell is still working on refinements of this transducer but the approach is characteristic for future trends.

Often there is not a compact transducer for sensing and conversion into a signal, but a system of several units is used for certain measurements. For example, a variety of nuclear radiation sources, detectors, and counters have been and will be developed to measure density and quantity of fuels in rockets and space ships. These systems will become more compact and approach the properties and features of transducers. A similar case is an absolute gravimeter, now being developed in-house at MSFC under the direction of Dr. O. K. Hudson. Figure 7 shows how a laser interferometer and two clocks measure the time required by a falling body for two successive distances. The interferometer fringes are counted (gate counting of pulses); this is a very accurate method for determining gravity by the equation:

$$g = \left(\frac{Nf^2\lambda}{\cos\theta}\right) \frac{n_B - n_A}{n_A n_B (n_A + n_B)}$$

where

N = overflow setting of fringe counter

f = oscillator frequency

λ = wavelength of light

θ = angle of deviation from vertical

n_A = count of clock for distance A

n_B = count of clock for distance B

The two successive distances eliminate uncertainties of the body release. Presently the system is very big but a compact version may be used on the moon.

A TO D TRANSDUCERS

The A to D transducers comprise transducers with analog sensing and electronic analog-to-digital conversion components. Formerly, transducers with analog output and A to D conversion somewhere after the transducer were used quite often to meet the requirement of digital input for the computers or other data processing systems. In recent years, however, it became very popular to put A to D converters into the analog transducer housing; with new microcircuitry techniques, this does not increase the size of transducers very much. Figure 8 shows an MSFC-developed circuit with an external converter attached to the transducer as one unit (located very close to the analog transducer). This technique uses the newly-developed paractor in which an electric current flowing in the input coil saturates the core, producing an output pulse with a polarity depending on the sense of saturation of the core. This output pulse is used to control a sequence of voltage steps in a successive approximation technique of A to D conversion. The voltage steps are fed back and inserted in series with the unknown input voltage. When the feedback

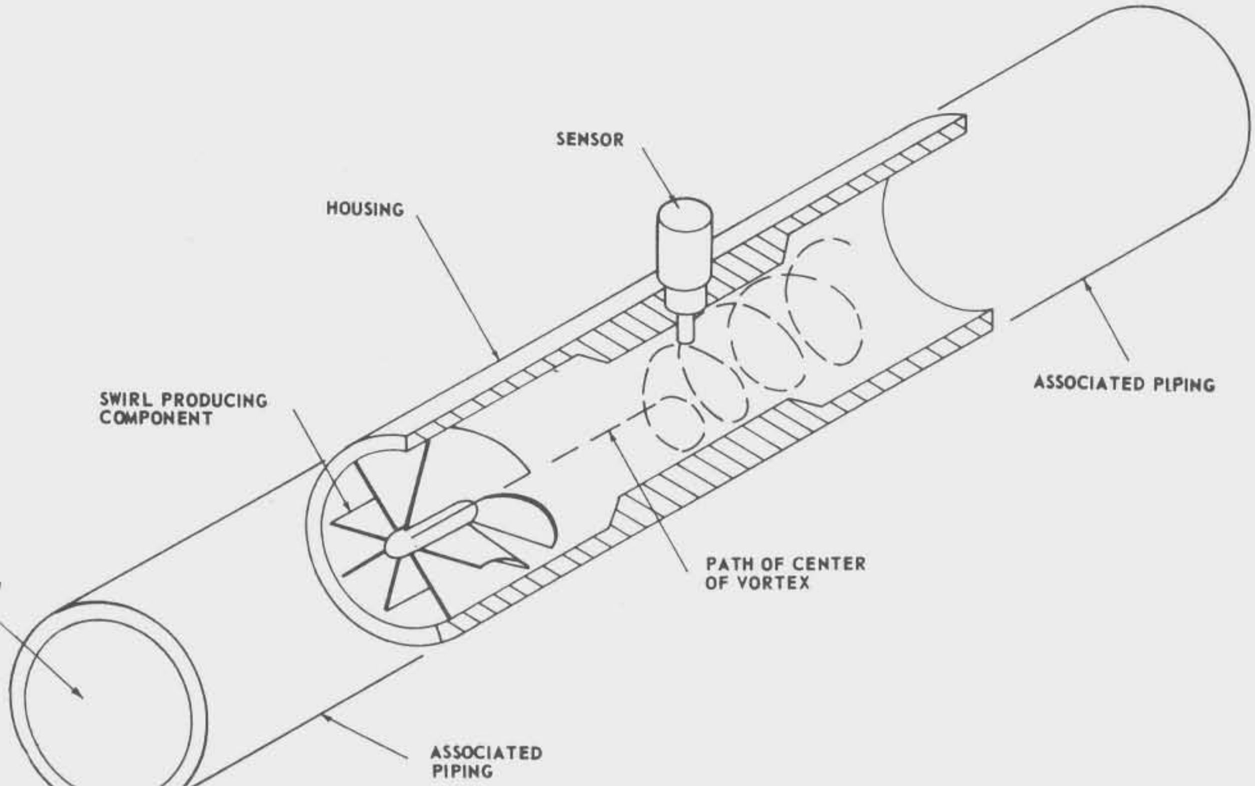

FIGURE 4. CUTAWAY VIEW OF A FLOWMETER BASED ON THE SIMPLIFIED VORTEX WHISTLE

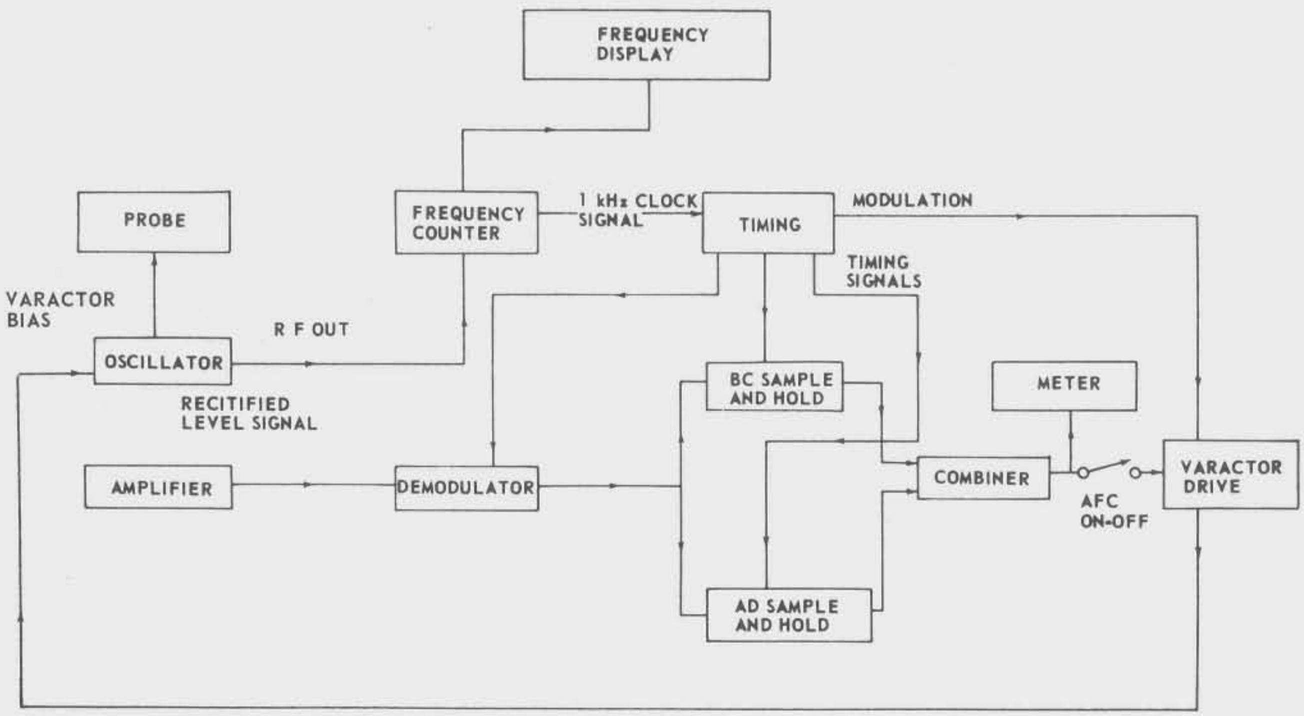

FIGURE 5. SIMPLIFIED BLOCK DIAGRAM OF A NUCLEAR RESONANCE THERMOMETER

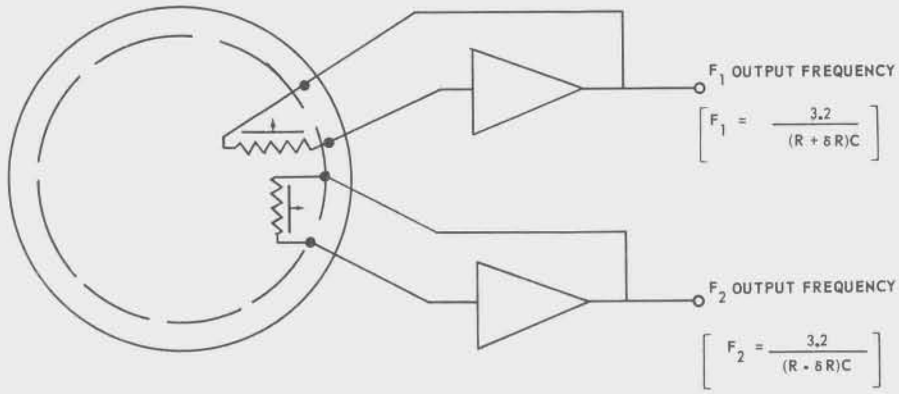

FIGURE 6. SOLID-STATE DIGITAL PRESSURE TRANSDUCER

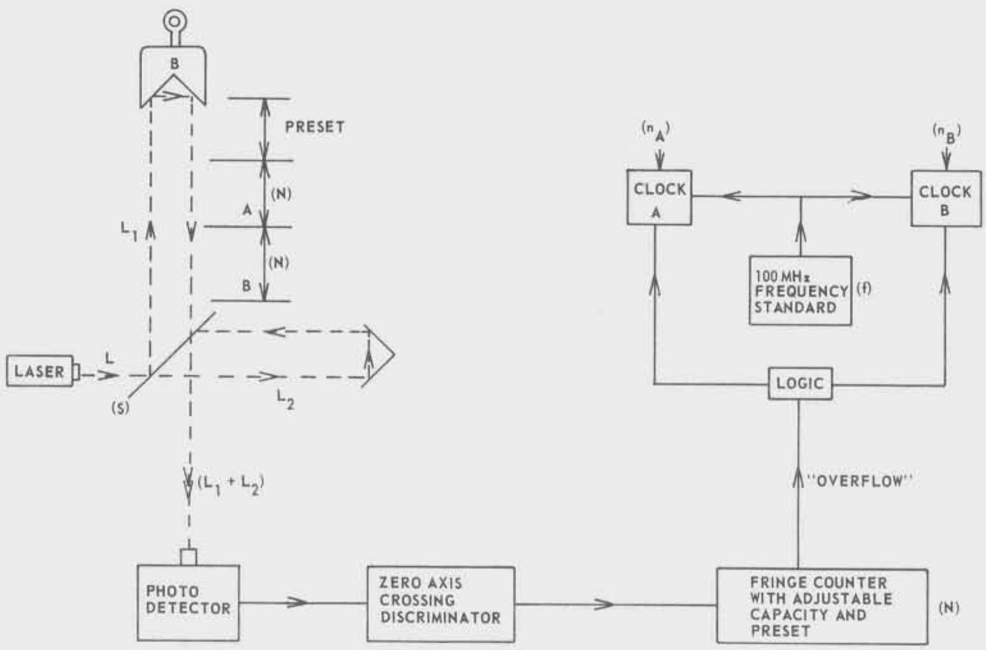

FIGURE 7. LASER ABSOLUTE GRAVIMETER

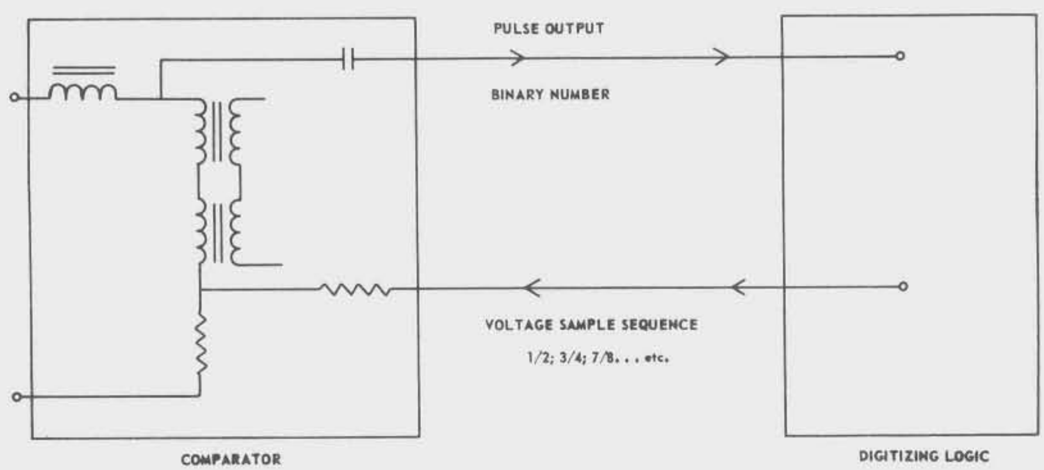

FIGURE 8. A TO D CONVERSION WITH PARACTOR TECHNIQUE

voltage equals the unknown voltage, the input coil current is zero and the core is not saturated. The paractor thus acts as a comparator of the known and unknown voltage. The paractor is very small and can be located near the transducers, remote from the logic control part of the system. This outside A to D conversion technique, described in Reference 5, has been developed for missile test stands where many analog sensors must still be used. A 120 channel system has been in use and is very satisfactory.

Figure 9 shows a digital pressure transducer with a standard analog sensor and a built-in A to D converter developed for MSFC by Metro-Physics, Incorporated. Again, the diagram does not show many details. This transducer uses successive approximation techniques in a pulsed mode to keep heating negligible. A unique comparator circuit does not require highly stable supply or reference voltages, nor are such voltages generated internally in the transducer. The resolution is one part in 1000.

Another A to D transducer is being built by Conrac and uses solid-state techniques similar to the Honeywell method. The main difference is in the electronics. While Honeywell uses the piezoresistive sensor as RC components of oscillator circuits, Conrac uses a resistance bridge and built-in A to D conversion, similar to the Metro-Physics version.

These new transducers with built-in A to D conversion are definitely an important part of future transducer developments. Displacements are greatly reduced and the accuracy depends mainly on precision resistors of ladders and the switches for reference voltage. These transducers have high speed and good resolution, and their accuracy approaches the one with closed-loop force balance, described under Indirect Digital Transducers.

Another candidate for a future A to D transducer is a digital level transducer. Trans-Sonic now builds a level gage with a capacitive sensor and a remote bridge that is automatically balanced by fixed resistors in a binary coded form, providing digital output. It is expected that this bridge with digital output will someday be included in the connector receptacle at the level gage flange.

Before closing this discussion of the different principles and features, a few remarks will be made about the employed classification. Because there is considerable disagreement, a new category will not be added. The indirect digital transducers are actually analog sensors with A to D conversion, but all transducers with nonelectronic A to D conversion should be separated from those with electronic A to D conversion since most people consider an A to D conversion to be electronic. Many indirect digital transducers now reduce displacement, motion, and other analog phenomena to a minimum and come close to the features of direct digital transducers.

The term "quasi-digital transducer" is strongly rejected by some people and sometimes it is used for transducers other than the type classified here as quasi-digital transducers. The time-based outputs are similar to digital outputs and have most of the advantages of digital transducers. They could even be considered true digital if the number base "one" is used.

CONCLUSIONS

Now we come to future trends, beginning with a brief look at the systems and interfacing equipment which operate with a large number of transducers. Data acquisition is becoming more and more an integral part of the total system concept, and modern technology with LSI circuits requires faster, better, and often direct digital transducers. Computers process information at an incomprehensive rate. Automation demands reliable, accurate, fast, and simple measurements. The Zeitschrift fuer "Messen-Steuern-Regeln,"[6] reports on the boom in Japan; Sperry Rand in their Engineering Review[7] discusses 10 bits/second, multiplexing of 64 channels, and 300 logic gates in a single silicon chip; and many other publications of this type discuss a gap between systems and transducer.

Naturally there are also many individual applications requiring individual considerations. For example, space ships use separate A to D converters before telemeters or computers because most of the data are analog electrical values and other analog signals.

Future research and development in the field of digital transducers will still continue in all four categories described, but transducers with built-in or attached A to D conversion will definitely be in front for the near future. Many systems require, and many individuals prefer, a discrete coded digital output of transducers. Advancements of large scale integration in electrical circuits and components enable conversion to 0.01 percent accuracy with even greater resolution. Reliable A to D transducers in compact and economic packages will be available. Solid-state sensors and other advanced or new techniques will reduce displacements and other analog parts or phenomena to a minimum.

Quasi-digital transducers with frequency, pulse rate, or pulse duration outputs will be a close second group. They will also use solid-state sensing, and often the varying frequency output allows direct sensing for most. The nuclear resonance frequency thermometer is a good example of this. The counting and gating techniques are very advanced, and in many cases frequency-to-digital conversion techniques will be used to satisfy requests for discrete coded digital signals.

The indirect transducers will rank third for the near future.

The search for a direct, inherently, or intrinsically digital transducer will continue at a rate depending on funds available for basic research. Optical and nuclear techniques, thin film, and other methods are being investigated, and in due time successful solutions will bring great advancements in digital transducer techniques.

REFERENCES

(1) Ludewig, Fred A., Jr., "Digital Transducers: Force Input . . Binary Coded Output," CONTROL ENGINEERING, Vol. 8, No. 6, General Electric Corporation, 1961.

(2) Richard, R. R., "Development of an Inherently Digital Transducer," Draft of Internal Report, NASA-Manned Space Center, Houston, Texas.

(3) Hartwig, Dr. William H., "Metal Insulated Semiconductor (MIS), Analog to Digital Conversion and Digital Transducer Concepts," 1968 Government Microcircuit Application Conference, DIGEST OF PAPERS, Vol. 1, Naval Ship Engineering Center, Washington, D.C.

(4) Neswald, Ronald C. (Contributing Editor), "Transducers: On to Solid-State," SPACE/AERONAUTICS, February, 1969.

(5) Greenwood, Thomas L., et. al., "Instrumentation for Ground Testing," RESEARCH ACHIEVEMENT REVIEWS, Vol. II, No. 12, NASA TM X-53793.

(6) "Development in the Japanese Measuring Instrument Industry" (Entwickzungen in der Japanischen Messgeraeteindustrie), Zeitschrift fuer Messen-Steuern-Regeln, No. 12, 1969.

(7) "Input/Output, 1968," Specialized Issue of the Sperry Rand Engineering Review, Great Neck, N. Y.

BIBLIOGRAPHY

(1) Chapin, W. E., "A Summary of Digital Transducer Development and Techniques," Transducer Information Center, Battelle Memorial Institute, Columbus, Ohio, Defense Documentation Center AD-465867.

(2) Mann, Douglas, "Summary Report on NMR Liquid Hydrogen Velocity Meter Program," Report No. 9730, National Bureau of Standards, Boulder, Colorado.

(3) Additional references on transducers are listed with brief abstracts in Battelle's accession lists available under Defense Documentation Numbers AD-611554, AD-616328, AD-617346, AD-628818, AD-479864, AD-487218, AD-802405, AD-806482, AD-622518 and AD-813191.

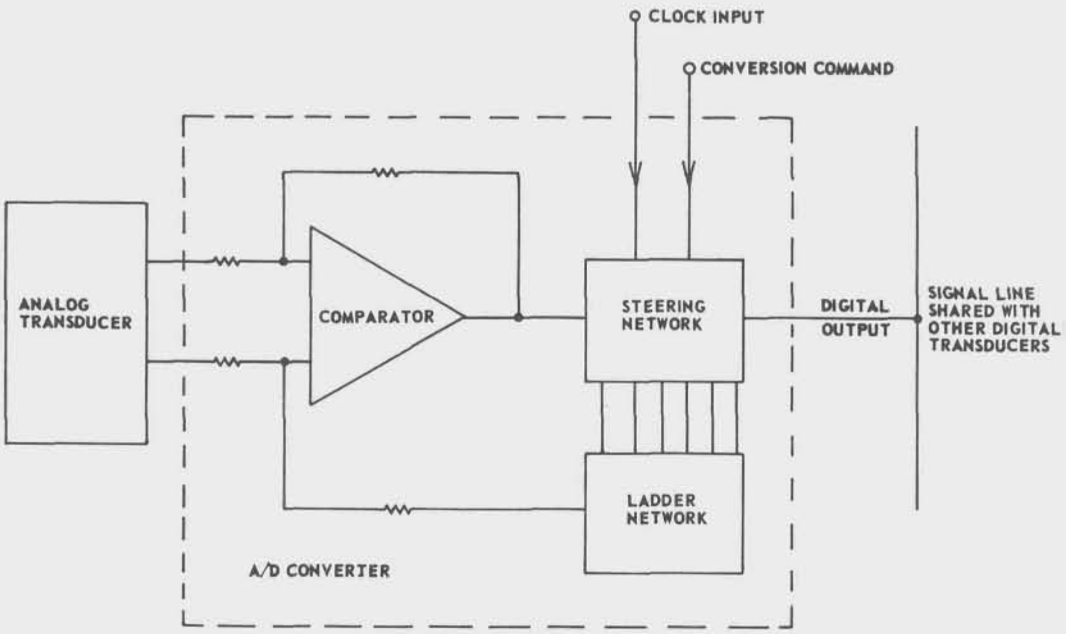

FIGURE 9. BLOCK DIAGRAM OF A DIGITAL TRANSDUCER

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