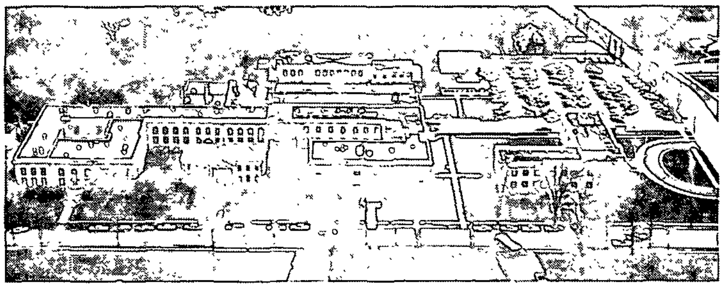

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USING A ROBOT BASED INSTRUMENT TO MEASURE THE IN-PLANE ULTRASONIC VELOCITIES OF PAPER

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ABSTRACT

This paper is a discussion of the development of an instrument that automatically determines with ultrasound the in-plane mass specific elastic stiffnesses of planer materials. It uses a standard laboratory robot to incorporate many of the features on an earlier apparatus (1). The result is more versatile, more reliable, and easier to manufacture instrument. Special broadband transducers were also built and they are discussed.

Introduction

In a previous publication (1), some of us described an instrument which automatically measures the in-plane velocities of ultrasound in paper samples. This was a custom designed, pneumatically-driven apparatus with specially developed electronic circuitry, all controlled by an Apple computer. Two ultrasonic transducers were suspended from a carriage above the sample. Air cylinders applied the transducers to the sample, at which time one was electrically pulsed and the resulting signal from the other was digitized and stored in the computer. The transducers then were lifted from the sample, their separation was increased, and a second signal was taken and stored. The time-of-flight velocity of ultrasound was found using a cross-correlation calculation to determine the difference in arrival times of the two pulses. The carriage was translated, and velocities at other positions on the sample were determined. The sample holder was mounted on a platter, which was rotated by a computer controlled stepping motor. This allowed the velocity of ultrasound to be found at different angles to the machine direction. Also, by rotating the transducers 90° about their axes, the computer could effect velocity measurements of both shear and longitudinal waves. The standard testing routine was to calculate the longitudinal velocities in the MD (the machine direction) and in the CD (perpendicular to the machine direction), the shear velocity at 45° to the MD, and the average of the shear velocities along the MD and the CD. Assuming the sample is orthotropic, this allowed the determination of the four independent mass specific elastic stiffnesses. Another test routine was the measurement of the longitudinal (or shear) velocities in 5° increments from the MD.

The purpose of this paper is to describe an improved, second generation instrument. A major drawback of the first instrument is that it consisted of custom designed mechanical and electronic components, making it difficult for others to build a comparable system. The new instrument is centered around a commercial, laboratory robot and uses almost entirely off-the-shelf electronics. The robot "end effecter" is a special item; however, a third party is willing to manufacture it. In addition to ease of reproduction, the new system provides higher quality measurements and is more versatile. As described below, new transducers, with higher bandwidth and greater modal purity, were designed and constructed for this instrument. These provide increased sensitivity and reduce the ultrasonic signal interferences encountered on problem samples. Repeatability in the coupling between the transducers and the sample is improved by deadweight loading the transducers instead of applying them to the sample with air pressure. Since the loading pressure was greatly decreased, the possibility of damage to low density paper samples is reduced. The new system is more convenient, as four samples (rather than one) can be tested without operator intervention. In fact, since the sample is not moved during testing, it would be straightforward to add a sheet manipulating mechanism and test a large number of samples in a single run. A final improvement is the replacement of the original Apple IIe computer with a PC AT compatible machine. This increases the speed of operation and provides the opportunity for performing more complex calculations.

General Description

The overall operation of the instrument is summarized by the schematic diagrams in Fig. 1 and 2. The manipulation of the probes, necessary to scan the sample and to orient the transducers for measurements in different directions relative to the MD, is achieved with a standard laboratory robotic arm, the Mitsubishi RM 501. The arm has five axes of rotation: (1) a "waist" rotation which determines a radial axis for the arm motion; (2) a "shoulder" rotation; (3) an "elbow" rotation which, in combination with the shoulder, defines the radial and vertical positions of the end of the arm; (4) a "wrist pitch" rotation which fixes the angle of the end of the arm to the vertical; and (5) a "wrist roll" rotation which turns the end of the arm about its axis. Attached to the end of the arm is a custom-built "end effecter". This is a carriage which holds the ultrasonic transducers. Computer-controlled air cylinders, mounted on the end effecter, can rotate each transducer 90° about its axis to allow both shear and longitudinal testing, while a third air cylinder can separate the transducers, so that ultrasonic waves with two different path lengths through the sample can be compared. Figure 3 is a photograph of a robot arm with an end effecter attached.

Figures 1-3 here

A typical velocity measurement proceeds as follows. The robot positions the end effecter at the proper position above the sample. With the carriage in the closed position, the transducers are lowered to the sample. Through a digital I/O port the computer triggers a Wavetek model 143 Function Generator to emit one cycle of an 80 kHz sine wave. This signal is applied to one of the ultrasonic transducers on the end effecter. A sound wave is generated in the sample and picked up by the other transducer. The received signal is amplified by a Panametrics model 5050AE Ultrasonic Preamplifier and sent to a Hewlett Packard 54200 Digital Oscilloscope. The oscilloscope, which was triggered at the same time as the function generator, digitizes the signal at a rate of 10 MHz and stores the signal. An adjustable number of additional ultrasonic signals are collected. By digital averaging, the oscilloscope produces a low-noise, composite signal and transfers it to the computer over a GPIB bus. The robot lifts the transducer from the sample and activates the air cylinder which separates the transducers. The transducers are returned to the sample, and another composite signal is produced. As described previously (1), the computer uses a cross correlation technique to calculate a time-of-flight velocity. The probes are again lifted, the robot moves the end effecter to a new position above the sample, and another velocity is determined.

There are two standard tests that can be performed. One is a determination of the orthotropic, in-plane, mass specific elastic stiffness of the sample. This is done by measuring longitudinal velocities in the MD and CD and shear velocities in the CD and at 45° to the MD. The only significant difference in the approach for the new instrument is that only CD shear is used rather than an average of CD and MD shear. For an orthotropic sample the shear velocities are the same in the two principal directions; however, shear measurements are to some extent contaminated by longitudinal impurities. Since bimorph transducers generate stronger CD shear waves than MD shear waves and stronger MD longitudinal than CD longitudinal waves, the CD shear is the much purer signal, and it gives a better measure of mass specific shear stiffness of the sample. The other standard test is to calculate the longitudinal or the shear velocities at 5° increments and to graph a "polar plot" of the results. A complete description of both tests, along with typical reports, is presented in the earlier publication (1). There are four stations, two of which can be seen in Fig. 3, that hold samples, and up to four samples can be tested per run.

End Effecter

Since it is a custom-designed apparatus, the end effecter deserves some additional description. Its function is to house the transducers and mount to the end of the robot arm. It also must provide a means to rotate each transducer about its axis and translate one transducer with respect to the other. The transducers are easily seen in Fig. 4, which is a photograph of the end effecter from the bottom side. They are attached to hardened splined shafts which are manufactured to fit into splined linear ball bushings mounted on the end effecter. When the dust seals are removed, a shaft will slide easily in its bushing, while the spline prevents rotation of the shaft in the bushing. When the end effecter is lowered to bring the transducers in contact with the sample, the shafts slide freely in their bushings, and the transducers are applied to the sample in a repeatable fashion with a force equal to the weight of a shaft and a transducer (about 20 grams).

The splined bushings fit snugly into custom machined Teflon sleeves, which are pressed into aluminum blocks on the end effecter. The sleeves allow the bushings to rotate between shear and longitudinal orientations, but at the same time, they prevent lateral play in the transducers. Rotation of the bushings, along with the spline shaft and transducers, is accomplished through double-action air cylinders. The air cylinder pistons connect to levers attached to the top of the splined bushings. The air cylinders are pivot-mounted so that they can swivel as the bushing rotates in the Teflon sleeve. A small magnet is epoxied to each lever, and Hall effect detectors are positioned to sense the presence of the magnets at the extremes of the 90° rotation. This allows the computer to verify that directed rotations have been completed.

As can be seen in Fig. 4, the end effecter frame is a light-weight aluminum yoke with two parallel steel shafts clamped across the gap. Aluminum blocks house the splined bushings and rest on the shafts. One block is rigidly clamped, whereas the other is mounted to ball bushings that ride on the shafts. A double-action air cylinder is attached to the fixed block, and its piston bolts to the other block. When prompted by the computer, the blocks can be pulled together or the mobile block can be pushed against an end stop. Switches attached to the mobile block feed back the location of the mobile block to the computer.

Figure 4 here

Transducers

The transducers designed for the robotic tester are modified versions of those used on the first instrument (1); therefore, a brief description of antecedent transducers is in order. They were constructed from standard 0.533 mm thick sheets of a lead titanate zirconate piezoelectric ceramic (PZT 5H). These sheets are parallel bimorphs. That is, they are composed of two layers of ceramic that are polarized in the same direction. There are conductive layers on the outer surfaces of a sheet and in the middle. The outer surfaces were grounded, and the inner layer became an electrically shielded active electrode. Mechanical motion could be generated by applying a voltage to the middle electrode. This caused one ceramic layer to contract, the other layer to expand, and the sheet to bend. Conversely, bending could be sensed electrically by monitoring the voltage at the center electrode. Construction of a transducer began by cutting a 6.35 mm wide by 10.30 mm long rectangle out of the bimorph sheet. One end was rounded to a radius of 4.0 mm. The other end was rigidly clamped into a transducer housing, so that the free length of the bimorph was 7.9 mm.

When two transducers as described above were applied to a paper sample, ultrasonic energy could be effectively transferred. Relatively pure longitudinal waves were generated if the transducers were facing each other, while transverse (or shear) waves were detected when the transducers were rotated 90° about their long axes. These transducers did operate satisfactorily, but they also had shortcomings.

First of all, the modal purity could be improved. In order to separately determine transverse and longitudinal velocities, it is important that only motion perpendicular to the transducer face is generated and received. If modes of oscillation (other than pure bending) are excited, the transducers can become sensitive to motion along the face. This creates less of a problem for the longitudinal measurement, since the longitudinal wave is faster, and the analyzed portion of the signal in the far spacing is usually complete before the shear wave arrives. However, the shear signal is invariably tainted by the longitudinal. In an anisotropic sheet, the shear wave has the same velocity in the MD and CD, but the longitudinal velocities are different. Therefore, modal impurity could cause the calculated shear velocity to have different values in the two principal directions. (In this case, the CD shear provides the more acceptable number, since the relative strength of shear to longitudinal coupling is much greater in the CD.) On very anisotropic samples (MD stiffness greater than four times CD stiffness), MD-CD shear velocity differences of a few percent are often encountered. In addition, a signal can be observed when the transducers are oriented at right angles. The amplitude is well below the normal shear and longitudinal signals, but it is worrisome.

Another limitation of these transducers is that they are narrow-banded. There is a strong resonance at about 55 kHz, and an excited transducer "rings" for many tens of cycles after the disturbance is complete. This compounds the just discussed problem of longitudinal interference with shear signals, since the longitudinal signal that precedes the shear is ramping up (instead of dying down) as the shear arrives. Also, the use of narrow-banded transducers precludes the possibility of achieving a temporal separation of the shear and longitudinal signals and making group velocity measurements on discrete pulses.

In light of these concerns, a mathematical and an experimental investigation of the normal modes of oscillation of these transducers was conducted. A PC based, finite element program was used to calculate the normal modes of oscillation of a rounded PZT beam with a clamped back end and free front end. When the dimensions of the original transducers were used, the analysis yielded a number of modes of oscillation in the operating frequency range. There was a second harmonic bending motion at about 70 kHz which was responsible for the main action of the bimorphs. However, there were also a fundamental "wobble" (predominantly rotation about the out-of-plane axis) and fundamental, first order, and second order "twists" (predominantly rotations about an axis parallel with the length). The twists probably would not efficiently transfer ultrasonic energy into the sample; however, the wobble could conceivably produce longitudinal waves when the transducers were aligned for shear and vice versa.

An experimental spectrum of the transducer response was obtained by placing the transducers on a paper sample. A continuous wave from a frequency synthesizer was applied to one transducer, and the other was input to a lock-in amplifier. The source frequency was swept, and the output of the lock-in was plotted. A strong peak was noted at 56 kHz. This is undoubtedly the second order bend. Its lower than predicted frequency is likely due to the less than perfect clamping afforded by the transducer housing. The next strongest peak was at 36 kHz. This presumably is the fundamental wobble which was predicted to be at 35 kHz. The experimental and calculated values are closer for the wobble, since perfect clamping is not as important in establishing the assumed boundary conditions.

From this analysis, it is clear that the transducers are being unwisely operated in a region with too many resonances. Secondary motions are being excited, and the transducers are not broadband. The straightforward solution is to simply shorten the transducers and rely on the fundamental bending motion. The wobble would be jacked out of the operating frequency range, and bandwidth would be increased by running below the lowest frequency resonances. Although the twists may not represent a problem, a concern is that the fundamental twist could be excited. This is avoided by decreasing the width, but not so much that the fundamental wobble comes into play. Another solution would be to reinforce the beam in some creative way. This was explored, but no promising scheme was uncovered.

All of these considerations led, of course, to the construction of miniature transducers. As demonstrated in Fig. 5, they are much shorter than the original ones. The transmitter has a bending length of 1.5 mm, and the receiver has a free length of only 1.3 mm. Mathematically and experimentally, these transducers have no resonances below 200 kHz. The receiver is cut smaller than the transmitter to increase its sensitivity and to avoid any coincidence of resonant frequencies. The bimorphs are epoxied into grooves in a Delrin housing in an effort to improve the clamping.

Figure 5 here

The miniature transducers do provide superior performance. It is now possible to generate pulses as short as 10 μsec. Minimum pulse widths previously were over 100 μsec. Sensitivity, as measured at the initial peak, was approximately tripled. The contamination of shear measurements by longitudinal impurities was reduced. This was verified by comparing the ratios of MD to CD shear velocities made on highly anisotropic sheets with the two types of transducers. For a set of ten sheets, with stiffness anisotropy ratios of over four, the miniature transducers gave an average shear anisotropy ratio of 1.04, while the original transducers produced a ratio of 1.08.

Conclusions

The robotic in-plane tester is a clear improvement over the previous automatic instrument. It is faster. The results are more reproducible. It can test more samples. It is much less likely to damage a specimen. It uses improved transducers. It is capable of performing complex mathematical analyses (to be discussed in another publication) on the results. These are all important advances, but perhaps the most significant feature is that the robotic system is suitable for commercialization. In fact, during 1989, RoboTest Corp. plans to manufacture and market a version of the robotic tester.

Acknowledgment

We appreciate the valuable assistance of Johnson Scale Co. in designing and manufacturing the end effecter. Portions of this work were used by BMP as partial fulfillment of the requirements for the Master of Science degree at The Institute of Paper Chemistry.

Reference

1. Van Zummeren, M., Young, D., Habeger, C., Baum, G., and Treleven, R., Ultrasonics 25:288(1987).

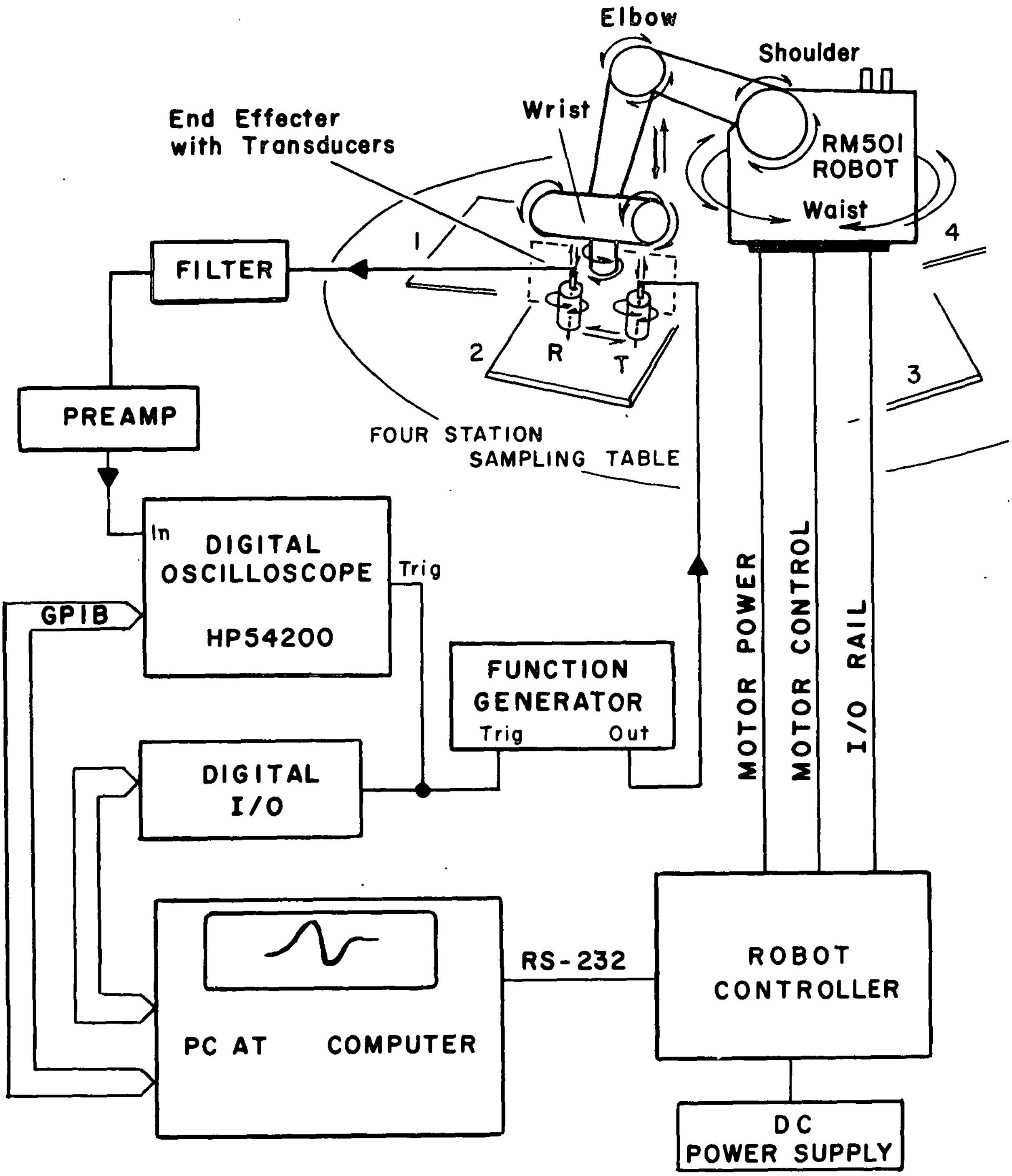
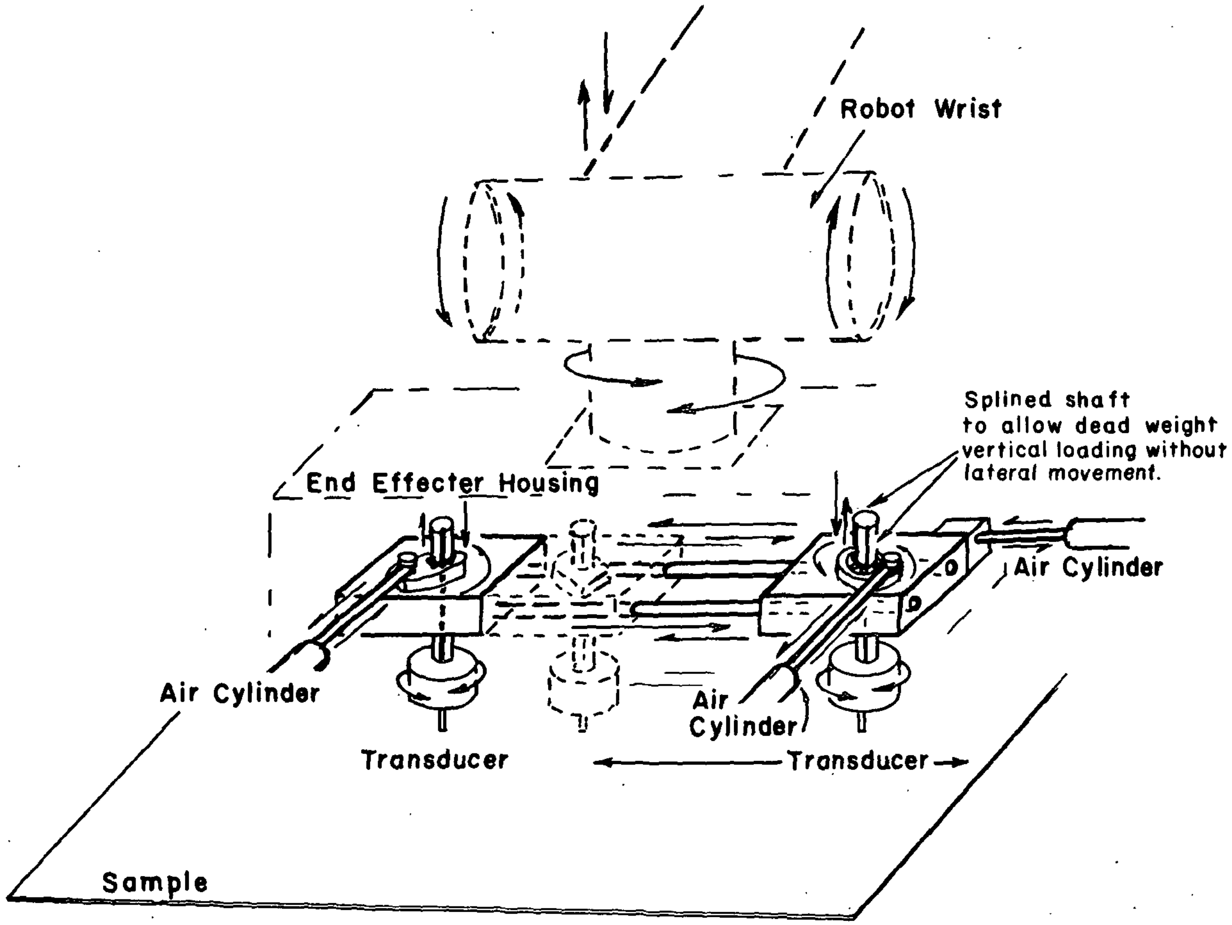


Fig. 1. Overall schematic of the robotic tester.



DETAIL OF ROBOTIC END EFFECTER WITH TRANSDUCERS

Fig. 2. Schematic of the end effecter.

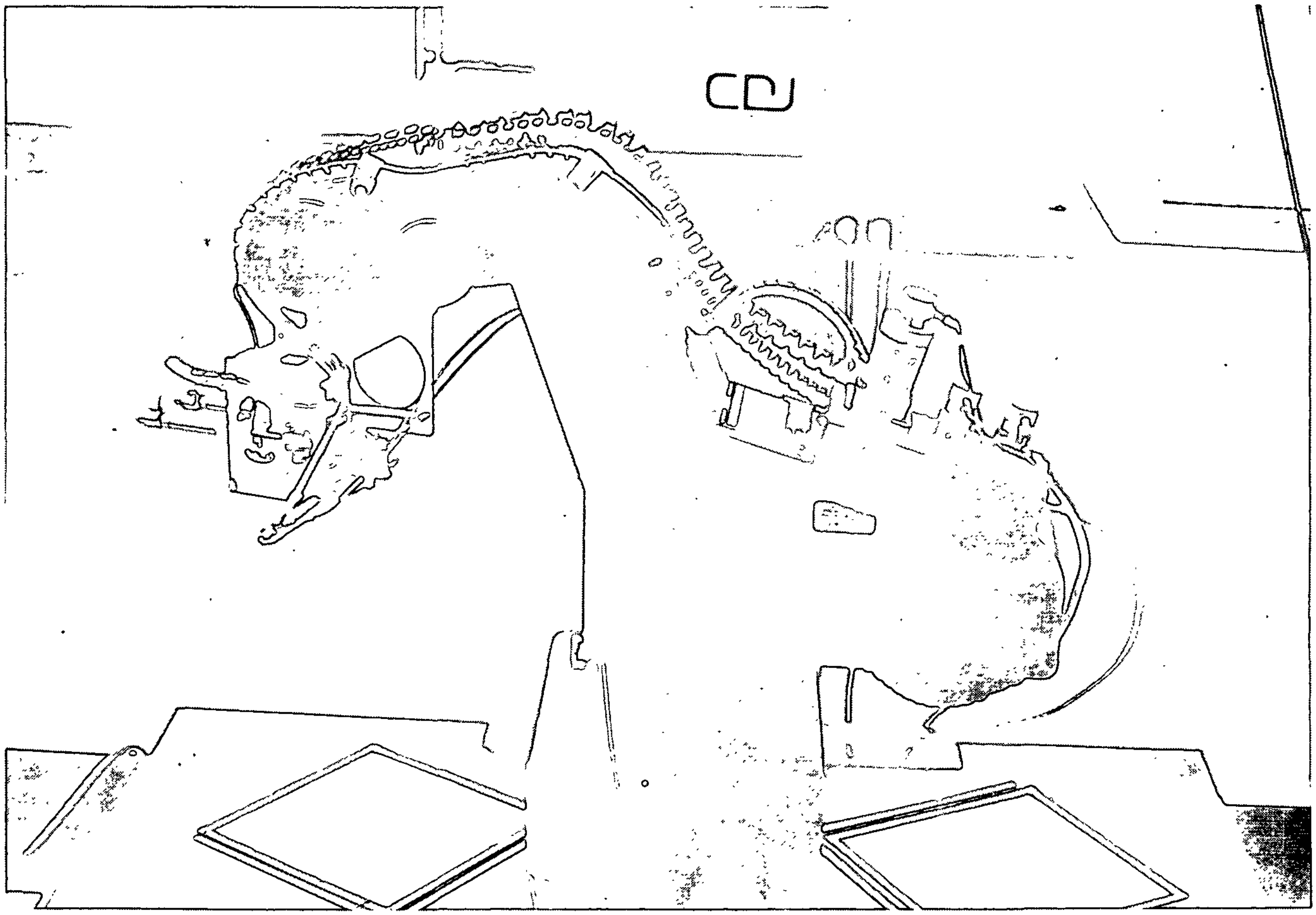


Fig. 3. Photograph of the robotic tester.

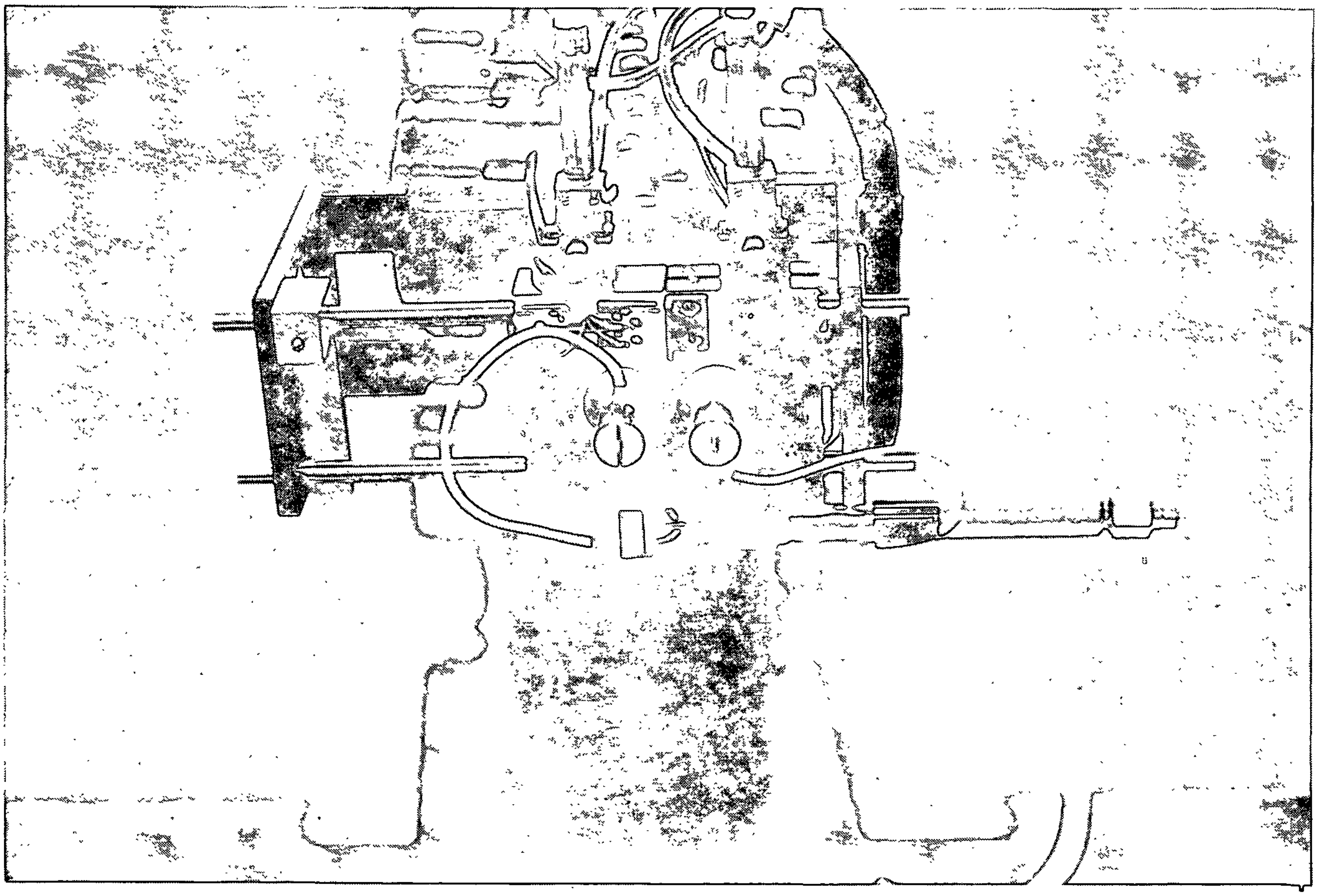


Fig. 4. Photograph of the end effecter.

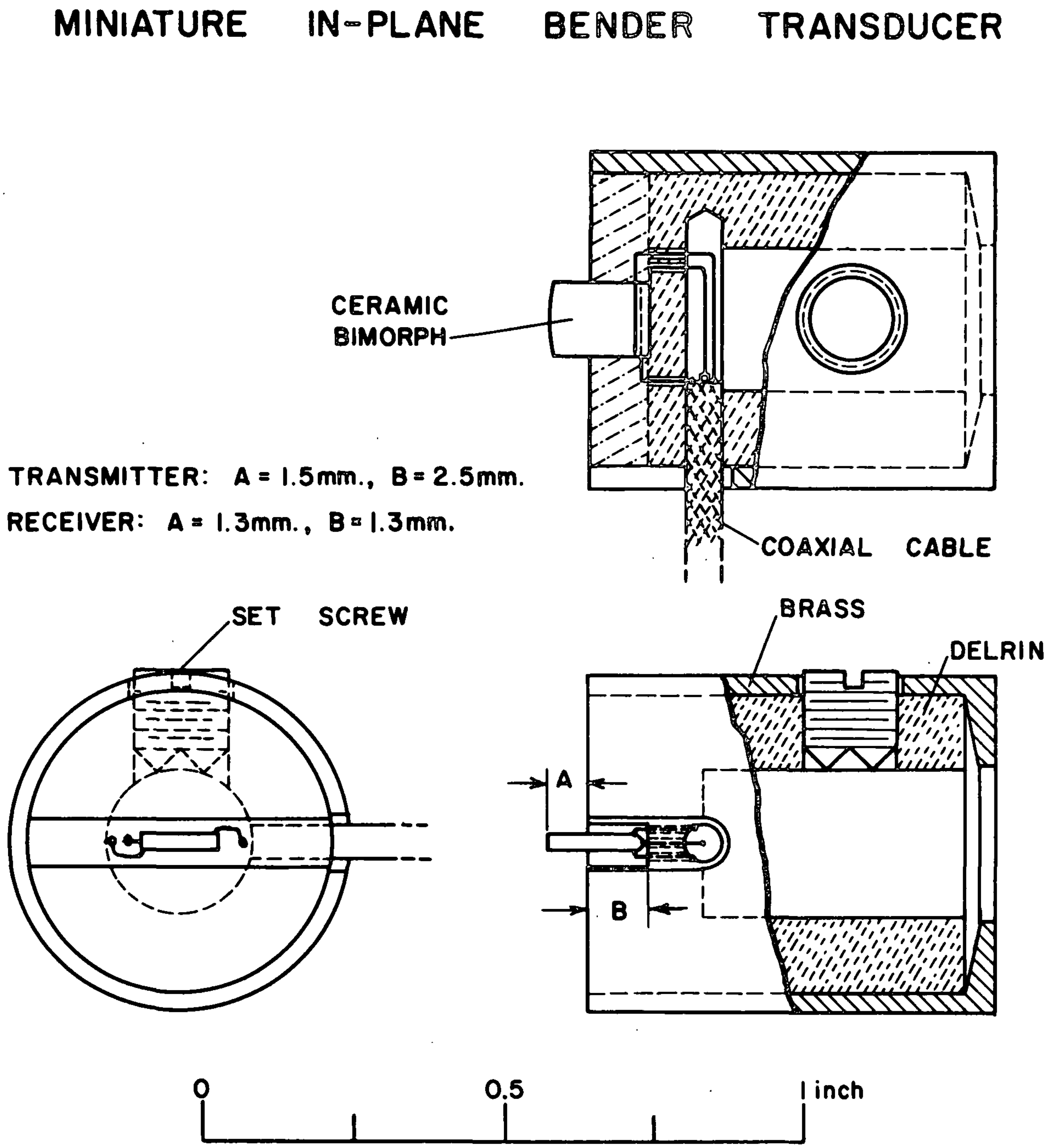


Fig. 5. Mechanical drawing of the transducers used in the robotic tester.