A SHEAR-WAVE MICROPROBE UTILIZING SURFACE-WAVE MODE CONVERSION

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INTRODUCTION

A very small aperture ultrasonic probe for detecting shear waves was desired for ultrasonic shear-wave field mapping [1-3]. Several designs of such a probe were developed and evaluated. During the course of probe development, a very interesting phenomenon was observed and was used to build an improved shear-wave microprobe that is unique in design and capability. This report describes design evolution, advantages, and applications of this new probe.

SHEAR-WAVE MICROPROBE DESIGNS

The probes described in this report (Fig. 1) use a metal cone with a sharp tip. The cone tip makes intimate contact with the solid specimen thereby coupling sound within the specimen to the cone. The tip contact area is small (typically 0.3-mm diameter) and may be considered a point contact for most ultrasonic applications. A piezoelectric element is used to convert acoustic energy in the cone into an electrical signal.

The progression of shear-wave microprobe designs began with right circular cones with a flat top for bulk-shear-wave reception by a shear-wave crystal (Fig. 1a). This design was improved by rounding the cone head to produce a caustic of mode-converted surface waves (Fig. 1b). The latest design utilized an extended cone with both a micro-piezoelectric crystal for surface-wave reception and a cylinder of surface-wave damping material (Fig. 1c).

Flat-Top-Cone Design

The flat-top-cone design consisted of a 3-mm diameter shear-wave piezoelectric crystal bonded to the cone-top and encapsulated with polyurethane. This device was able to receive a 0° shear wave

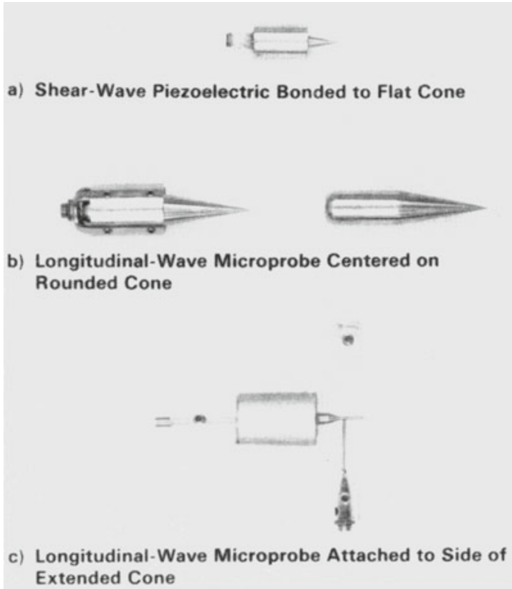


Fig. 1. Shear-wave microprobe design utilizing steel cones

transmitted by pulsed excitation of a shear-wave piezoelectric crystal bonded to a 5-cm thick glass cube. However, the signal response, as shown in Fig. 2, contained many spurious signal-reverberations from the cone. To further investigate the source of the extraneous signals, several cone designs were made and evaluated by using the existing shear-wave microprobe as a diagnostic instrument by sliding the microprobe cone tip against the periphery of the cone being evaluated.

A strong signal was observed from two opposite sides on the top-surface of the flat cones. Each signal then propagated from the corner toward the center of the cone-top. A hypothesis was that the bulk shear wave impinged upon the corner and resulted in either a diffracted shear wave or a mode converted surface wave. To minimize this effect, the next generation of probes consisted of rounded cone heads (Fig. 3).

The signal response from a microprobe place at the center of a cone with a spherical head indicated that the signal consisted of both a shear-wave precursor and a large surface-wave response (Fig. 4). The arrival time of the precursor corresponded to a bulk shear wave traveling from the cone tip to the cone-head center. The arrival time of the main signal response corresponded to a surface wave traveling along the cone periphery. Although signals were previously noted traveling up and down the cone sides, they were thought to be from divergence of the bulk shear wave and its interaction with the sides of the cone.

Further surface-wave confirmation occurred by observing the signal response from an asymmetrical point on the cone (Fig. 5). Signal reception was accomplished by a longitudinal-wave microprobe applied to the cone surface to detect the surface normal component of the surface wave. The small-diameter crystal also enabled reception of high frequency signals since the crystal was contained entirely within either a compressive or rarefactive zone (10 MHz for a 0.3-mm microprobe aperture). Arrival times between signals 1 and 5 and signals 2 and 6 were predicted to equal 54.2 μs and measured 57.8 μs and 57.6 μs, respectively. Another supportive point was the match between the surface-wave

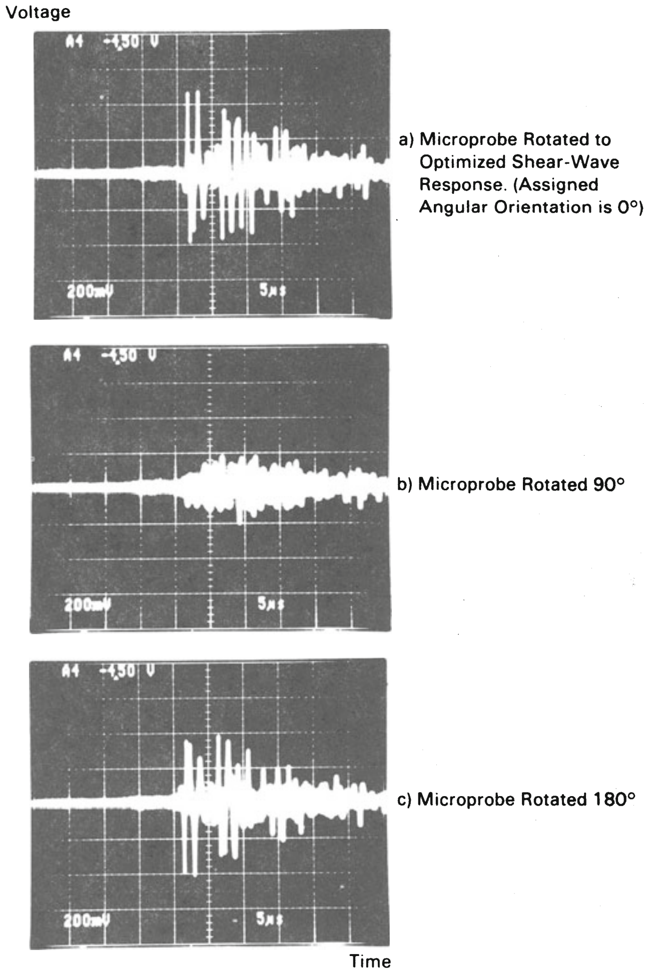


Fig. 2. Shear-wave polarization displayed by RF signals from a flat-cone microprobe

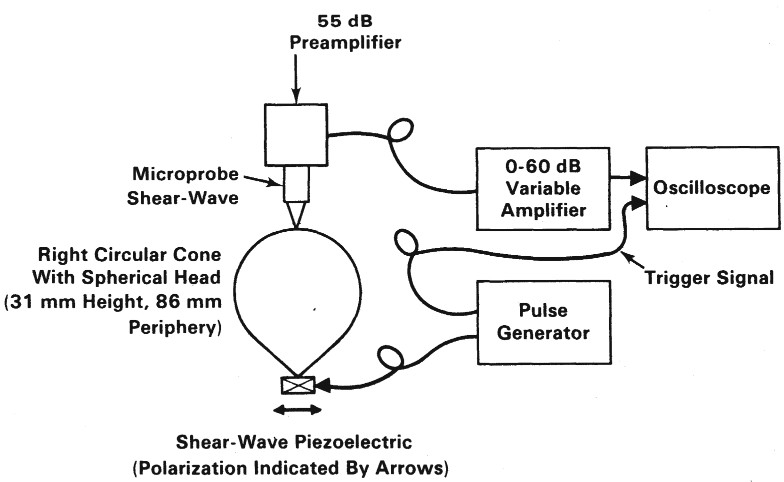


Fig. 3. Block diagram of instrumentation for determining wave-propagation mechanism in cones

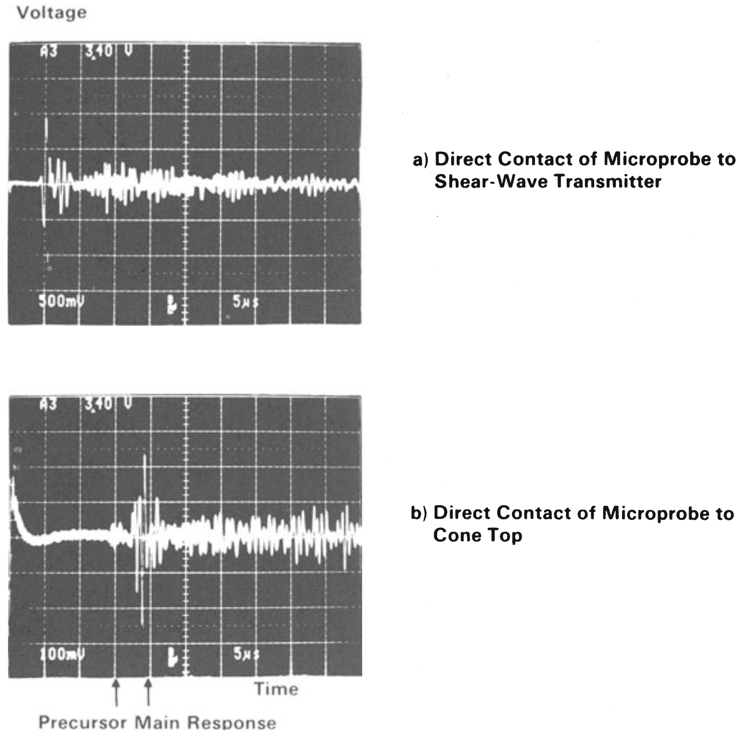


Fig. 4. Signal response of shear-wave microprobe applied to center of a spherical cone head

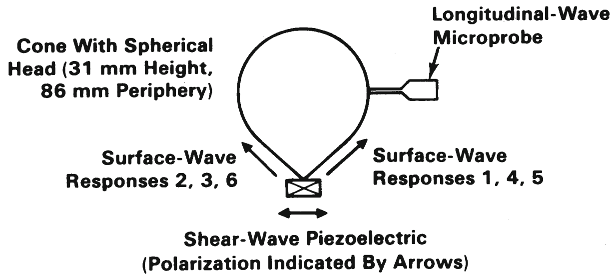
pattern based on the arrival times of signals 1 and 2 and that of the remaining signal train.

Rounded-Cone-Top Design

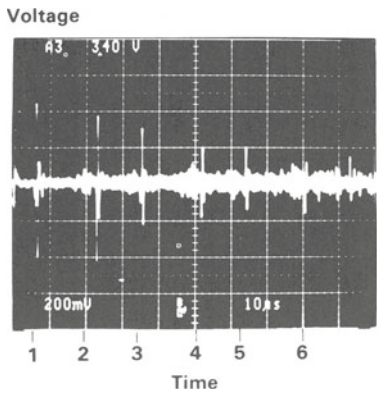
A rounded-cone-top design (Fig. 1b) was made which guided the surface waves to the cone-top center in order to form a caustic. A longitudinal-wave micro-crystal was bonded at the focal region; unfortunately, sensitivity was lower than expected. Misplacement of the micro-crystal from the cone center was examined by removing the steel shield around the cone top, shearing off the crystal, and monitoring signal reception by means of a longitudinal-wave microprobe coupled to the cone with petrolatum. Sensitivity decreased as the crystal was centered. A hypothesis that was formulated and confirmed was that the two surface waves were phase reversals of each other (Fig. 6). Thus, off-axis placement of the microprobe selectively caused high and low sensitivity to various frequencies because of interference. Another approach to provide greater fidelity was reception of only one surface wave.

Extended-Cone Design

An extended cone (Fig. 1c) was made in which the cone-vertex angle was made small in order to restrict the energy redistribution around the cone to increase sensitivity. The longitudinal-wave microprobe was placed close to the tip to minimize sound loss; and the extraneous, surface-wave reverberations were damped by inserting the extended cone into a cylinder of putty. To evaluate signal reception, a reference



a) Placement of Longitudinal-Wave Microprobe on Cone



Signal No.	Arrival Time (μS)
1	6.4
2	22.8
3	35.8
4	51.8
5	64.2
6	80.4

b) Microprobe response

Fig. 5. Surface-wave response from a longitudinal-wave microprobe applied to side of cone with spherical head

signal was provided by bonding a shear-wave transducer to a 51-mm thick glass cube. The received signal from the extended-cone, shear-wave microprobe, as shown in Fig. 7b, displayed limited signal ringing and was much improved over the initial flat-top-cone design. A hypothesis was that the latter portion of the main-signal response might be from the surface wave on the far side and other wave modes coupled between the two cone-sides. If true, application of the longitudinal-wave microprobe to the tip region of a cone used in the previous designs would weaken the interaction by increasing the distance between the cone sides, thus increasing signal clarity. As observed in Fig. 7c, the main signal response was improved, which indicates that a possible means of improving the present design is to use an extended cone having a larger vertex angle. Another recommendation is to use a smoother transition in cone cross-sectional diameter as a function of displacement along the cone axis.

ADVANTAGES AND POSSIBLE USES OF THE SHEAR-WAVE MICROPROBE

These probes are very durable since the cone tip is hardened steel and the longitudinal-wave microprobe is rigidly held in place against the cone-side. The microprobe can be quickly moved away from the applied surface, and reapplied to another location using a small force normal to the surface. No problems were noted with frequent application of the microprobe except that the cone tip may leave a small

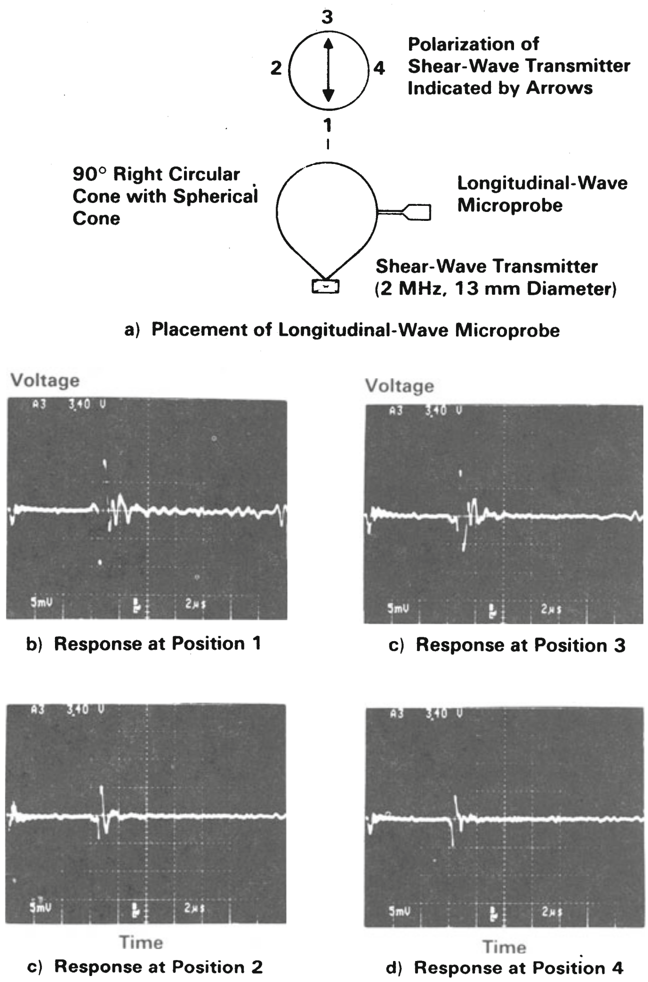
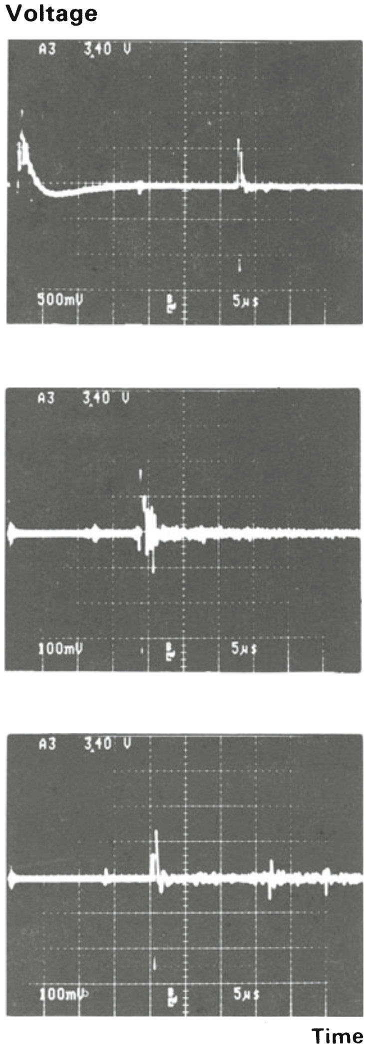


Fig. 6. Examination of surface-wave phase from shear-wave excitation of cone tip

depression in the material. Futhermore, a small normal force is preferred since sensitivity enhancement due to increased force (just below where plastic deformation was observed) is marginal.

The probe is not sensitive to misalignments away from the surface normal up to 10°. No observable change in the time-domain signal was noted when the probe was applied to a polished glass block and angled at 10°. The polished surface also permitted the probe to remain in contact with the block while traversing the probe to different points. This may be very conducive to mapping shear-wave fields in various materials.

Since the microprobe is essentially a point receiver, directivity is expected to duplicate the theoretical predictions of Roderick [4] and Pursey and Miller [5]. The cone design also makes the probe conducive for use on small parts. Work is underway to transmit surface waves down the cone-sides and by reciprocity produce a shear-wave point transmitter. Thus, a paired set of probes (transmitter and receiver)



a) Pulse-Echo Response from Shear-Wave Transmitter (50.8 mm Thick Glass Block)

b) Signal Response of Extended Cone Shear-Wave Microprobe (1.1 mm Diameter Cross Section)

c) Signal Response of a Truncated Cone With Longitudinal-Wave Microprobe Applied at a 2.5 mm Diameter Cross Section

Fig. 7. Response of extended-cone microprobe to an incident shear wave

might be used for applications such as solder joint inspection for integrated circuits as well as ultrasonic welding by the transmitter.

Surface-wave probes (longitudinal-wave piezoelectric crystal mounted on a critical angle acrylic wedge) were used to test the microprobe's capability for surface-wave reception. Excellent sensitivity was observed for surface waves at varying distances away from the surface-wave transmitter.

Use of the extended-cone shear-wave microprobe for high temperature work may be possible. The cone is steel and may be effectively cooled. Special heat shielding and active cooling would also be necessary to protect the longitudinal-wave micro-crystal mounted on the cone. However, this design would remove the piezoelectric crystals from direct contact with an inspection piece.

Surface waves were shown to propagate up the cone sides in a symmetrical or anti-symmetrical fashion, if the cone tip was displaced in a normal or tangential manner, respectively. If two longitudinal-micro-crystals were placed symmetrically opposite each other, then the received signals would be in phase or phased reversed, and would detect an incident longitudinal wave if summed and an incident shear wave if subtracted. Furthermore, an added crystal pair with a difference output might enable both shear-waves polarizations to be received. Surface waves could also be discriminated by examining the phase relation between a received longitudinal- and shear-wave response. Thus, a single point receiver might be capable of receiving all three wave-modes simultaneously while also being able to uniquely discriminate each mode.

CONCLUSIONS AND SUMMARY

A novel shear-wave microprobe was developed which utilizes mode conversion to surface waves. Advantages of probe usage include: durability, consistency of signal reception with probe misalignment up to 10°, couplantless inspection, true point receiver, suitability for use on small parts, good sensitivity to surface waves, possible application to high temperature work, and possible simultaneous reception and discrimination of longitudinal, shear, and surface waves.

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