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Monitoring Microinch Displacements in Ultrasonic Welding Equipment

Abstract: This communication describes two non-contacting techniques for dynamic measurement of high frequency microinch displacements, which have been applied in monitoring the dynamic displacement of the magnetostrictive transducer system used in ultrasonic welding. One technique consists of a light reflecting scheme that uses a fine fiber optic probe. The probes are available in a range of sizes and, in general, can be used to measure displacements of from zero to 0.030 in. at low frequencies and from 5 to 5000 μin. at any frequency below 100 kHz. The second method, an acoustical technique, leads to results similar to those obtained with the reflective system and can be used with a 0.030-inch diameter acoustic probe; this technique has been used in a frequency range well above that usually associated with probe tube measurements.

Introduction

Typical commercial ultrasonic bonding systems are used either to join materials that cannot easily be connected by other processes, or to eliminate thermal limitations that preclude other joining methods under some conditions.

Ultrasonic welding, because of the advantages of its small probe tip, low thermal exposure, and lack of back voltage exposure, is very useful for discrete-wire interconnection of circuits. While considerable technical literature [e.g., 1–4] and commercial experience exists in the ultrasonic welding of semiconductor chip and module joints, the product requirements for discrete-wired interconnections are significantly different. In the first case the individual interconnections require relatively little structural strength, and each group of connections is protected in a sealed unit. For discrete-wired interconnections, however, the need is to produce low deformation and high structural strengths of 60 to 80 percent UTS (Ultimate Tensile Strength). It has been found that the tensile strength of an ultrasonic wire bond is closely related to the oscillation amplitude of the bonding tip during welding.

This communication contains a description of two techniques for monitoring the motion of small ultrasonic bonding tips. The bonding units contain magnet-ostrictive transducers that are driven by regulated power supplies having a constant-current or constant-voltage output at a frequency of 60kHz. A coupler and horn are attached to each transducer to provide the physical displacements at the welding tip required to produce a satisfactory weld. The tip displacement is usually between 50 and 600 μin. at the excitation frequency of 60 kHz. A typical ultrasonic bonding system is shown in Fig. 1.

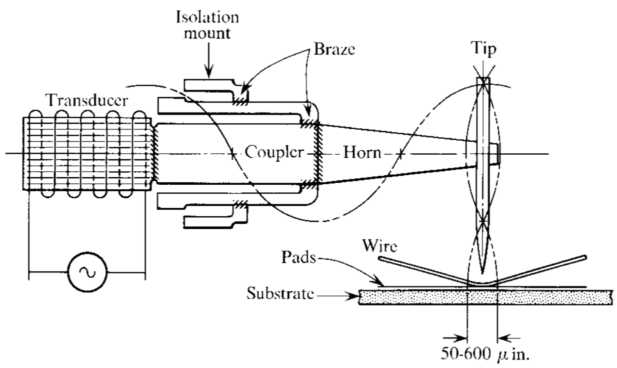


Figure 1 Typical ultrasonic bonding system.

The mechanisms that produce a bond are not completely understood and are not considered in detail in this communication. Simple surface melting or solid state bonding do not adequately explain the process; the bond is evidently formed by a scrubbing action that takes place at high unit pressures when a fine wire is clamped between the groove in the welding tip and a substrate. This scrubbing action causes local plastic de-

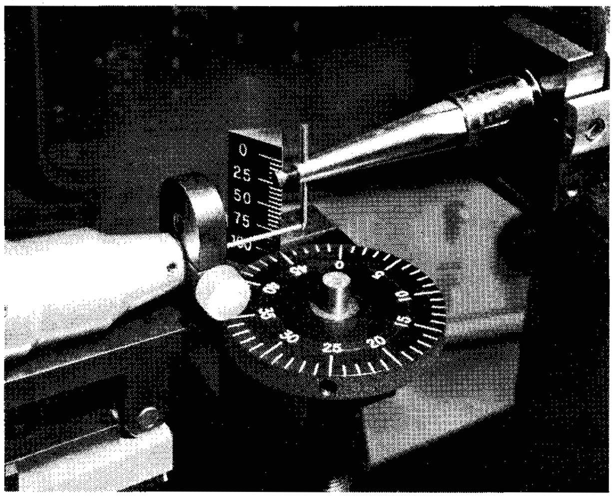


Figure 2 Characterization tool with optical probe.

formation and heating of the surface atoms of the materials. When the crystal structure of the materials is compatible, diffusion takes place.

Because the goal of this program was to develop techniques for producing welds having uniformly high tensile strength, several different parameters were varied to achieve this goal. Various wire materials and platings, and the effects of groove-shape, welding pressure, welding time, and energy input were investigated. It became clear during the course of this study that a method of monitoring the tip motion would be highly desirable for several reasons:

First, it was found that the ultimate criterion, bond strength, was closely related to tip displacement no matter which of the parameters such as welding tip loading, power input, excitation, materials, and tooling were varied.

Second, it was not possible to transfer a weld schedule from one power supply or transducer to another without an empirical study, since the parameter values for a given displacement were different for one unit than for another.

Third, there are a number of process variations that can take place during the bonding cycle; among them are changes in tip clamping forces, non-symmetrical clamping, the extension of the tip above or below the horn, material variations, tip and horn resonance points, transducer mountings, tip loading, and surface conditions at the tip-to-wire interface. Tip displacement appeared to be the most desirable single parameter to monitor during the weld cycle to detect such variations.

Only non-contact monitoring systems were considered, because most of the process variations mentioned above would be affected by mechanical loading of the system.

Prior to this application, no dynamic microinch displacement measurements by either of the techniques we describe were known to exist within IBM, and technical literature searches have not revealed any quantitative displacement measurements of welding equipment by these methods to date. Recent publications indicate that an acoustical technique has been used in a qualitative manner [1], and alternative optical techniques have been tried [2]. Laser holography and interference microscope techniques have also been tried but they are limited to repetitive uniform observations and are not too useful for dynamic measurements. Another difficulty with the latter techniques is that under certain conditions, connections are made in a "nest" of wires, and monitoring with a complex optical system that requires a low-vibration environment is not always practical. In addition, the tip motion is known to change during the weld cycle and monitoring of these dynamic changes is difficult with optical techniques, which are most suited for steady-state measurements. Accordingly, the advantages and disadvantages of a reflected-light optical system and an acoustical system were studied.

Optical technique

The first technique [5] used to measure displacement was the reflected-light system, for which a commercial unit equipped with a fiber optic probe was supplied by Micro Technology, Inc. The optic probe has a patterned distribution of elements and is divided into two bundles, one for light transmission and one for reflectance detection.

The unit is capable of measuring dynamic displacements of the welding tip or other points on the system in the 5- to 5000-μin. range at frequencies from dc to 100 kHz. The nominal operating frequency of the ultrasonic driver is 60 kHz, and thus is well within the probe's range. The system can be used with a wide range of reflective surfaces by making a calibration run.

The front end of the tip can be conical or flat so long as the probe is smaller than the reflecting surface. Since the reflected output of the sensor is averaged, slight slope or arc changes during bonding are well within normal experimental error. Some positive and negative slope can be tolerated because of the small dimensions involved.

Figure 2 shows the free-air characterization tool that was built to hold the reflected-light sensor. The tool consists of a micro-positioner for alignment and movement of the sensor, a stand for the transducer mounting bracket and a jackscrew anvil that can be used to raise and lower the tip to measure the effect of tip toeing or heeling on a wire. Similar tooling is used to make measurements during bonding, with the anvil area being made large enough to hold a substrate with a vacuum chuck. A

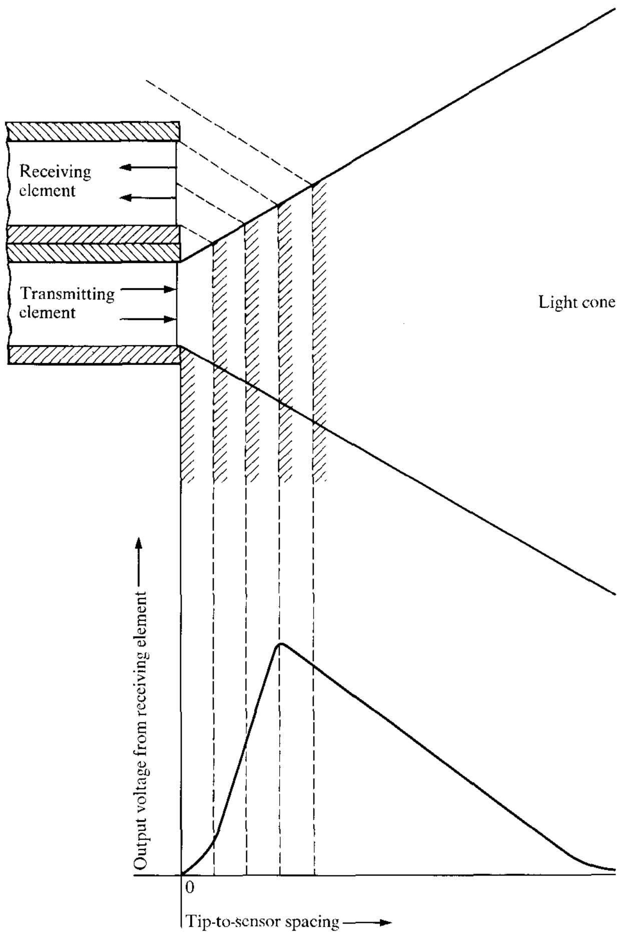


Figure 3 Operation of adjacent light elements.

storage oscilloscope is used to observe the displacement during the welding cycle.

The same system, with adapters, is used to measure displacement during actual bonding. Changes to the tip motion as a function of geometry, mass, frictional loading, clamping, drive systems, and any number of key variables that might be expected to be found in production, can be identified by examining the standing wave on the bonding tip.

The probe tip of Fig. 2 is composed of randomly distributed filaments. The energy transfer between two adjacent fibers is a function of the distance between the probe end and the surface being monitored. The output of the system as a function of this spacing is shown in Fig. 3.

The relationship between spacing and energy transfer is approximately linear near the point of inflection, which is the point of maximum energy transfer. When the total surface area of the receiving element is illuminated by the reflected cone of light, the slope is zero. If the spacing is increased beyond this maximum point, the relationship between the spacing and illumination is

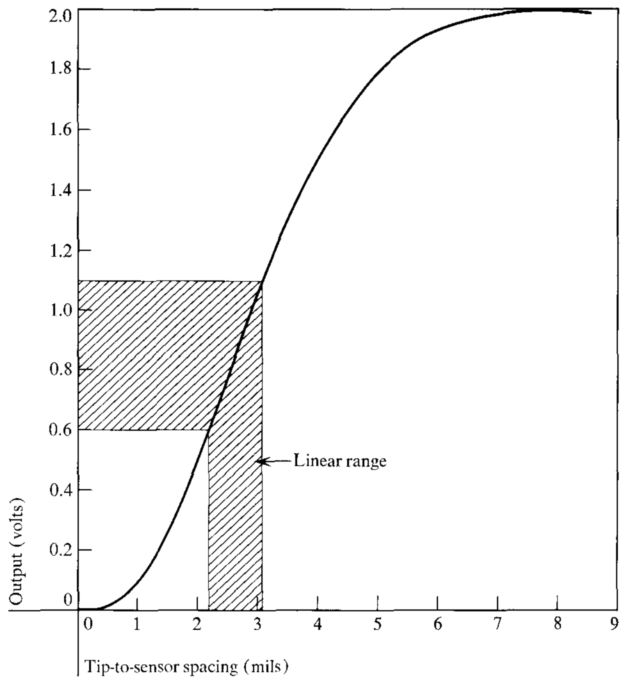


Figure 4 Typical output voltage vs tip-to-sensor spacing for reflected light from 30-mil probe. (The reciprocal of the slope on the positive side is 1.84 μin./mV in the linear range.)

again approximately linear near the point of inflection on the negative slope of the curve. In order to obtain an accurate displacement measurement, the active area of the probe should be smaller than, and parallel to, the surface being measured, so that the dynamic changes in spacing represented by the tip displacement will remain within the linear range of the probe.

The reciprocal of the positive slope of the calibration curve (Fig. 4) for the 30-mil (active area) probe is approximately 1.84 μin./mV over the linear region, and the positive-slope linear region is about 1000 μin. long. The reciprocal of the negative slope in its linear region ($\approx$5000 μin.) for this probe is approximately 14.73 μin./mV (Fig. 3).

The fiber optic probes are available in various geometries, sizes and angles, and this system of non-contact dynamic displacement measurement can readily be extended to other applications.

Acoustical technique

Initial efforts using a microphone were intended to result in a qualitative tool that could be used in process control for gross changes in the ultrasonic welding system. The sound pressure levels in very close proximity to the welding tip were approximately 100 dB (re 2×10^{-5} N/m^2). It became apparent that, with a small capacitor microphone, displacement results could be obtained that would be similar to those obtained from the optical

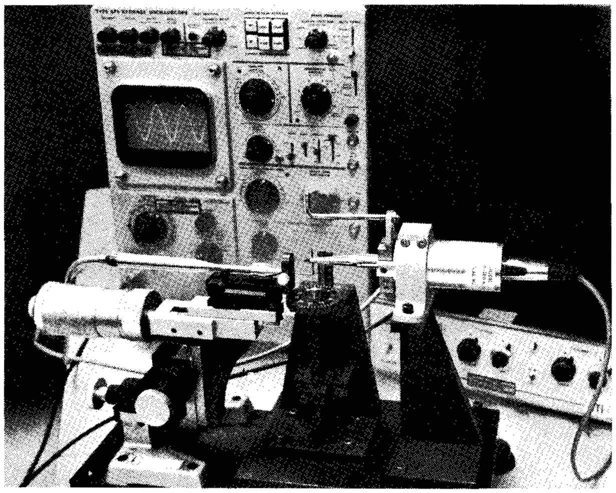
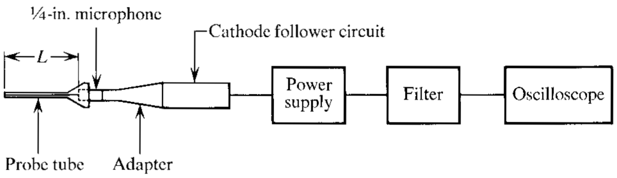


Figure 5 Characterization tool with acoustical probe.

Figure 6 Block diagram of acoustical monitor.



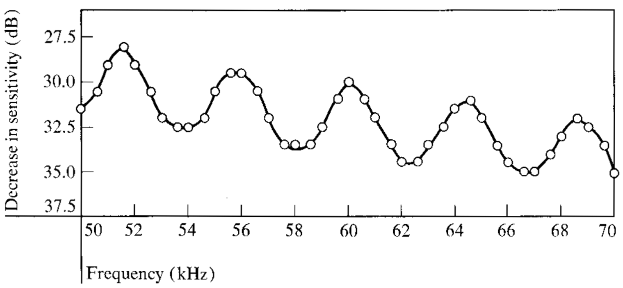


Figure 7 Sensitivity loss vs frequency for probe microphone.

probe. The microphone system (Fig. 5) has proved to be a second useful means for monitoring the motion of a welding tip in sinusoidal motion.

A block diagram of the acoustical instrumention system is shown in Fig. 6. The cathode follower, power supply, and filter have a gain of approximately unity. The filter is used only to eliminate unwanted sounds, and may be set so that its upper and lower cutoff frequencies are approximately one-half octave above and below the 60-kHz driving frequency.

The capacitor microphone is a pressure-sensitive device; however, it can be used to monitor displacement by measuring the near-field pressure in the vicinity of the moving object. The pressure field for a small source in harmonic motion is proportional to the source strength (which in turn is proportional to velocity amplitude) and frequency. If the displacement amplitude (or velocity amplitude) varies rapidly with position along the tip, the microphone, because of its finite size, will produce an output approximately proportional to the average displacement near the microphone.

One of the microphones used in this study had an effective diameter of 1/8 in. (Brüel and Kjaer Type 4138), and a reasonably good estimate of the motion of the tip could be made. Because the pressure response of the microphone system is known, absolute pressure measurements are possible. For optimal results, this microphone should be operated without its grid cap, and care must be taken to avoid damage to the diaphragm, particularly when it is placed in close proximity to a vibrating surface.

For this reason, the possibility of using a probe tube and a 1/4-in. diameter microphone (Brüel and Kjaer 4136) was investigated. The pressure response of a system containing a probe microphone is more difficult to obtain; however, absolute calibration is of relatively little importance because the device can be calibrated by other techniques such as the Fotonic sensor or a laser interferometer. A uniform response as a function of frequency is, however, desirable.

For the measurements reported here, the probe tube length L was approximately 1.58 in. and the interior diameter D was approximately 0.030 in. Normally, probe tubes are used in the low frequency region where the length of the probe L is small compared with the wavelength λ of the incident sound. In this region, the response can be made relatively uniform. When L is comparable to λ, standing waves within the tube normally produce large fluctuations in the pressure response characteristics. In the application reported here, the tube was several wavelengths long ($L/\lambda \gg 1$) and the diameter was small. In the frequency region of interest, viscous losses at the tube boundaries produced propagation losses in the tube, and although the sensitivity of the system was considerably reduced, the response was not too irregular.

The probe tube and microphone can be represented at least approximately by a tube opening into a cavity having a volume of 16 mm^3, and the reduction in sensitivity can be estimated by a circuit model of the system that takes into account the viscous and thermal conductivity losses mentioned above.

By the method just described, the reduction in sensitivity of the system has been computed and is given in Fig. 7 for a probe tube having the dimensions given above. For the frequency range of 50 to 70 kHz, the peak-to-peak variation in sensitivity is approximately $\pm$ 1 dB. It is felt that, because the driving frequency is

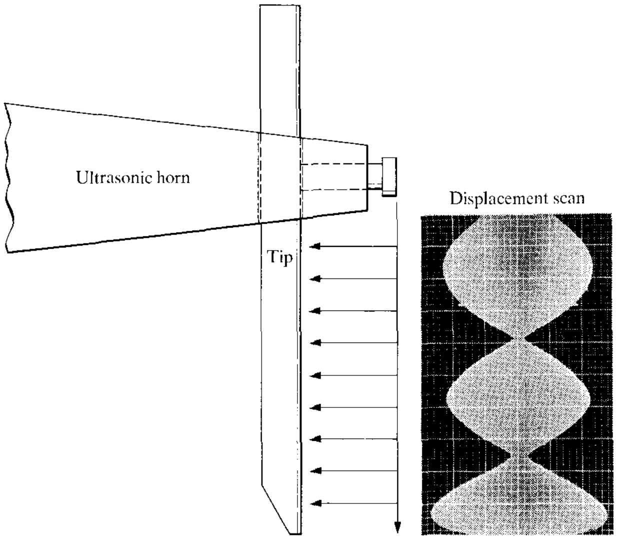


Figure 8 Displacement scan of welding tip.

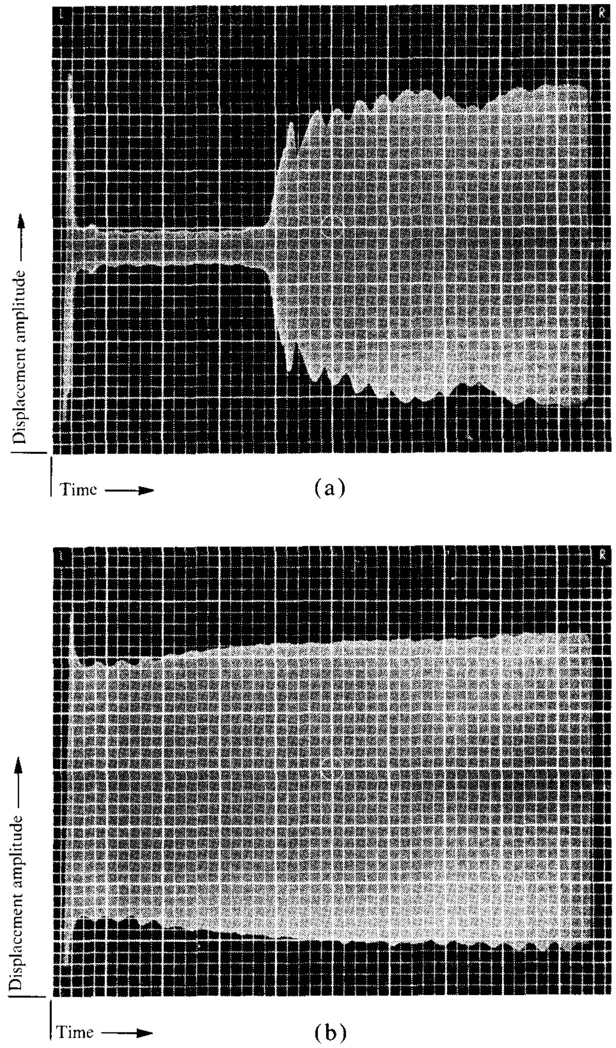


Figure 9 Tip displacement amplitude vs time during welding for (a) type X and (b) type Y bonding tips.

nearly constant at 60 kHz, because an absolute calibration is not important, and because the levels being monitored are relatively high, the response of the system is adequate.

The use of a probe tube has several advantages: 1) The effective diameter of the probe tube opening is small; 2) the microphone diaphragm is protected from damage; and 3) the tube can be placed in an area that is difficult to reach with the 1/8-in microphone and its associated cathode follower.

Results and discussion

Both the optical and the acoustical system were found to have advantages. In the acoustical system the relationship between tip displacement and sound level is complicated by the complex geometry of most practical welding tips and the importance of propagation losses in the probe tube. The output of the system does, however, correlate well with that of the optical unit when relative displacement along the tip is measured, and when the system is used for monitoring. The optical system has the advantage that one can obtain an absolute calibration with an optical unit. However, variations in the reflectance of the tip surface and small variations in the distance between the tip and the probe can disturb the calibration of the unit.

Figure 8 shows the output for a typical scan of the welding tip; this trace can be produced by either technique and the displacement is shown for all points from the area just under the horn to the very end of the tip.

Figure 9 shows displacement amplitude vs time for two different tips that were monitored during a bonding cycle. Figure 9(a) shows the effect of very heavy loading during the first half of the cycle for a type "X" bonding tip while Fig. 9(b) shows the response for a type "Y" tip under identical conditions. Type Y exhibits the desirable property of relatively uniform displacement throughout the bonding cycle, and the analytical capabilities of the technique are obvious from this example.

Figure 10 shows a typical graph of bond peel strength vs peak-to-peak tip displacement. The applied power was also measured and is shown as a second independent variable for comparison. The wire used was a 2.5-mil diameter alloy wire.

Measurements obtained from the two systems show good correlation; Fig. 11 is a representative example.

The acoustical technique can be used as a manual probe, or "sniffer," that will locate various points in a system at which the source pressure level is high or there is a change in level. (Such effects can be caused,

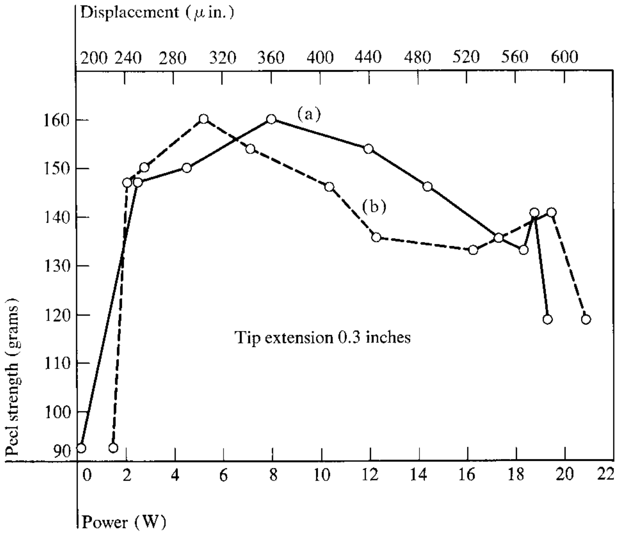


Figure 10 Bond strength vs (a) displacement and (b) power.

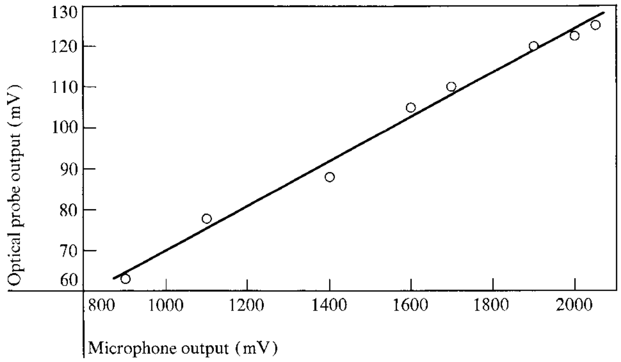


Figure 11 Correlation between reflected-light and acoustical output measurements.

for example, by loose screws, defective mountings, or changes in the power supply.) Potentially, one might construct a complete monitoring system by locating a microphone in the vicinity of each bonder in a process line and periodically sensing to determine whether any shift in frequency or level has occurred.

Similar uses in other applications might well be expected, particularly in cases for which the very small displacements must be dynamically measured without contact and the access space for a sensor is limited. It seems probable, also, that either technique can be readily adapted to automated control.

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