

**An Alternating Magnetic Field System for Tracking  
Multiple Speech Articulatory Movements  
in the Midsagittal Plane**

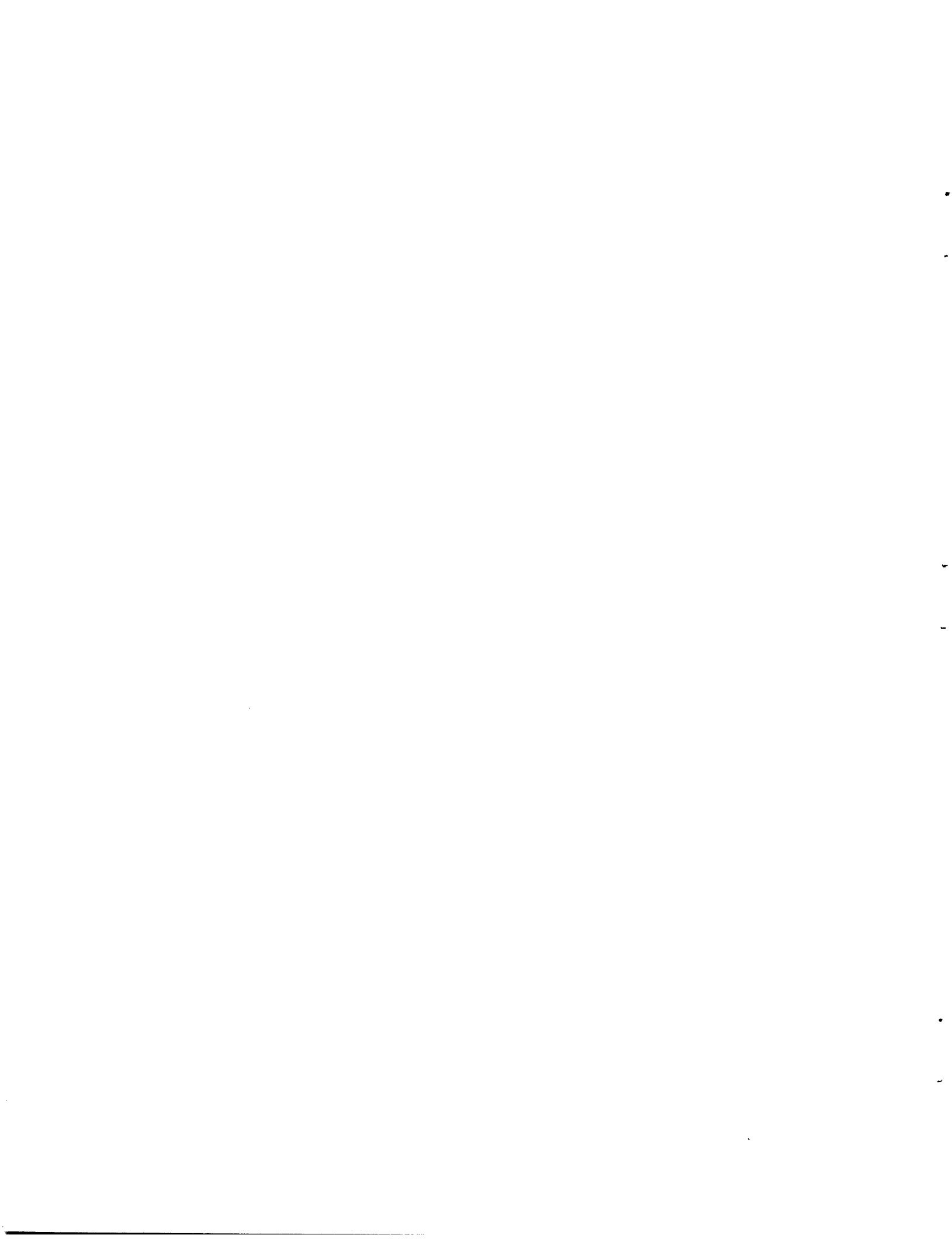
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**Technical Report 512**

February 1986

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This work has been supported in part by the National Institutes of Health under Grant 5 R01 NS04332 and in part by the Clarence Lebel Professorship in the Department of Electrical Engineering and Computer Science at M.I.T., held by Professor Kenneth N. Stevens.



# An Alternating Magnetic Field System for Tracking Multiple Speech Articulatory Movements in the Midsagittal Plane<sup>1</sup>

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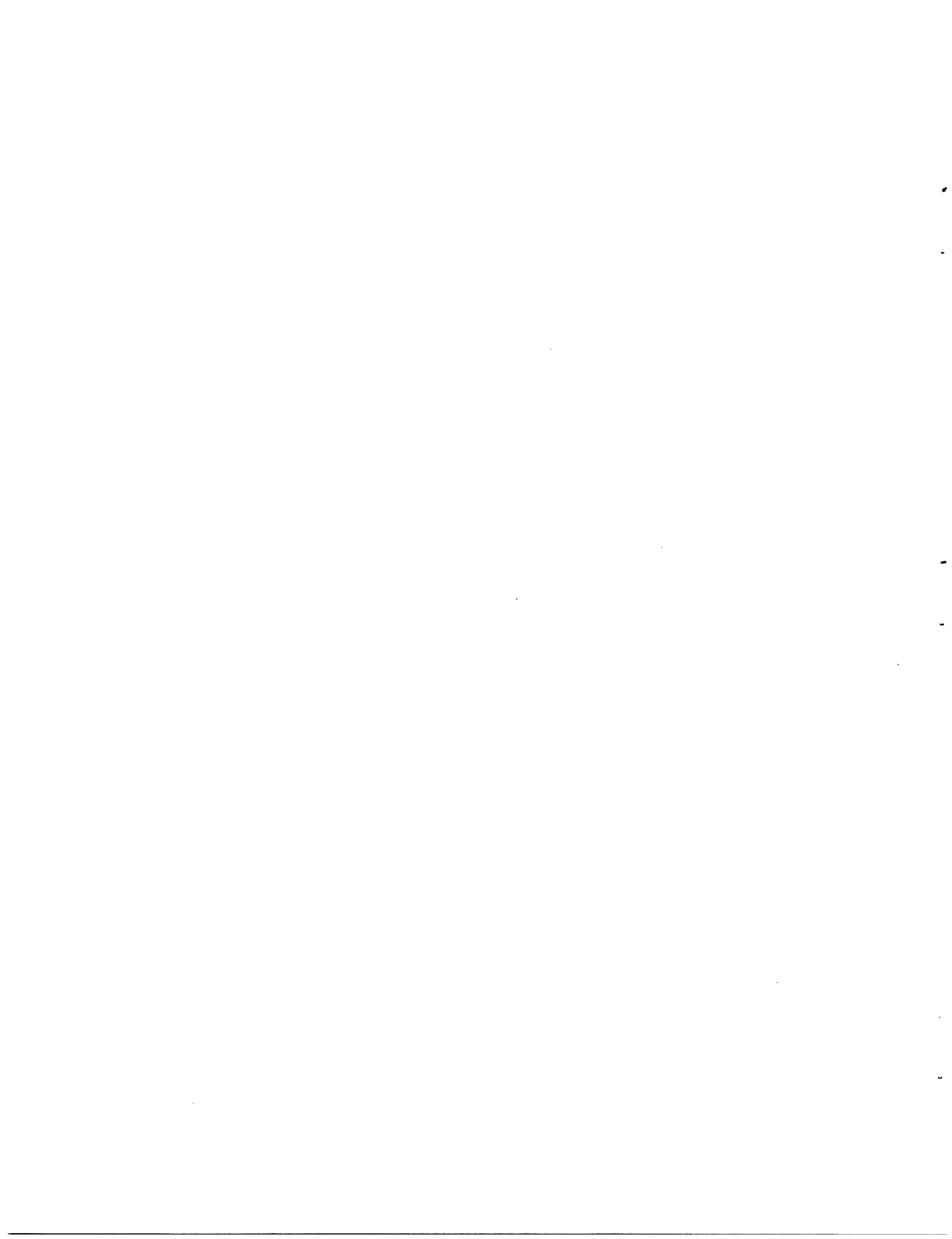
## ABSTRACT

This report describes the design, construction, evaluation and operation of a system that utilizes alternating magnetic fields for transducing articulatory movements during speech production. The system simultaneously tracks the movements of a number of points on vocal tract structures in the midsagittal plane, inside and outside the vocal tract. It has been under development for several years, and it now exists as a finished laboratory apparatus which can be used to collect large amounts of data.

February, 1986

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<sup>1</sup>This report is an expanded version of two papers given at the 109th meeting of the Acoustical Society of America (Perkell and Cohen, 1985; Cohen and Perkell, 1985).



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## 1. Introduction

A useful way of making comprehensive studies of the coordination of articulatory movements in speech production is to simultaneously track movements in the midsagittal plane of multiple points on articulatory structures, both inside and outside the vocal tract. Early studies of such movements used cineradiography (cf. Houde, 1968; Kent, et al., 1974; Perkell, 1969), but growing awareness of the hazards of ionizing radiation has led to a marked decrease in the use of this technique. For this and other reasons, cineradiography is completely impractical for collection of the large quantities of data needed to study the widespread variability that is found in speech production (cf. Hughes and Abbs, 1976; Perkell and Nelson, 1985; Perkell and Klatt, 1986). The original development of the x-ray microbeam (cf. Fujimura, et al., 1973) and its implementation as a nationally-shared facility (Nadler, et al., 1985) are responses to the acknowledged need for safe and efficient means of obtaining this kind of data. Alternating magnetic field devices (cf. Hixon, 1971; van der Giet, 1977; Schonle, et al., 1983) offer a locally-useable alternative to the x-ray microbeam; however, up to now, no magnetic-field system has been developed, calibrated and evaluated to an extent which should be required of such a measurement apparatus.<sup>1</sup> This report describes the design, comprehensive testing and operation of a system which meets these requirements.

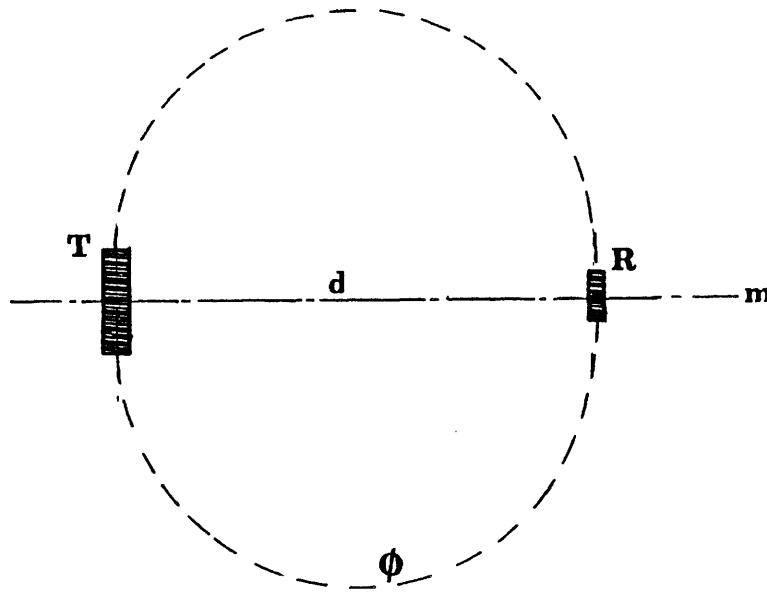
## 2. Background

### 2.1. Theory of Operation

Figure 2-1 illustrates the basic principle of operation of the system. It shows a transmitter coil, T, and a receiver coil, R, separated by a distance,  $d$ . The coils have their long axes parallel to one another, and their midlines fall on the same axis,  $m$ . The transmitter coil, excited by a sinusoidal signal, generates an alternating magnetic field. At the midline,  $m$ , lines of magnetic

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<sup>1</sup>A magnetic field system to transduce speech movements is available from Special Instrument AB, Stockholm, Sweden; however, this system is not designed to transduce movements inside the vocal tract.

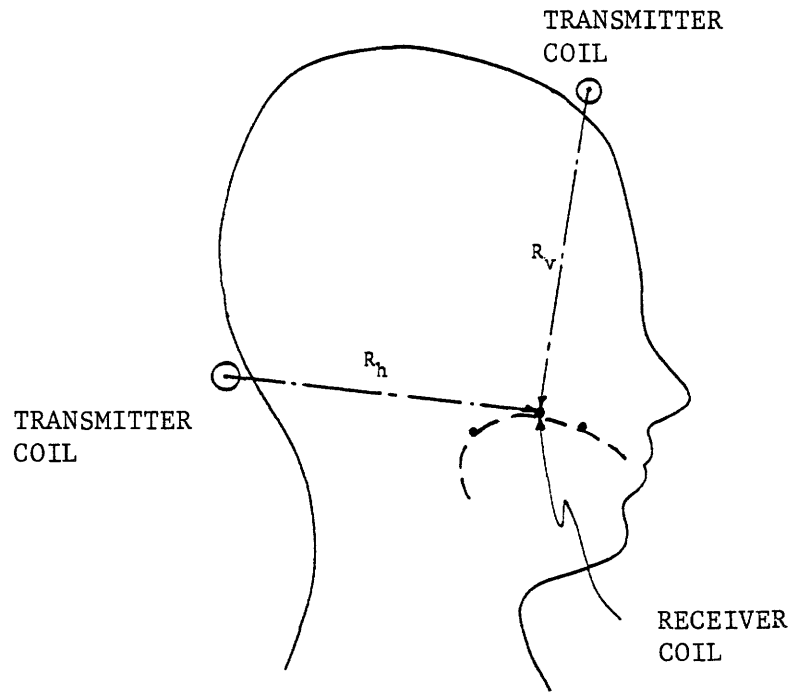


**Figure 2-1:**

A transmitter coil, T, for generating an alternating magnetic field and a receiver coil, R. The coils are separated by a distance,  $d$ , measured along their midline,  $m$ . Lines of magnetic flux are indicated by the dashed line labeled  $\Phi$ .

flux, indicated schematically by a dashed line labeled  $\Phi$ , are parallel to the coil axes. Assuming that the receiver coil is in the far field of the transmitter, the flux density is inversely proportional to the cube of the distance from the transmitter. The alternating magnetic field passing through the receiver coil will induce within it an alternating signal at a level proportional to the flux linkage, which is proportional to the effective cross-sectional area of the receiver coil and the flux density. With parallel orientation of transmitter and receiver axes, the level of the signal induced in the receiver gives a measure of the distance,  $d$ , between the transmitter and receiver.

Figure 2-2 shows a schematic diagram of the system, which was originally based on the design of van der Giet (1977). Two transmitter coils are mounted above and behind the head, with their axes parallel to one another and perpendicular to the midsagittal plane, i.e., the plane of the figure. Each transmitter coil is driven at a different frequency. Small receiver coils are

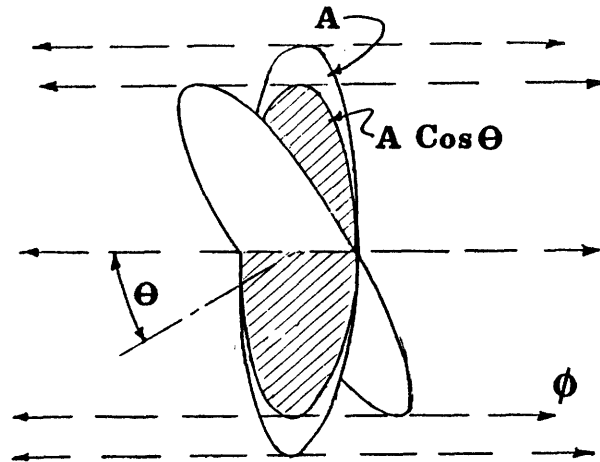


**Figure 2-2:**

A schematic diagram of an alternating magnetic field movement transducer system.

mounted with the same orientation, straddling the midline of the articulatory surfaces. Fine, twisted lead wires (brought out of the corner of the mouth) are connected to receiver electronics. The signal induced in each receiver coil consists of the sum of two sinusoids. It is processed to produce slowly-varying signals with levels that are functions of distances between the receiver coil and transmitters. The structures of the head are effectively transparent to the magnetic fields and do not influence the flux linkage and levels of induced signals. Receiver coil locations in the midsagittal plane can be calculated by triangulation.

In previous work with an early version of the system, it was determined that when a receiver coil is attached to the surface of an articulator, parallel alignment of the receiver coil and transmitter axes cannot be assured because of deformations of articulators when they move (Perkell and Oka, 1980; van der Giet, 1977). Figure 2-3 shows an expanded view of a single winding of a receiver coil, illustrating that if the axis of this coil "tilts" with respect to the direction of lines of magnetic flux, the projected area of the receiver coil is reduced by the cosine



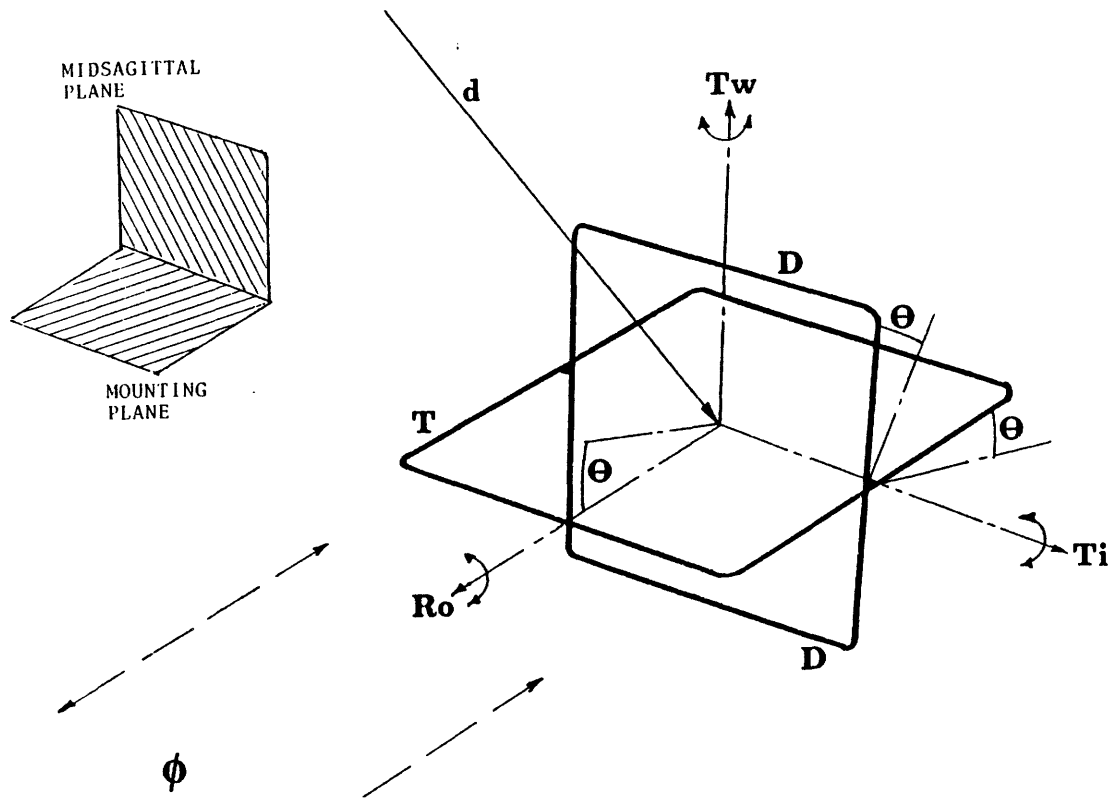
**Figure 2-3:**

A schematic diagram of a winding of a receiver coil, illustrating the decrease in projected area as a result of receiver tilt.

of the tilt angle,  $\theta$ . Thus, the result of tilt is a decrease in the flux linkage and level of the induced signal by a factor of cosine  $\theta$ , and the measured distance from the transmitter is artificially greater than the actual distance.

## 2.2. A tilt-compensating biaxial transducer

Van der Giet's (1977) suggestion of the use of an additional orthogonal field to detect and correct for tilt was explored (Cuevas, 1980), with the conclusion that it would be difficult to control (for) the resulting complex field geometry. As an alternative solution, a biaxial transducer was devised to compensate for tilt; its design is illustrated schematically in Fig. 2-4. The transducer consists of two concentric, orthogonal receiver-coil windings. The inner winding, labeled D, for distance detection, has its axis, labeled  $R_0$ , parallel to the lines of flux and perpendicular to the midsagittal plane. The outer winding, labeled T, for tilt detection, has its axis, labeled  $T_w$ , in the midsagittal plane, perpendicular to the lines of flux. The distance from the transmitter coil in the midsagittal plane is indicated by the vector labeled  $d$ . The transducer



**Figure 2-4:**

A schematic diagram of a tilt-compensating biaxial transducer. See text for details.

is attached to the articulator surface with the axis  $R_o$  parallel to the transmitter axes and lines of flux,  $\Phi$ . Because the transmitter is attached to the articulator surface, it cannot "twist" (rotate in the plane of attachment) around the axis labeled  $T_w$ . Therefore, without left-to-right turning or twisting movements of the articulators, the only rotational movement which will affect the output of the D winding is tilt, indicated by the angle  $\Theta$ , and reflected in decreased output of the D winding and increased output of the T winding.

Under ideal conditions, namely, identical cross-sectional areas of the D and T windings, absolute perpendicularity of the D and T windings and virtually no "twist", the distance,  $d$ , can be determined independent of tilt according to the following relationships.

$$V_D = \frac{K}{d^p} \cos \theta \quad (1)$$

$$V_T = \frac{K}{d^p} \sin \theta \quad (2)$$

$$\sqrt{V_D^2 + V_T^2} = \frac{K}{d^p} \sqrt{\cos^2 \theta + \sin^2 \theta} = \frac{K}{d^p} \quad (3)$$

Where

$V_D$  = voltage induced in the translation winding

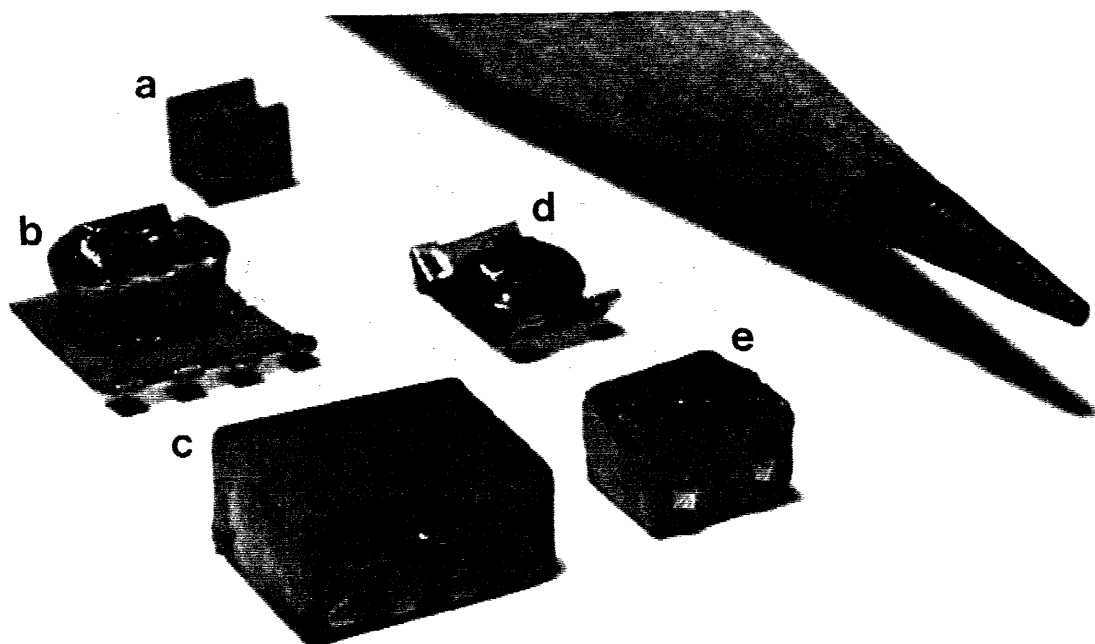
$V_T$  = voltage induced in the tilt winding

$K$  = the "field strength constant"

$d$  = distance between transducer and transmitter

$p$  = exponent describing decrease of field strength with distance

$\theta$  = the angle of tilt



**Figure 2-5:**

Biaxial transducers: (a) an H-shaped ferrite core piece, (b) the initial, larger version, (c) the initial version encased in epoxy, (d) the second, smaller version, (e) the smaller version encased in epoxy.

Biaxial transducers were manufactured according to the design illustrated in Fig. 2-4.<sup>2</sup> Figure 2-5 shows the first and second generation versions of these transducers. They are made from a

<sup>2</sup>Biaxial transducers are custom manufactured by Piconics, Inc., Tyngsboro, Mass.

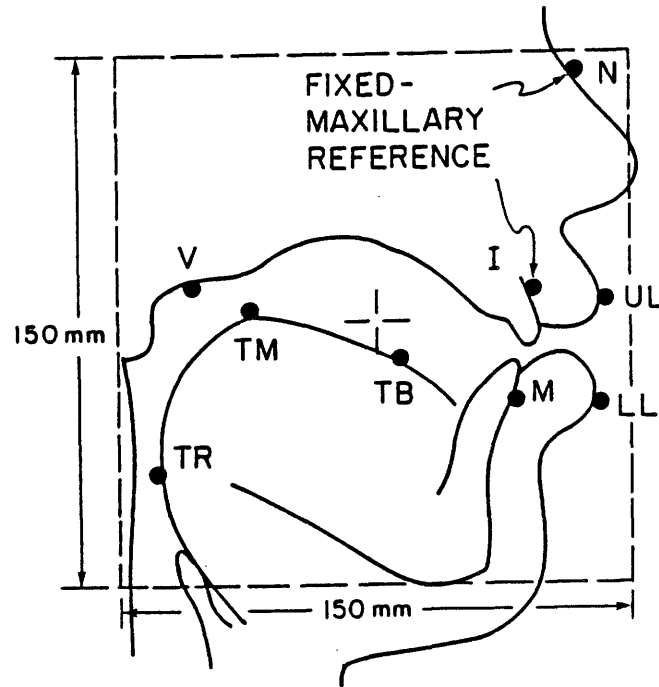
cube-shaped ferrite core piece cut into the shape of an H (a), with the two slots of the H containing the inner, distance-detecting winding (D in Fig. 2-4). The first, larger version is shown on the left (b). Initial testing demonstrated the usefulness of this transducer for making tilt-independent distance measurements with an accuracy of .5 mm. over a distance of 11-17 cm. (Perkell, 1982); however, its size, when encased in epoxy (c), would have made it interfere with articulatory movements. A second, smaller version was manufactured (d). When it is encapsulated (e), it is about 4 mm. square by 2.5 mm. high, a size that interferes minimally with speech articulations. For connection to receiver electronics, fine twisted lead wires are attached to soldering tabs, and the transducer is covered with insulating dope. Lead wires from intraoral transducers are brought out of the corner of the mouth.

### 3. System Design

The design of the final system is based on the properties of the smaller biaxial transducer and a number of other considerations. Figure 3-1 is a schematic midsagittal view of a subject with transducer locations indicated by filled circles. As illustrated in the figure, the system is designed to track the movements of as many as 9 points at once.<sup>3</sup> Transducers are attached with adhesive to fixed points on the bridge of the nose (N) and the upper central incisors (I) for a maxillary frame of reference, and movable points on the the mandible (M), lips (UL,LL); tongue (TB,TM,TR) and velum (V). A possible alternative velar placement is accomplished by attaching a transducer to a mylar strip and inserting it through the nose, so it rests on the dorsal surface of the velum. The area to be covered is from the rear wall of the pharynx to the anterior-most excursion of the lips, horizontally, and from the bridge of the nose to the base of the tongue, vertically. For a subject with a large vocal tract, an effective measurement area of 150 mm. square covers these structures.

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<sup>3</sup>The actual limitation on the number of transducers is a practical one, determined by the number of channels of receiver electronics, recording channel capacity and the number of transducers with accompanying lead wires that can be attached to and tolerated by the subject.



**Figure 3-1:**

A schematic midsagittal view of a subject with example transducer locations indicated by filled circles. See text for details.

The desired resolution is determined approximately by the smallest dorsal-ventral tongue displacement at the place of maximal constriction for the vowel /i/ that could produce a perceptually-significant change in the acoustics. On this basis a design goal was set for a resolution and repeatability of measurements of better than .5 mm. Because some transducers, such as the ones on the upper lip and upper incisors could come within 1 cm. of one another, it is necessary to avoid distortion of measurements which could result from interactions between adjacent transducers. This requirement dictates that transducers do not resonate, possibly generating large enough local currents (and therefore fields) to make them interact with one another.<sup>4</sup> Without the gain advantage of resonating the transducer windings, field strengths must be relatively high, about 1 gauss peak, to obtain a sufficiently strong induced signal. Frequencies around 60 kHz. were chosen to make possible simultaneous, interference-free measurements of lower bandwidth physiological signals such as EMG.

<sup>4</sup>Also see Appendix I.



### 3.1. Biological effects of the magnetic fields

According to existing literature and experts on the biological effects of non-ionizing radiation, there are no data on such effects in the ranges of frequency and field strength of this design (Gandhi, 1980; Sheppard and Eisenbud, 1977; Taylor and Cheung, 1977; also, see Acknowledgements). Researchers have used similar fields with strengths around 1 gauss peak for a number of years to measure eye rotational movements in human and non-human primates (cf. Robinson, 1963, 1981). Apparently there have been no observations of any biological or physiological effects of these fields, and the technique is now used clinically for the evaluation of ocular motility. On these bases an upper limit of 1 gauss peak for field strength in any part of the head was established.

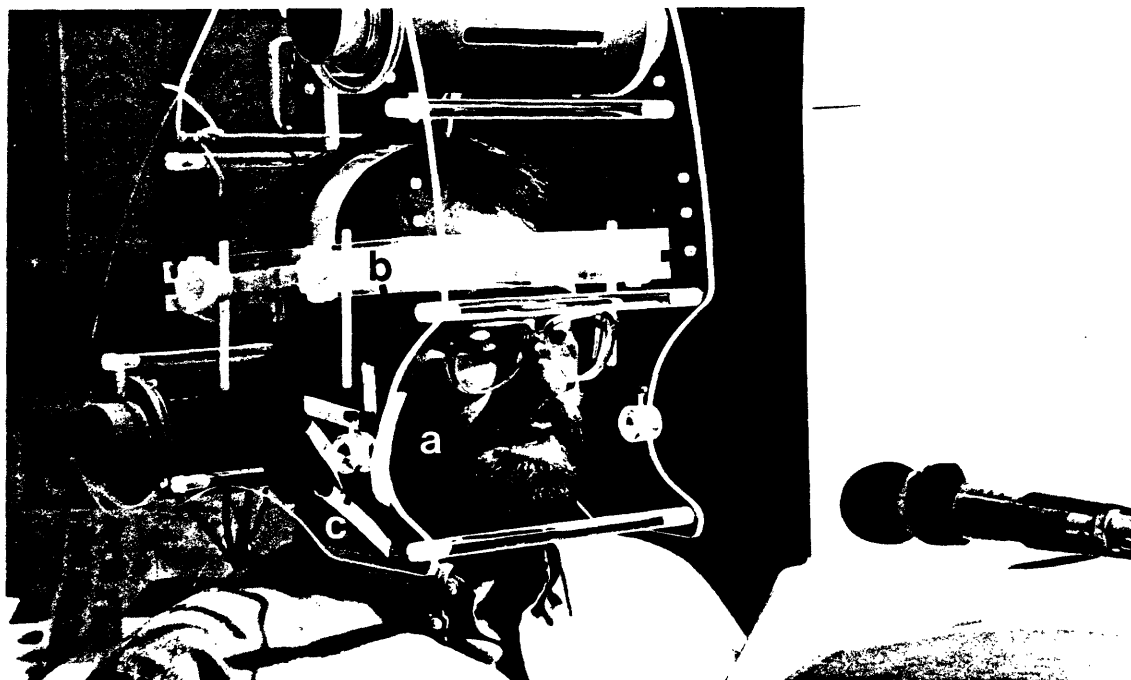
### 3.2. Determination of bandwidth and physical dimensions

Most supra-glottal speech movements that are generated by muscle contractions have very low bandwidths, i.e., below 15 Hz. (cf. Nelson, 1977; Muller and McLeod, 1982). Exceptions to this rule are moderately fast raising and lowering movements of the tongue tip (with velocities in the range of 80 cm./sec. - cf. Perkell, 1969) and much faster, aerodynamically-influenced movements such as those accompanying separation of the lips in release of a plosive, bilabial stop (cf. Fujimura, 1961). Thus, to capture all supraglottal movements, the bandwidth of the system should range from DC up to about 500 Hz. However, a number of additional factors place demands on the design of the electronics. These factors include: practical limits on performance (signal to noise ratios, stability) of electronic components and circuits, resolution of the recording device (limited by a 12 bit A/D converter), desired spatial resolution (.5 mm. in 150 mm.), a field strength that is decreasing by a factor of  $1/d^3$ , the level of field strength needed to induce an adequate signal in the transducer, maximum field strength permitted by human subject considerations (above) and the range of physical dimensions of different-sized subjects.

The bandwidth limitation is imposed by low-pass filtering in the output stage of the receiver

electronics. When all of the above factors were taken into account, a low-pass cutoff frequency of 100 Hz. (with a moderate roll-off rate of 18 db./octave) was chosen as a compromise which should capture all but the fastest, aerodynamically-influenced speech movements.<sup>5</sup> The same factors were also taken into account in establishing the distances between transmitter centers and the center of the measurement area at 275 mm.

#### 4. System Description and Operation



**Figure 4-1:**

The transmitter assembly in place on a subject.

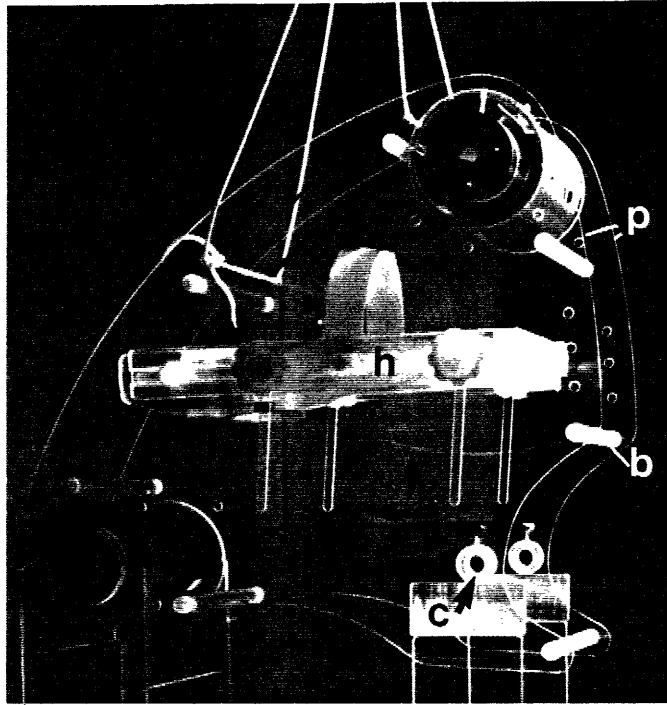
From the preceding design considerations, a system was built that consists of a transmitter assembly and headmount, transmitter and receiver electronics, and mechanical components for: calibrating the magnetic fields and individual transducers, and mounting transducers on articulatory structures.<sup>6</sup> In order to avoid any possible interference with the magnetic fields,

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<sup>5</sup>Exploratory work on higher bandwidth receiver electronics is in progress.

<sup>6</sup>Overall system design and construction of electronics components is by P.V.I., Inc., Boston, Mass., and design and construction of mechanical components is by I. Garabieta, Lexington, Mass.

most mechanical components are made from non-ferrous materials (plastics). The transmitter assembly is shown in place on a subject in Fig. 4-1. It is rather cumbersome, so it is normally suspended from the ceiling on a counterbalanced pulley system.



**Figure 4-2:**  
The transmitter assembly. See text for details.

Figure 4-2 shows the transmitter assembly more closely. Each transmitter (55 mm. in diameter) consists of concentric primary and secondary windings. The primary winding is driven by a 100 watt audio power amplifier (Crown, Model DC-300A Series II). Oscillators with feedback provide the input to the power amplifier and maintain constant amplitude and frequency of the transmitted field. The secondary winding is a high Q, resonant LC circuit (with the capacitor suspended within the air core of the winding). The transmitters are driven at their resonant frequencies, 58 and 63 kHz. The transmitters are held in a transmitter assembly consisting of two side plates (p) connected by spacing bars (b). The headmount (h) fits precisely between the side plates of the transmitter assembly. It is attached to the transmitter assembly

side plates in a way which allows for appropriate positioning of the effective measurement area with respect to individual subjects, and it adjusts to fit different sized heads. The center of the measurement area at the circular collar (c) is positioned over the cheek. The two transmitters and center of the measurement form a right triangle with 275 mm. distances between each transmitter center and the measurement area center and 389 mm. between transmitter centers. Arcs are inscribed on the side plates to show the partial outline of the measurement area ((a) in Figs. 4-1 and 4-2).

A separate channel of receiver electronics is needed for each transducer winding. Each receiver circuit performs amplification and synchronous demodulation, followed by low-pass filtering at 100 Hz. The result of this processing is two slowly-varying signals, one corresponding to the voltage induced by each transmitted field. (Appendix I contains a description of the theory of operation of the transmitter and receiver electronics, and Appendix II describes electrical safety considerations.) A pair of receiver circuits (one for each winding) for each biaxial transducer is contained on a separate PC board. The two windings of each transducer are connected via isolation transformers to the two circuits on a receiver board by very fine 4-conductor lead wires (consisting of 2 twisted pairs of .002" insulated magnet wire which are in turn twisted together<sup>7</sup>). Thus, each receiver board produces 4 slowly-varying output voltages that correspond to signals induced in a transducer, one output from each transducer winding, for each transmitted frequency. Receiver boards are mounted in cases that fit into a standard 19 inch rack card-cage assembly. The card cage is positioned so as not to influence the fields, while being near enough to the subject to allow for connection to transducers with lead wires about 1 meter long.

Because of small variations in characteristics of individual transducers, it is necessary to

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<sup>7</sup>Connecting wire is manufactured by California Fine Wire, Inc., Grover City, Calif.

control for individual channel gains through the system. This control is more effectively and reliably accomplished by using calibration data and gain compensation in software, rather than attempting to do so in hardware. Procedures for determining the gains are described in Sections 5 and 7, and in Appendix III.

With a maximum of 9 transducers, 36 output voltages must be recorded. For this reason, and to avoid inaccuracies introduced by an intermediate analog recording, output voltages are digitized directly, along with the acoustic and other physiological signals. Data processing algorithms are implemented using the MITSYN signal processing utilities (Henke and Perkell, 1982). The data processing consists of 5 main steps.<sup>8</sup>

- (1) Channel gains are equalized.
- (2) Signals from the two transducer windings are combined to correct for tilt.
- (3) The voltage signals are converted to distances from the transmitters using individual calibration factors.
- (4) Radial distances from the transmitters are converted to Cartesian coordinates by triangulation.
- (5) Coordinates are converted to the maxillary frame of reference by translation and rotation to a system defined by the fixed, recorded points on the upper incisors and bridge of the nose.

These steps are discussed in further detail in following sections.

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<sup>8</sup>The first three steps take into account factors which are specific to individual transducer windings, receiver channel gains and transmitters. These factors are described below in Section 5.

## 5. Evaluation of the System: Bench Tests

Several characteristics of the system were investigated:

(1) The magnetic field strength on an axis along its midline, perpendicular to the transmitter axis (m in Fig. 2-1), i.e., the voltage output versus distance characteristic for each transmitter.

(2) Properties of the biaxial transducers.

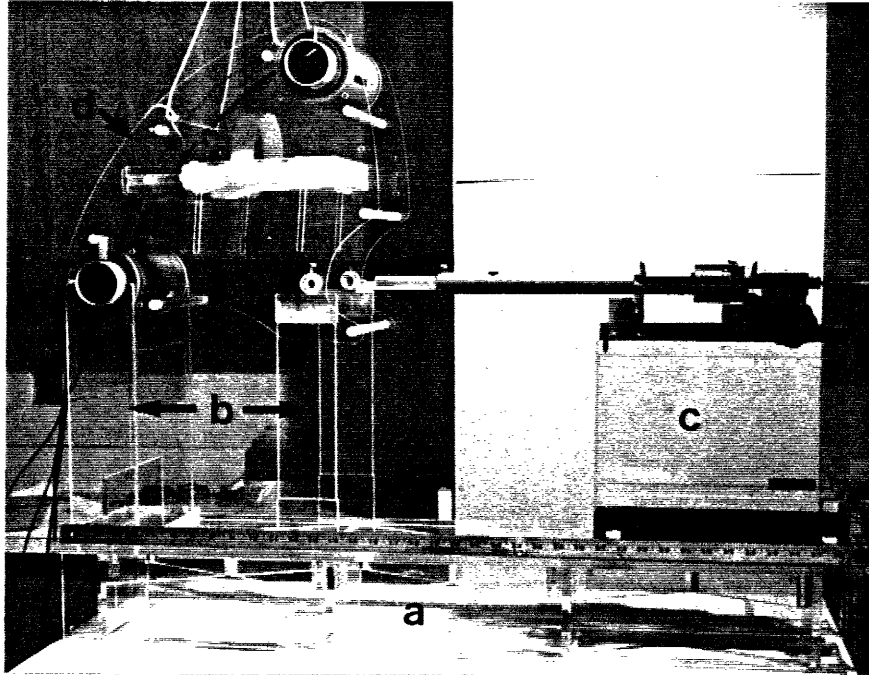
(3) The repeatability and resolution of the displacement measurement with arbitrary amounts of transducer tilt.

(4) The effects on measurement repeatability and resolution of: a) limited amounts of transducer "twist" in the plane of attachment to an articulatory structure, b) off-midsagittal plane transducer placement, c) close proximity of two transducers, d) the presence of amalgam dental fillings in the field and e) the presence of fine-wire EMG (electromyographic) electrodes in the field.

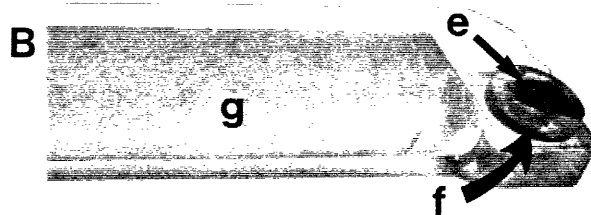
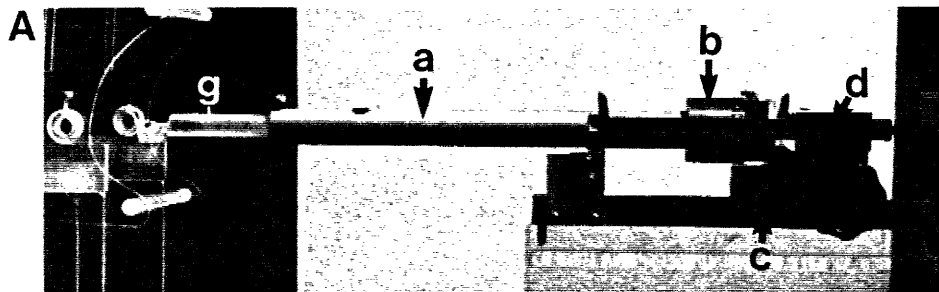
(5) The effect of the magnetic fields on EMG signals.

### 5.1. Testing Equipment and Procedures

An apparatus was constructed to calibrate the field in the measurement plane. It is shown in Fig. 5-1. It consists of a platform (a) on which are mounted a holding jig (b), on the left and a transducer positioning stage (c), on the right. The transmitter assembly (d) is placed in the holding jig which locates a transmitter in relation to the positioning stage. Either transmitter can be placed in this position by turning the transmitter assembly around. The positioning stage (Fig. 5-2) consists of several parts: a tubular cantilever beam (a), a rotation stage (b) in which the cantilever beam is mounted for tilting the transducer around its mid point, a rack and pinion (c) on which the rotation stage is mounted for translating the transducer, and a digital caliper

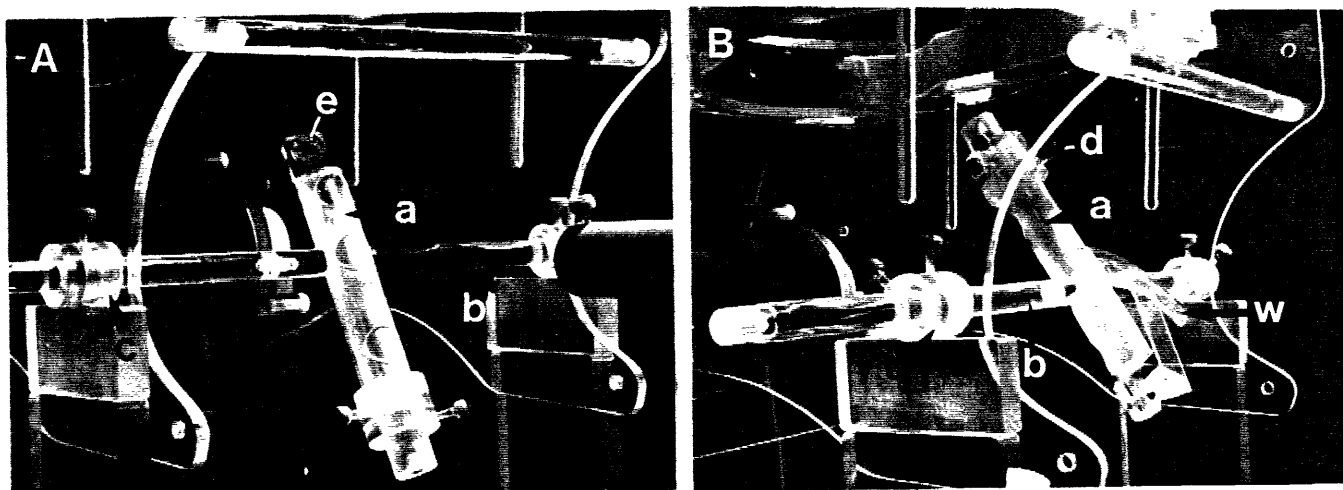


**Figure 5-1:**  
The field calibration apparatus. See text for details



**Figure 5-2:**  
A: The positioning stage. B: The transducer holding rod (g), mounting stage (f) and a transducer (e), mounted with dental impression material. See text for details.

(d) for measuring displacements. A transducer (e) is attached to a mounting stage (f) on the end of a plexiglass holding rod (g) which slides into the end of the cantilever beam. The mounting stage can be rotated to orient the transducer for maximum output from a winding (i.e., for zero "twist"). Using the rack and pinion, the transducer can be moved through a distance of 80 mm. on either side of the center of the effective measurement area. Translation of the transducer is precise, with a .01 mm. resolution on the digital readout of the caliper.



**Figure 5-3:**

Two views of the device for rotating the transducer through a circle in the measurement plane. A wrench (w) for "twisting" the mounting stage (and recording the angle of twist) is shown in view B. See text for further details.

It was decided that a rigorous test of the system's spatial linearity and repeatability is to rotate the transducer through several revolutions of a circle (in the measurement plane), and determine if, after processing, the output describes coincident circles. To test the adequacy of tilt correction, the output should remain unchanged when the transducer is then tilted through some angle and again rotated through the same circle. To perform this test, a device was designed for rotating the transducer through a circle of arbitrary radius at any desired tilt angle



in the measurement plane. The device is shown in Fig. 5-3. It consists of a tube (a) which is attached to an axle (b) that passes through the collars in the side plates (c) of the transmitter assembly at the center of the measurement area (perpendicular to the measurement plane). The transducer-holding rod (described above) is placed in the tube and held with a set screw (d). The holding rod can be turned in the tube (to set the degree of tilt) and slid along the length of the tube (to set the radius of the circle). In addition, the transducer mounting stage (e) is rotated (twisted) in the mounting plane so that the transducer is oriented with the axis of its distance-detecting winding perpendicular to the measurement plane (for maximum output - i.e, at zero "twist"). For these tests, it is necessary to mount the transducer as precisely as possible in the center of the mounting stage. This is done under a dissecting microscope using an elastic dental impression material (Impregum) as an adhesive.

## 5.2. Test results

**Field and transducer calibrations** Sixteen data points are collected at 10 mm. intervals in the desired measurement range (200 mm. to 350 mm. away from the transmitter). Voltage at each position is read by a 5 1/2 digit DVM. The sixteen voltages and distances form input data for a log-log regression to estimate the parameters p and K in the field calibration equation

$$V = K/d^p$$

where K represents the "field strength constant" and p describes how rapidly the field intensity drops off with distance, d. A typical value for p is 2.95 with a range of +/- .04. Correlation coefficients for the regression are typically above 0.99, indicating that the estimate for p is essentially constant over the measurement range. The fact that the exponent is slightly less than 3.0 indicates that the measurement range is in the transition region between the near and far-field regions of the transmitters and is dominated by the far field (Kraus, 1953). For each transducer-receiver circuit combination, a field calibration is obtained for the D winding, with

respect to each of the two transmitters, giving two sets of values of  $K$  and  $p$ .<sup>9</sup> Because of slight variations of  $K$  and  $p$  from one calibration to the next, the current mode of operation is to perform individual calibrations for each transducer-receiver circuit combination, to ensure maximum accuracy of measurements.<sup>10</sup>

While performing the field calibration, it is not possible to know the absolute location of the receiver with respect to the transmitter.<sup>11</sup> The data gathered for the regression are therefore relative rather than absolute. This is reflected in the fact that the field strength constant,  $K$ , must be adjusted subsequently to make the field calibration reflect the absolute distance between transmitter and transducer. (See Section 7 and Appendix III.)

**Perpendicularity of transducer windings** The transducers are extremely intricate and in manufacture it is not possible to ensure that the translation and tilt windings are precisely perpendicular. In order to correct for transducer tilt, it is necessary to know the degree to which the two windings are effectively out of perpendicular with respect to one another. To make this determination, the cantilever beam which holds the transducer can be rotated through an arbitrary angle (to "tilt" the transducer). The angle of rotation can be read off the vernier of the rotation stage which has a resolution of 12 minutes. The effective angle between the two windings is determined by the difference between readings off the vernier at which there is zero voltage induced in each winding of the transducer. The lack of perpendicularity of tilt and translation windings, i.e., the angle  $\Delta$ , ranges from 0 to 3 degrees.

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<sup>9</sup>Because of the nature of the equations (1-3) above, the exponent,  $p$ , must be the same for the D and T field calibrations. Furthermore, only small amounts of tilt are expected, making the magnitude of  $V_D$  much greater than that of  $V_T$ . Therefore, the exponent,  $p$ , in equation (2) is constrained to be the same as that in equation (1), and only the D winding is calibrated.

<sup>10</sup>Additional testing may indicate that it is sufficient to use standard values of  $p$  and  $K$ .

<sup>11</sup>The transducers are potted in epoxy, with the result that their exact orientation and positioning within the epoxy is not observable and not the same from one transducer to the next. Therefore, it is impossible to determine the precise location of the geometric and/or magnetic center of a transducer. In addition, for reasons discussed in Section 6, the effective centers of the transmitters are not exactly at their geometric centers.

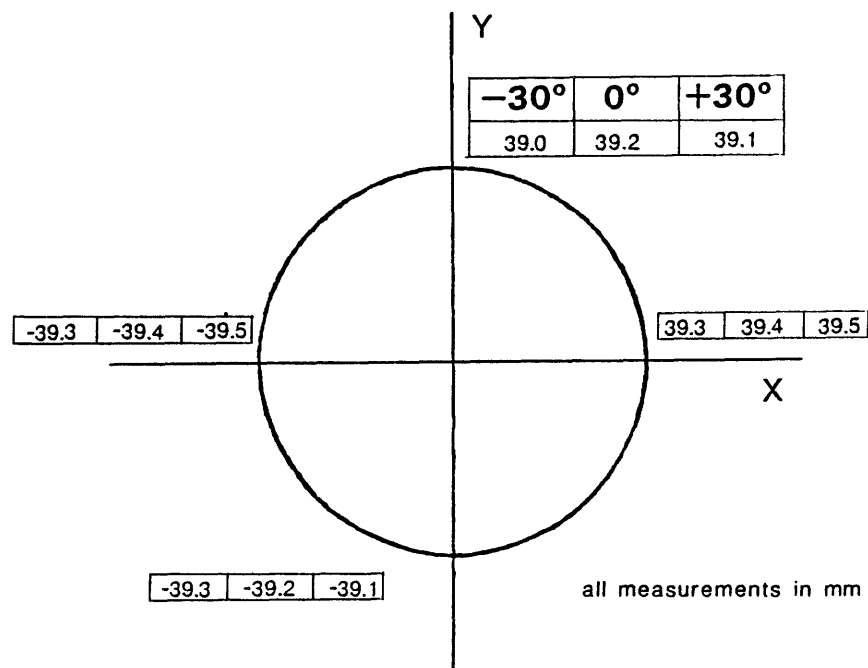
**Measurement accuracy** The accuracy of the system in measuring absolute displacement is determined by:

- The resolving power of the A/D converter (12 bits). The least significant bit (lsb) corresponds to 2.4 mV. at the input to the A/D converter. At 350 mm. from the transmitter, a change in the lsb corresponds to a 0.25 mm. change in displacement.
- The "goodness of fit" of the field calibration equation to the calibration data.
- The amount of twist of the transducer. The voltage induced in the transducer decreases as the cosine of the angle of twist. Whereas tilt is compensated for by using the bi-axial transducer, twist must be controlled for. During field calibration, twist is set at zero by rotating the transducer mounting stage to achieve maximum output. The gain factors for each channel assume no twist. Therefore, zero twist is preserved when mounting a transducer on an articulator.

Absolute accuracy was tested by translating a transducer through a known linear distance (read off the digital caliper of the translation stage - Fig. 5-2). In this test, accuracy (transduced distance/known distance) is .9875 (19.75/20mm.). The system is intended to transduce relative, rather than absolute displacements; therefore, this degree of absolute spatial accuracy is more than adequate.

The **signal-to-noise ratio** of digitized signals (determined in DFT spectra) is about 60 dB.

## Measurement reproducibility and spatial distortion



**Figure 5-4:**

The computer output resulting from a test in which a transducer is rotated through several circles of the same radius in the measurement plane, with different amounts of transducer tilt.

Figure 5-4 shows the the result of a test in which the transducer is rotated through a circle in the measurement plane. The output is copied from the storage scope of the computer which is used for data processing. The horizontal and vertical axes correspond to lines drawn from the two transmitters through the center of the measurement area. The figure shows the result of 3 test conditions. The transducer was rotated through several revolutions at a fixed radius, first with 0 degrees of tilt, and then with -30 and +30 degrees of tilt. The resulting circles are coincident. The values of the radius (in mm.) as the circle crosses each axis for the three test conditions (0, +30, -30 degrees) are given in the figure. At an angle of tilt (of +/- 30 degrees) which may be considered to be extremely severe, the system maintains repeatability to within .25 mm. The standard deviation of the means of radii for multiple revolutions at a fixed tilt angle did not exceed 0.1 mm. These results indicate that resolution is limited by the A/D converter (.25 mm.).

When the same circles were plotted over themselves with 90 degrees rotation, they were coincident, indicating virtually no spatial distortion (i.e., good spatial linearity) in the plane of measurement.

### **Effect of transducer mounting inaccuracies**

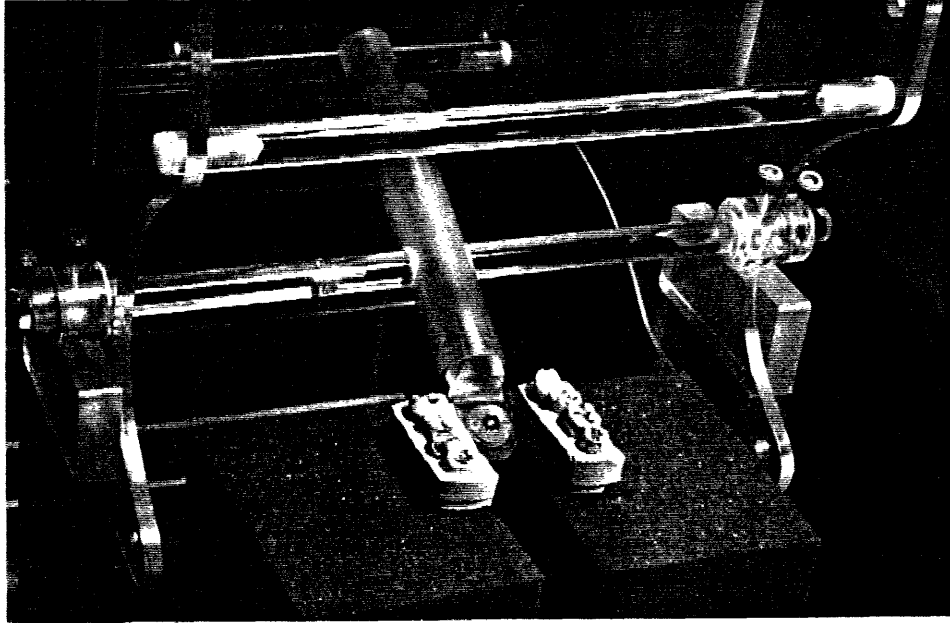
The same type of test was performed, but with the addition of +/- 5 degrees of **twist**. This amount of twist is assumed to be greater than would result from a large amount of inaccuracy in attaching transducers to subjects (with the device described below in Section 7), in combination with (presumably) negligible twisting movements of articulators. At this amount of twist, combined with 10 degrees of tilt, there was an absolute displacement error of approximately +/- .5 mm. at a circle radius of 30 mm.

Because of expected, slight lateral misalignments in mounting the transmitter assembly on subjects heads and mounting transducers on articulators, the effect of a reasonable amount of **off-midsagittal plane transducer placement** was explored. The circle drawing apparatus was moved sideways + and - 10 mm. and then + and - 5 mm. away from the center. Compared to the circles drawn on the midsagittal plane, a circle radius of 45 mm. changed by 0.5 mm. for the +/- 10 mm. off midsagittal shift, and was unchanged for the +/- 5 mm. off midsagittal shift.

While a small amount of inaccuracy of absolute distance measurement results from mounting inaccuracies, there should be negligible effects on relative measurements during an experiment.

**Interactions between transducers** To test for interactions between transducers, one transducer was held stationary, while a second transducer was moved as close as 8 mm. to the first. There was no change in transduced coordinates of the first transducer under this condition.

## Effects of objects in the field



**Figure 5-5:**

Illustration of a test in which extracted teeth containing large dental fillings are placed on either side of a transducer as it is rotated through a circle.

The same apparatus was used to investigate the effect of **dental fillings** on the measurements. Figure 5-5 shows extracted teeth containing large amalgam dental fillings mounted in dental cement and placed 25 mm. on either side of the transducer. When the transducer was rotated through several circles, no difference in transduced position could be detected with and without dental fillings.

The effect of the presence of a **fine-wire EMG electrode** was explored. A fine-wire electrode was inserted into a thumb muscle of one hand of a subject and the electrode was connected to an amplifier. One hand, and then the other was placed in the measurement area, adjacent to a stationary transducer. There was no difference in the output from the transducer in the presence of the "inserted" versus the uninserted hand.

**Effect on EMG signals** The thumb-muscle EMG signal was examined on an oscilloscope

while the inserted hand was held in the measurement area, adjacent to a transducer. The EMG signal was amplified and band-pass filtered between 10 Hz. and 1 kHz. When the movement transducer system was turned on and off, there was no observable difference in the EMG signal.

### 5.3. Summary of bench test results

The system makes high-quality measurements of transducer displacements with more than adequate accuracy, resolution and repeatability. It achieves this performance with angles of transducer tilt of up to 30 degrees; proximity of another transducer of 8 mm.; and in the presence of dental fillings and bipolar fine-wire EMG electrodes (without interfering with EMG signals). If a transducer is mounted on an articulatory surface up to 10 mm. lateral to the midsagittal plane, and/or with some small amount of twist (assuming that articulatory movements do not produce significant additional twist), there can be small errors of absolute displacement. For relative and repeated measures in experiments on speech articulatory movements, the effects of such errors are negligible.

### 5.4. Disadvantages of the system

The bench testing revealed several shortcomings of the system.

1. The intricate nature of the windings of the transducer result in the distance and tilt-detecting windings not being precisely perpendicular. The angle by which they are not perpendicular is important for the accuracy of tilt correction. Measurement of the angle and applying it to the tilt-correction algorithm is somewhat time consuming.
2. The orientation (angle of "twist" in the mounting plane) of the transducer relative to the transmitters during calibration must be maintained when attaching the transducer to articulatory structures. Failure to do this results in inaccuracy in measures of absolute displacement but not relative displacement (as long as there are no significant "twisting" movements of the articulators).
3. Several factors associated with each transducer must be individually determined: field exponent, gain equalization factors and lack of perpendicularity of the the distance and tilt-detecting windings.

## 6. A three-transmitter system

A three transmitter system (Schonle, et. al., 1983) has been designed which should theoretically overcome the above disadvantages. The three transmitters are driven at three different frequencies, and single axis transducers are used. The transmitters are positioned at the vertices of an equilateral triangle. As a transducer tilts, the voltage induced by each transmitter is reduced by a common factor (cosine of the tilt angle). The transmitters appear to move away from the transducer, but the ratio of the correct distance to the distance with tilt is equal for each transmitter-to-transducer distance, independent of the amount of tilt. The position of a transducer within a coordinate system defined by the geometry of the transmitters can be solved for directly.

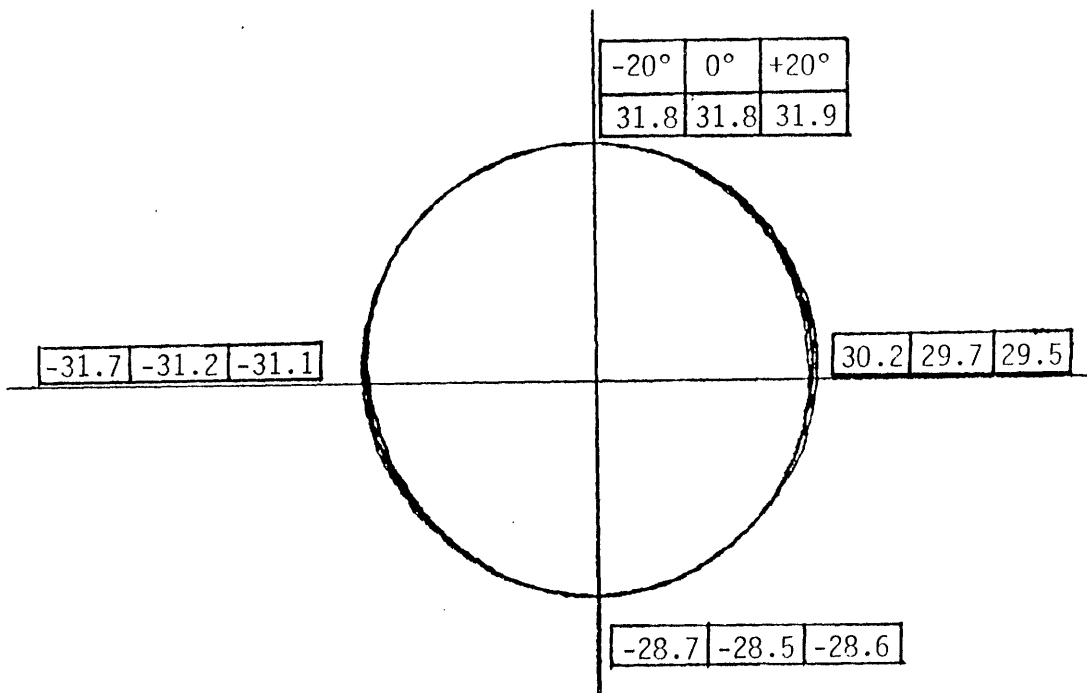


Figure 6-1:

An example of the best output that could be obtained with the three transmitter system in an attempt to reproduce circles of the same radius at three different degrees of transducer tilt (0, + and - 20 degrees).



Although none of the disadvantages of the 2-transmitter, biaxial-transducer system prohibit its use, the existence of an alternative that could significantly reduce them, at least theoretically, prompted the exploration of the three-transmitter design. A system was built after this design, using the same type of transmitters and receivers as the two-transmitter system. The distances between transmitter centers and center of the measurement area is 275 mm. This system was tested in the same manner as was the two-transmitter system, but it could not be made to correct for tilt in a satisfactory fashion, in spite of a considerable amount of effort. Figure 6-1 shows one of the best results which was obtained by rotating a transducer through a circle at three different tilt angles. Detailed exploration of the problem suggested that the lines of flux from the three transmitters are not absolutely parallel to one another in the measurement plane, and that the tilt-correction algorithm for the three transmitter system is extremely sensitive to this condition.

Consideration of the design of a transmitter reveals that the generated field could not possibly be symmetrical with respect to the physical axis of the transmitter. This is because the connections of the ends of the transmitter windings to the capacitor (to make an isolated, resonant LC circuit) forms a loop (inside the transmitter coil) with an axis that is perpendicular to the long axis of the transmitter. The geometry of the transmitted field is the result of a vector summation of the fields generated by the windings around the long axis and the one orthogonal loop. Although the same imperfections exist in the two-transmitter system, it was concluded that the nature of the two-transmitter/biaxial transducer design, along with individual transducer calibration compensates adequately for the asymmetry of the transmitted fields. A considerable amount of further work would be needed to make the three-transmitter system (designed and tested as described above) equal the performance of the two transmitter system.

The large size of the transmitters and their close proximity to the measurement area means that measurements are made in a region that is dominated by the "far field" but is somewhat influenced by the near field (Kraus, 1953). As mentioned above, this is reflected in the fact that the exponent which describes the decrease of field strength with distance is closer to 3.0 than 2.0. If it were possible to have smaller transmitters located further from the measurement area, the transmitters would effectively look like point sources from within the measurement area, and some of the problems associated with field geometry would be reduced. However, even in the far-field region, the tilt-correction algorithm for the three-transmitter system is sensitive to misalignment of transmitters and off-midsagittal plane transducer placement, because of curvature of lines of magnetic flux.

Further work on a three-transmitter system should include: 1) design and construction of transmitters which generate symmetrical fields, 2) design and construction of a device which would allow for the positioning (in 3 dimensions) and rotation (around 3 axes) of a probe coil with enough precision to accurately map out field geometry, 3) design and construction of a transmitter assembly which would permit precise adjustment of transmitter position and orientation, and 4) the use of these devices in testing system performance as described above. The approach should include increasing field strengths and receiver gains to allow the maximum possible distances between transmitters. This step should help to minimize the detrimental effects of radius of curvature of lines of magnetic flux on the effectiveness of the tilt-correcting algorithm.

## 7. Use of the two-transmitter system

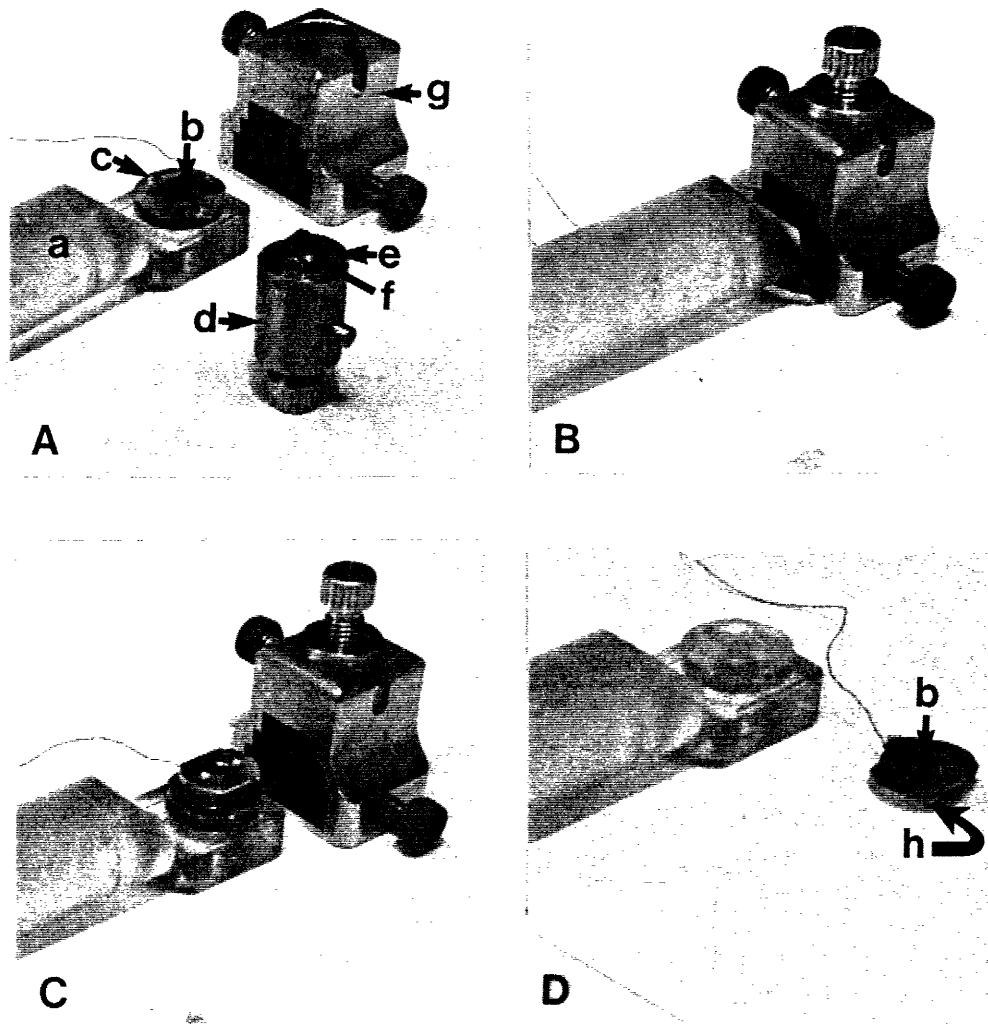
### 7.1. Set-up procedures

Procedures and additional hardware were devised to facilitate the use of the two-transmitter system. 1) Algorithms were developed to facilitate the a) determination of channel gain factor(s),  $G(s)$ , and b) refinement of transducer-specific values of the angle,  $\Delta$  (which describes the effective "lack of perpendicularity" of transducer windings). 2) A set of precision mechanical devices was designed and manufactured for mounting transducers on the subject with the same orientation in the mounting plane at which they were calibrated (i.e., with negligible "twist"). With these algorithms and devices (described below) and previously-described equipment and procedures, the following steps are taken in preparation for using the system on a subject.

(1) Individual transducer-specific field calibration values of  $K$  and  $p$  and initial estimates of  $\Delta$  are obtained, using the calibration stage and procedures as described above in Section 5.

(2) Calibration data are gathered for determination of each individual (transducer winding-receiver circuit) channel gain factor,  $G$ , and refinement of  $\Delta$ . As described above, a transducer is attached to the center of the transducer mounting stage with an elastic dental impression material (Impregum). The transducer holding rod is then placed in the tube of the circle-drawing apparatus and the mounting stage is twisted until the output of the translation-detecting winding is maximized. Then, the outputs are recorded while the transducer is rotated through circles at 3 different degrees of tilt (0, +/- 30 degrees - see Fig. 5-3). Appendix III describes the algorithm for the determination of  $G$ .

(3) The transducer-holding rod is removed from the tube and the end containing the transducer is placed in a jig (Fig. 7-1). A removable plunger (keyed to a slot) fits into the jig. A small, removable aluminum disk slides into the end of the plunger. The disk has two parallel edges

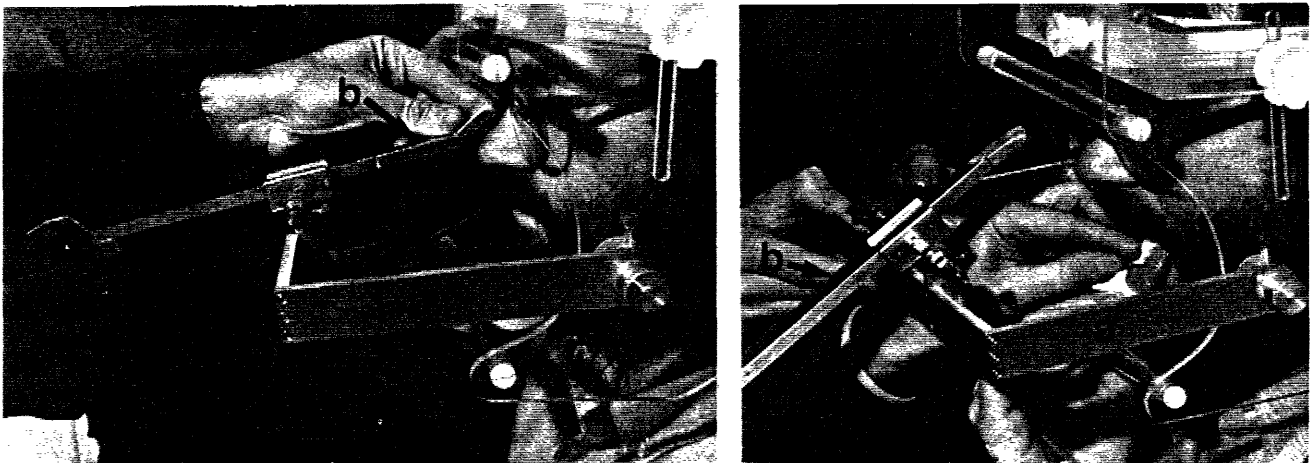


**Figure 7-1:**

Apparatus and steps for transferring a transducer from the calibration apparatus to a "holding disk" with preservation of "zero twist". A: The holding rod (a) with the transducer (b) mounted on the mounting stage (c). The plunger (d) with a disk (e) mounted on the end, containing dental impression material (f). The jig (g). B: The holding rod inserted into the jig with the plunger and disk in place while making an impression of the transducer. C: The holding rod removed from the jig, now with the disk attached by impression material to the transducer. D: The disk, holding the transducer in its impression (b) removed from the mounting stage of the holding rod. Note the registration groove on one of the two, parallel edges of the disk (h).

containing registration grooves, a round central depression and a smaller diameter central hole. The central depression is filled with dental impression material, and the plunger is lowered over the transducer, making an elastic transducer holder which is aligned mechanically with the measurement plane. When the impression material has set, the plunger is detached from the disk, and the transducer-holding rod (now with the disk attached to the transducer) is removed from the jig. The transducer can then be detached from the mounting stage and stored in its impression within the disk.

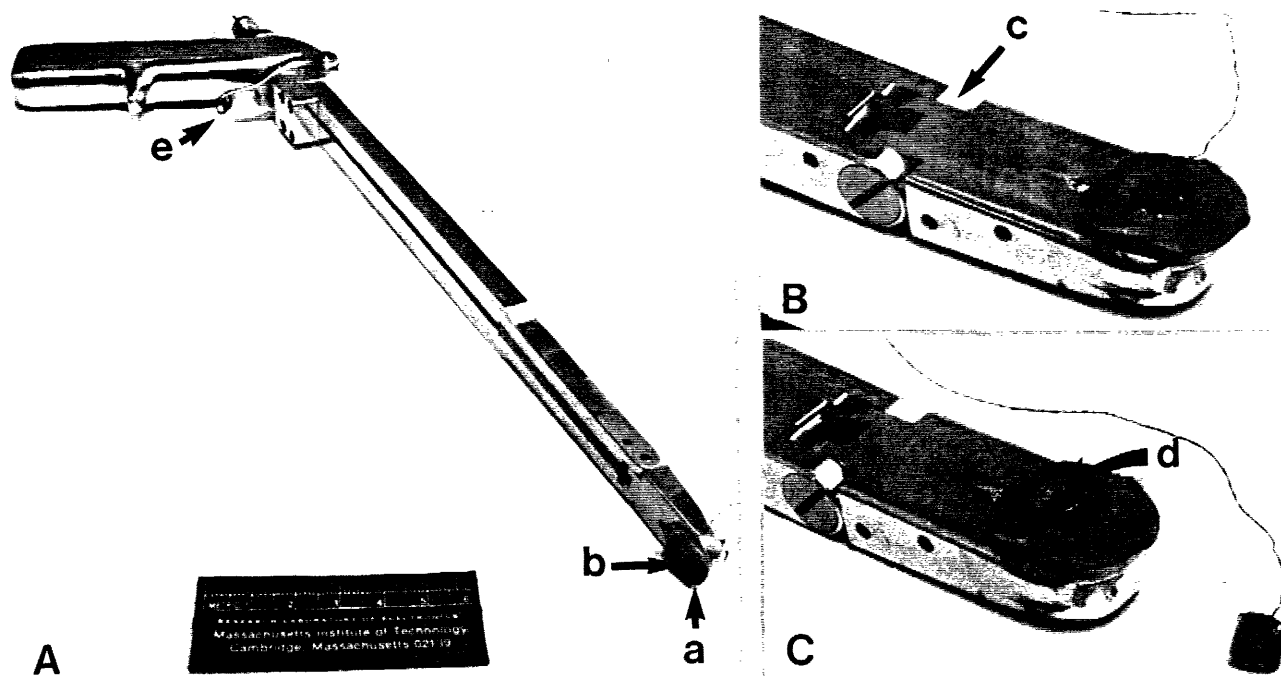
(4) The calibration and impression procedure is repeated for as many transducers as will be used in an experiment (with a separate disk for each transducer and each transducer connected to a specific card of receiver electronics).



**Figure 7-2:**

Two views of the registration bracket (a) containing the mounting forceps (b) in place on the transmitter assembly. See text for details.

(5) When transducers are to be placed on the subject, a registration bracket is fitted to the transmitter assembly (Fig. 7-2). To mount a transducer, its disk is placed in the end of a special mounting forceps (Fig. 7-3). The registration grooves in the disk fit precisely into two keyed slots in tip of the forceps to insure that alignment in the forceps is the same as when the

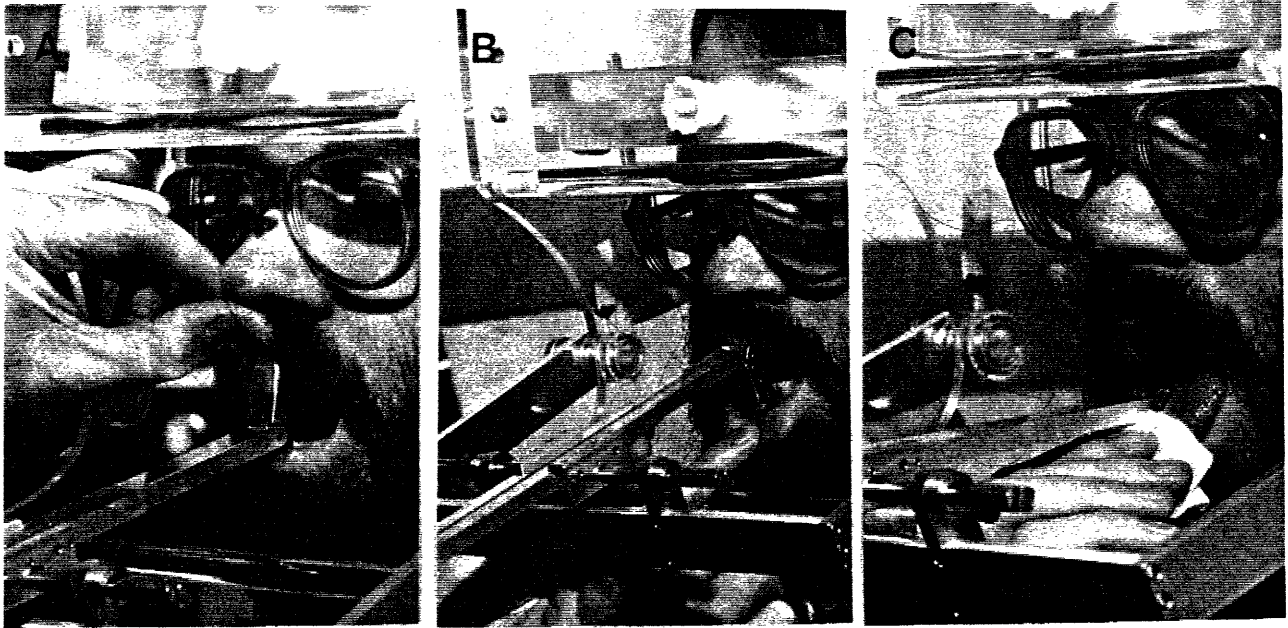


**Figure 7-3:**

The mounting forceps. A: the entire forceps. B: The tip of the forceps with a transducer-holding disk (a) and transducer (b) in place. The registration grooves of the disk assure correct alignment of the transducer with respect to the long axis of the forceps. Note the axis (c) around which the tip of the forceps can rotate. C: The plunger (d) activated by the trigger (A-e) which pushes the transducer out its impression once the mounting adhesive has set.

transducer was calibrated. The tip of the forceps can be swiveled (up or down) to help align the surface of the transducer with the articulator surface to which it will be attached (vertical for the incisors, horizontal for the tongue surface). The forceps is then placed in the registration bracket which holds the long axis of the forceps parallel to the measurement plane, while allowing for all other types of movement. (See Figs. 7-2 and 7-4.) This procedure ensures that the transducer is attached to the articulator with the same angle of twist as during calibration.

(6) Adhesive is placed on the transducer and it is pressed against the articulatory structure while the adhesive sets. Once the adhesive is set, a trigger is pulled on the forceps, causing a plunger to push (through the hole in the center of the disk) the transducer out of its impression,



**Figure 7-4:**

Placement of transducers on the upper incisors (A), lower incisors (B) and tongue (C).

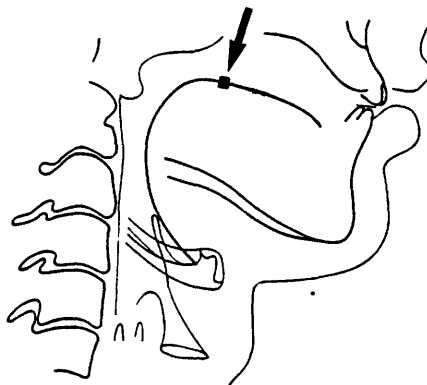
freeing it from the mounting forceps (Fig. 7-3.C). Figure 7-4 shows placement of the transducer on the upper incisors (A), lower incisors (B) and tongue (C).

(7) To help minimize interference of intraoral structures with connecting wires to transducers mounted on the tongue, the wires are given sufficient slack and brought around the back of the last upper molar tooth on one side. A thin, custom-made acrylic "wire guide" (held in place by an elastic ligature around a molar tooth) is used to hold the wires in place and bring them forward along the lateral aspect of the upper teeth to the corner of the mouth.

## **8. Trial experiments with a human subject**

In order to test the operation of the system with a subject, two experiments were performed.

### 8.1. Experiment 1



**Figure 8-1:**

A mid-sagittal schematic drawing indicating the approximate location of the transducer on the tongue surface in Experiment 1.

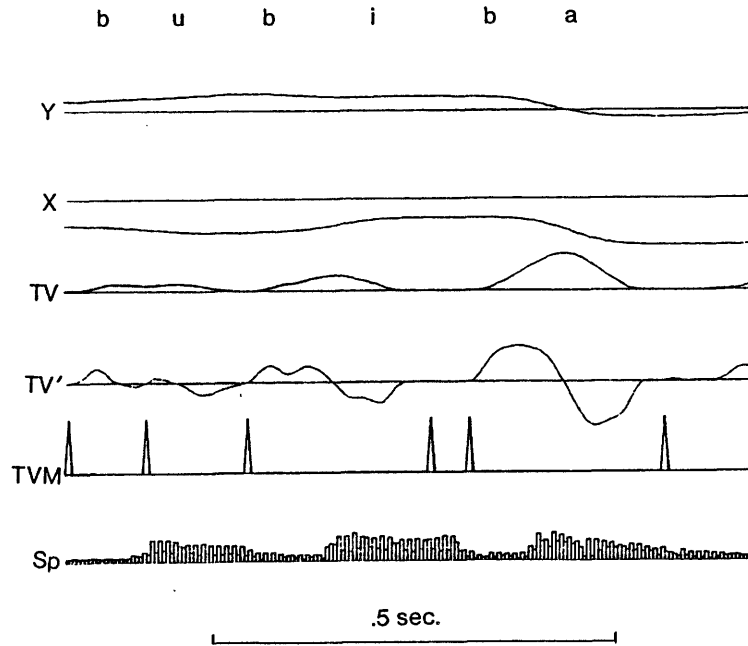
**Procedures.** The first experiment was designed after a vowel repetition study (Perkell and Nelson, 1985) which used data from the x-ray microbeam (Fujimura, et al., 1973). For this study, only one transducer was used, without the benefit of the mounting and alignment apparatus. The transducer was attached to the tongue body using Durelon (a dental cement) in a position shown approximately in Fig. 8-1. The subject read a list containing 100 repetitions of six 3-syllable nonsense utterances arranged in random order. The utterances are /babiba, babuba, bibuba, bibaba, bubiba, bubaba/, with stress placed on the second syllable. With only one transducer, the movements of the tongue body were measured relative to the transmitters and not to a maxillary frame of reference. The acoustic signal was digitized (at 8192 Hz.) simultaneously with the four voltage outputs (at 256 Hz.) from the receiver electronics. At the end of the experiment, a transducer (attached to a flexible plastic rod) was drawn along the hard palate to trace its outline.

Data processing consisted of:

1. Algorithmically identifying and labeling repetitions of each of the utterances from the acoustic signal.
2. Converting the recorded voltages to receiver-transmitter distances.

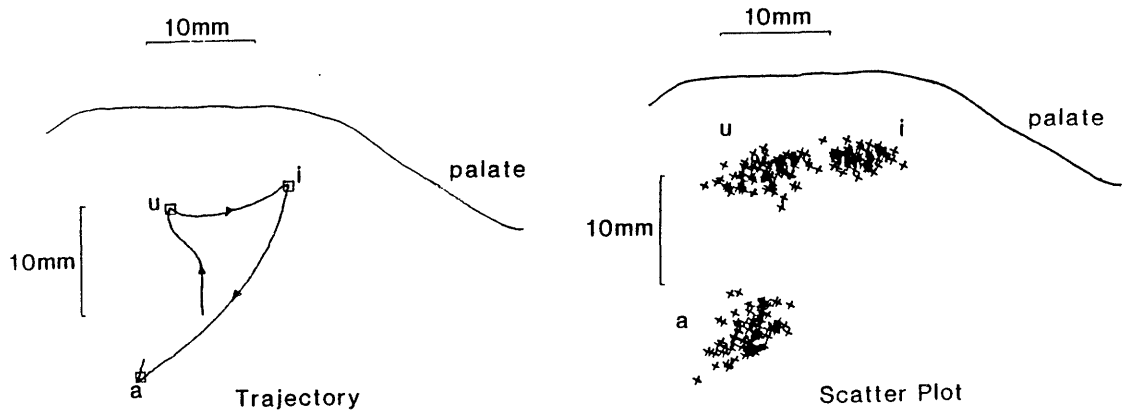


3. Converting distances to locations in Cartesian coordinates defined by the two transmitters in the midsagittal plane.
4. Automatically locating the target position (at time of zero tangential velocity) for the tongue point during each stressed vowel.



**Figure 8-2:**

An example of time signals for the utterance /bubiba/ resulting from Experiment 1. See text for details



**Figure 8-3:**

A: A midsagittal plane trajectory for the same example of the utterance /bubiba/ as in Fig. 8-2. B: a scatter plot showing "target" positions for a number of repetitions of the stressed vowels /i/, /u/ and /a/ from Experiment 1.

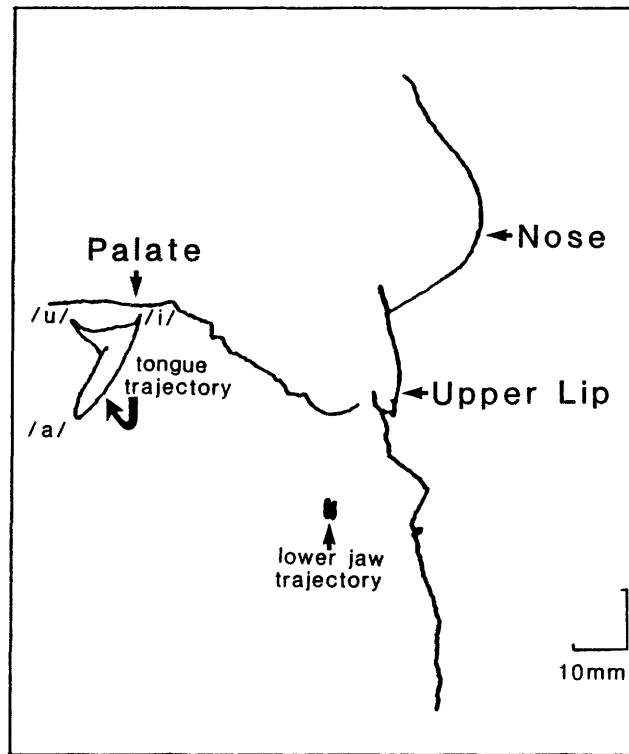
**Results.** Figure 8-2 shows an example of signals for one repetition of the utterance /bubiba/. The y and x coordinates of the point on the tongue, the tangential velocity (TV), the derivative of tangential velocity (TV'), times of zero tangential velocity (TVM) and the energy in the speech signal (Sp) are plotted as functions of time. Figure 8-3.A shows the trajectory of the point on the tongue during one repetition of the same example of /bubiba/. The boxes on the trajectory in part A show the algorithmically-identified target position (at times of zero tangential velocity) of the tongue for each vowel. Figure 8-3.B shows a scatter plot of targets for multiple repetitions of the stressed vowels in the corpus. In these figures, coordinates have not been converted to the maxillary frame of reference.

During the experiment, the value of transducer tilt (available in the processed data) did not exceed 3 degrees.

## 8.2. Experiment 2

**Procedures.** In the second experiment, the movements of 4 points were recorded, along with the acoustic signal. The points were on the bridge of the nose, the embrasure of the upper central incisors, the tongue body and the mandible (embrasure of the lower central incisors). (See Fig. 3-1.) The procedures and equipment described above were used for calibration and transducer placement (see preceding figures). Impregum proved effective for mounting transducers on relatively hard structures, and Durelon was used for attaching the tongue body transducer. The utterances were similar to those in the first experiment. As a control, the distance between the two fixed transducers (bridge-of-nose to upper incisors) was measured with a caliper. Signals were digitized as in Experiment 1.

Data were processed as in the first experiment, with the addition of correction to the maxillary frame of reference, and with manual instead of algorithmic identification and labeling of acoustic events.

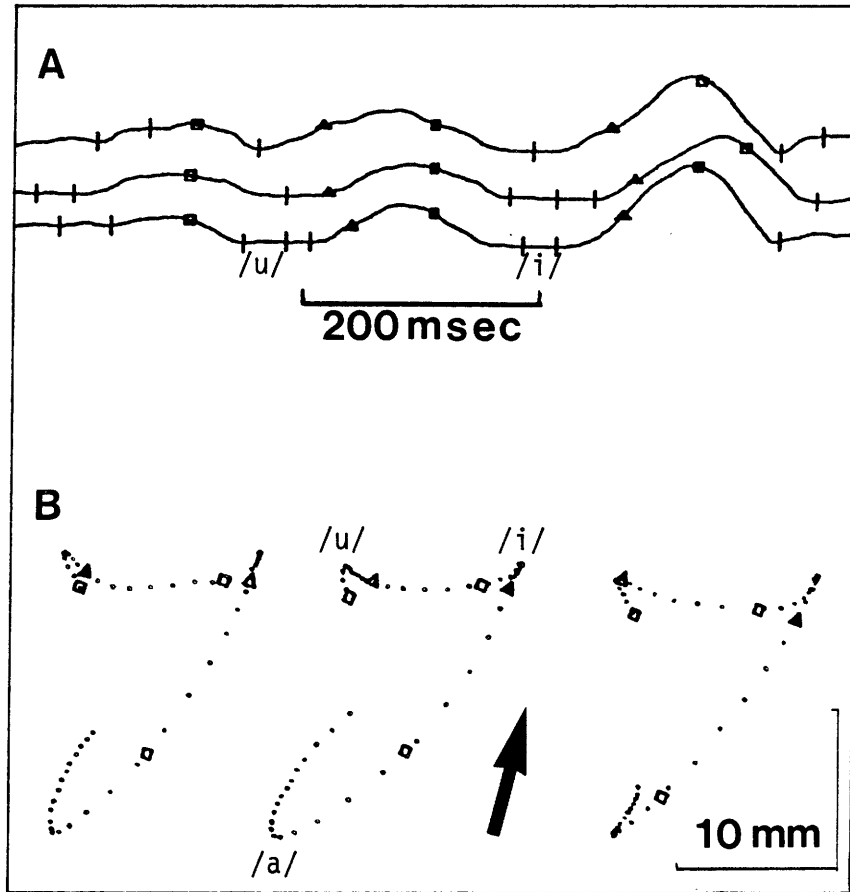


**Figure 8-4:**

A midsagittal plane plot of outlines of the subject's face and hard palate, produced by tracing their midlines with a transducer, and trajectories of the tongue and mandible transducers for the utterance /bubiba/.

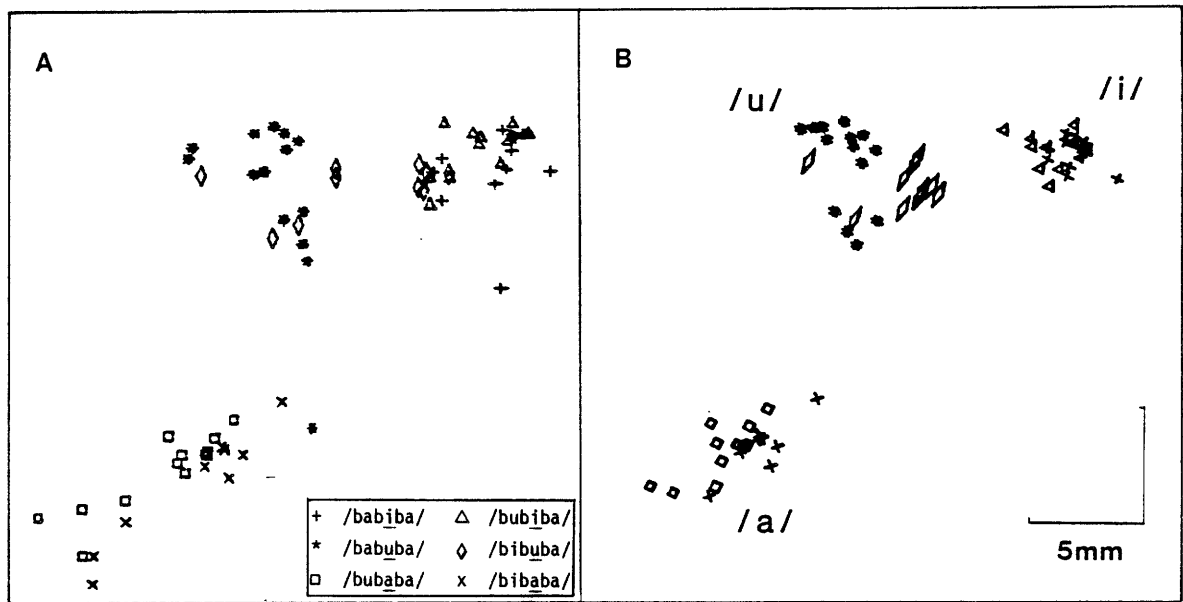
**Results.** The distance between the two fixed transducers was transduced as 48.8 mm. versus 49 mm. measured by the caliper (which could only be considered to be accurate to within about a millimeter).

Figures 8-4, 8-5 and 8-6 illustrate results from Experiment 2. Figure 8-4 shows midsagittal plane plots of the outline of the subject's face and hard palate, produced by tracing them out with a transducer, and trajectories of the tongue and mandible transducers for an example of the utterance /bubiba/. The mandible movement is minimal in relation to the magnitude of the tongue movement. This observation is consistent with findings of Alfonso and Baer (1982) from a cineradiographic study.



**Figure 8-5:**

Data from the tongue transducer for three repetitions of the utterance /bubiba/. A: tangential velocity versus time. Vertical tick marks correspond to algorithmically-identified times of minima in tangential velocity. Boxes mark the times of consonant releases and triangles mark times of consonant onsets. B: midsagittal plane trajectories for the same examples. The symbols on the trajectories correspond to the same events as in part A. Trajectory points are spaced at equal time intervals. Vertical orientation in part B is indicated by the arrow.



**Figure 8-6:**

Scatter plots of points representing targets for repetitions of the stressed (underlined) vowels /i/, /u/ and /a/, spoken in the utterances given in the figure. Parts A and B show the same data. In part A, coordinates are not corrected to the maxillary frame of reference and in part B, they are.

Figure 8-5 shows data from three repetitions of the utterance /bubiba/. Fig. 8-5.A shows traces of tangential velocity versus time. Vertical tick marks correspond to algorithmically-identified times of minima in tangential velocity. Boxes mark the times of consonant releases and triangles mark times of consonant onsets, as identified interactively in the time-synchronized, high-bandwidth acoustic signal stream. Part B shows midsagittal plane trajectories for the same examples. The symbols on the trajectories correspond to the same events as in part A. Trajectory points are spaced at equal time intervals (20 msec.), with inter-point spacing giving a visual impression of transducer velocity. Most of the rapid portions of the tongue movements occur during consonant closures.

Figure 8-6 shows scatter plots of points representing algorithmically-identified targets for

repetitions of the vowels /i/, /u/ and /a/. Symbols are keyed in the figure. Parts A and B show the same data. In part A, coordinates are not corrected to the maxillary frame of reference and in part B, they are. Correction to the maxillary frame of reference results in tighter clustering of data points for each of the three vowels and separation within each group of subgroups corresponding to the vowels as produced in different contexts. The differences between parts A and B indicate that there is some movement of the head with respect to the transmitter assembly, and that it is important to calculate displacements with respect to fixed points on the maxilla.

### **Procedural observations**

From beginning to end, the second experimental session consumed approximately 3 hours, a duration which depends on the number of transducers placed, but which should decrease with experience. All components functioned as designed. Considering the complexity of the procedures and the fact that they were being tried for the first time, the session proceeded very smoothly.

Preparation for an experiment consists mainly of wiring up, testing and performing calibrations on transducers. These procedures consume approximately 2 hours per transducer. This time should also decrease with experience.

Additional, useful controls in future experiments will be to: a) check mandible displacements by having the subject bite on several plastic rods of different diameters, and b) draw a transducer over the tongue surface at rest position, to trace the tongue outline and determine the location of attached transducers with respect to the tongue tip.

## 9. Conclusions

The two-transmitter, biaxial-transducer version of the system meets design specifications. It provides the capability of recording the simultaneous movements of a number of points inside and outside the vocal tract along with acoustic and other physiological signals. While considerable set-up time is needed to perform all necessary preparations for an experiment, the actual running of an experiment is reasonably efficient, allowing for the collection of large amounts of accurate data on articulatory movements.

## 10. Acknowledgements

A number of people have made invaluable contributions to the development of the system. David Oka (Oka, 1980) built an initial prototype that was used to evaluate the feasibility of the idea. Carlos Cuevas (Cuevas, 1980) carried out testing of the initial prototype and explored field geometry. Stephen Slenker, President of Piconics, Inc. helped to design and supervised construction of the biaxial transducers. Anne Jacques (Jacques, 1981) and P.-L. Wan tested the performance of the initial biaxial transducer. Richard Frankel of the National Magnet Lab, M.I.T. and Tom Tenforde of the Biology and Medicine Division, Lawrence Berkeley Laboratory gave helpful advice on the biological effects of electromagnetic radiation. Tom Warner and the staff of P.V.I., Inc. produced the overall electronic design of the final system and designed and assembled the electronic components. Ignaki Garabieta designed and constructed the mechanical components. Tom Carrell served as the subject in the trial experiments. John Cook of the Research Laboratory of Electronics did the photographic work for this report.

This work was supported by N.I.H. Grant No. NS04332 and funds from the Clarence Lebel Professorship in the Department of Electrical Engineering and Computer Science at M. I. T., held by Prof. Kenneth N. Stevens.



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# I. Theory of Operation of Transmitter and Receiver Electronics

## Transmitter

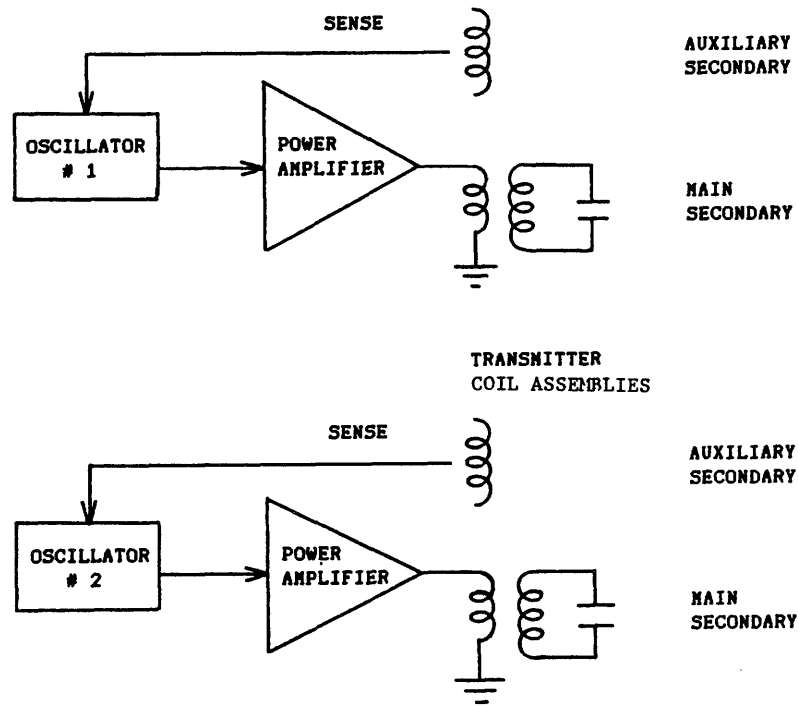


Figure I-1:

A schematic block diagram of the transmitters.

Figure I-1 shows a schematic block diagram of the transmitters. Each circuit consists of a sine-wave oscillator, a power amplifier and the transmitter coil assembly; the latter consists of a primary winding, a secondary winding, and an auxiliary secondary winding whose purpose is explained below.

There are numerous ways of generating a fixed frequency, sinusoidal waveform in the vicinity of 60 kHz. In this application, an important requirement is that the magnitude of the radiated field remain constant, because variations in this magnitude would be indistinguishable from variations in transmitter-to-transducer spacing. Another important requirement on the oscillator is a moderate degree of frequency stability, since, for reasons outlined below, the main secondary winding is connected to a capacitor to form a high-Q, parallel-resonant circuit. A simple circuit

that meets both these requirements is a quadrature oscillator with automatic amplitude control. For a detailed discussion of this circuit see, for example, Roberge (1975). The feedback signal to control the gain is provided by the auxiliary secondary winding on the transmitter coil. By sensing the radiated field amplitude, the feedback compensates for all gain variations in the forward path, whether produced by the oscillator, the power amplifier, or detuning of the transmitter secondary resonant circuit.

The power amplifier needs to provide mainly current gain, since the oscillator output is from an operational amplifier, capable of supplying milliamps, while the transmitter coil primary needs to be driven with several amperes. The low input impedance of the transmitter coil primary and the frequency range suggest that a high quality audio power amplifier is well matched to this application (while requiring no circuit design time). Further, in a stereo power amplifier, amplifiers for both transmitters are available in one package.

The signal that is used to drive the synchronous demodulators in the receivers (discussed below) is also derived from the auxiliary secondary winding.

## Receiver

A block diagram of a receiver circuit for use with a tilt-compensating transducer is shown in Figure I-2. The output of each of the two perpendicular windings of a transducer feeds an isolation transformer, each of which in turn feeds a separate receiver circuit. To help optimize the common-mode rejection capability of the system, the isolation transformer is wound with a center tap on the input side that is AC grounded.<sup>12</sup> The improvement in common-mode rejection arises from the fact that the center tap produces a situation in which stray pickup by the two leads from each transducer winding will be of equal amplitude and 180 degrees out of phase with one another, thereby canceling the effect of stray pickup or emissions to a large extent. Each demodulating circuit performs synchronous demodulation at the two transmitter frequencies.

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<sup>12</sup>We are grateful to Peter Branderud of Stockholm University and Special Instrument AB for this suggestion.

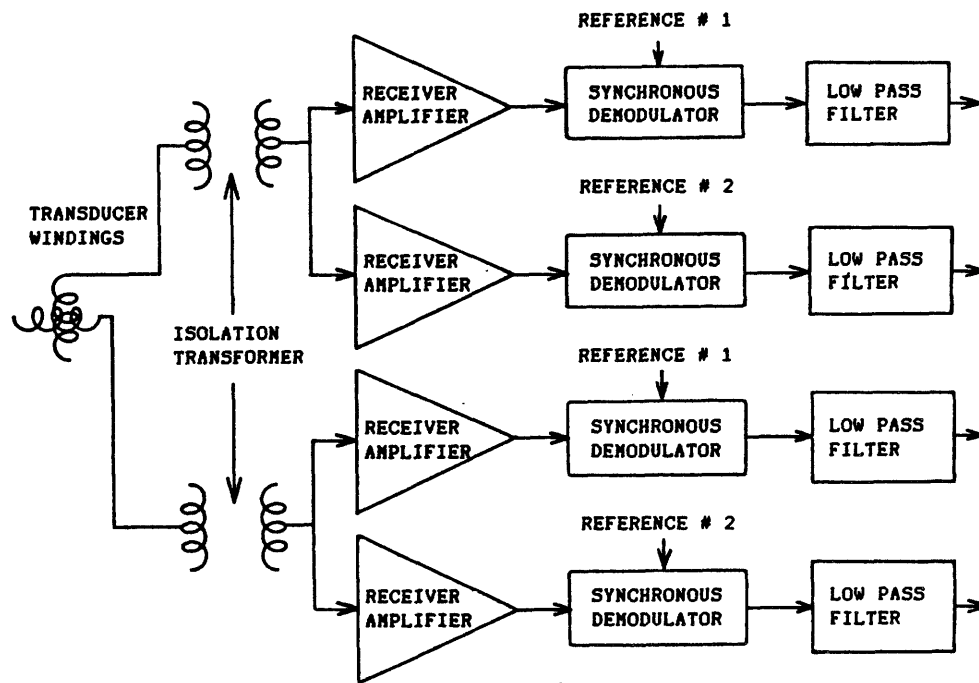


Figure I-2:

A block diagram of a receiver circuit.

It is tempting to try to resonate the receiver windings in order to produce a larger signal. However, the resulting circulating currents might cause adjacent transducers to interact with one another, thereby producing inaccurate displacement measurements. Consequently, the currents through the transducer windings are kept small by having them drive high impedance inputs. Another potential problem with resonating the transducers is that two different transmitter frequencies are used. Therefore, the resonant frequency of the circuit containing the receiver winding would have to be centered half way between the two transmitter frequencies. If the  $Q$  of the receiver circuit were sharp enough to achieve a significant increase in gain, transmitted frequencies would be on sloping regions of the amplitude-vs.-frequency characteristic of the receiver circuit, making the amplitude of the resulting output highly sensitive to drift of both amplitude and frequency of the transmitted signal.

The main requirements for the receiver amplifier are that it have a stable gain of about 2000, introduce minimal phase shift and have low noise. Although these requirements are difficult to achieve in a single amplifier, they can readily be achieved using a cascade of three, operational-amplifier based gain stages. The motivation to have a stable gain in the receiver is the same as it is for the transmitter; unlike the transmitter, however, gain stability is achieved in the receiver by using 1% resistors to set the gain of the operational amplifiers. The need for minimal phase shift through the amplifier arises from use of the synchronous demodulation that follows the amplifier. Minimal phase shift is accomplished by choosing amplifiers that permit the required gain and still have a 3 dB bandwidth significantly higher than the received frequency. Low offset and noise are achieved by choosing the appropriate operational amplifiers.

Synchronous demodulation of each of the amplified received signals is accomplished with an integrated circuit. Since each transducer winding picks up signals from both transmitters, the output of each amplifier feeds two synchronous demodulators, each of whose reference inputs is fed by one of the transmitter frequencies. The output from each synchronous demodulator is fed to a low pass filter which sets the upper limit on the speed with which the received signal will follow the movements of the transducer. From this point on, care is taken to keep DC shifts to a minimum, as such shifts will be indistinguishable from transducer position variations.

Combining of the outputs of the four resulting signals - one from each transducer winding for each transmitted frequency - to produce the desired tilt independent distance measurement is performed in software.

## II. Electrical Safety Considerations

### Transmitter

Each transmitter coil consists of a primary winding, a secondary winding, and a sense coil winding. The primary and sense coil windings share a common ground with the transmitter amplifier while the secondary winding leads are completely isolated. The primary coil is driven from a low voltage source, approximately 30V, while the sense coil, with less than 1V Rms across it, is monitored by a high impedance amplifier. The secondary winding is connected to a capacitor, and the combination driven at their resonant frequency. While the peak secondary coil current, 23 A, and the peak capacitor voltage 100 V, are high, the stored energy, 2.5 mJ, is low. The two windings and the capacitor are housed together in a strong enclosure that prevents any direct contact with the electrically active parts. Further, should this enclosure be broken through accident or misuse, a shock hazard exists only across the terminals of the secondary coil/capacitor combinations which are internal to a PVC form, around which the turns of the secondary are wound. With the secondary leads isolated, both leads must be contacted in order to receive a shock. The mechanical design makes it virtually impossible to accidentally contact both leads simultaneously. Finally, the stored energy delivered by a shock from the secondary winding is above the threshold for sensation but well below the thresholds for pain and injury.

### Receiver

Each transducer is potted in an insulating material and insulated wires connect the transducer outputs to the input of the receiver circuitry. Solder points of connecting wires to the transducer are coated with insulating dope. Hence there is only a remote possibility that a subject would come in contact with electrically active parts of the winding or connection wires.

The open circuit voltage developed across each winding that is generated by the interception of the field will be less than 5 mV peak. The winding short circuit current will be less than 100  $\mu$ A peak. Hence, in the unlikely event that a subject should come in contact with the outputs of the windings there would be no electric shock risk.



Although only millivolt level signals are normally present on the output of the transducer windings, a radical failure in a receiver circuit could possibly connect higher voltages to the transducer. Since the transducer could be placed in a subject's mouth, the use of isolation transformer is a prudent precaution for blocking DC and 60 Hz AC from entering the transducer.

Following the secondary of the isolation transformer, the input of the demodulating circuit is the input to an operational amplifier. Although the input bias current is 80 nA maximum, the possibility exists that a radical failure within the operational amplifier could connect the input to +15 VDC or -15VDC; these being the amplifier supply voltages. The power supply that provides the +/-15 VDC has a 60 Hz transformer on its input. A radical failure within the power supply could place approximately 28 V, 60 Hz on the supply lines. Thus it would take two radical failures - one in the operational amplifier and one in the power supply - to connect 28 V 60 Hz onto the secondary of the isolation transformer. The leakage of the isolation transformer of 2  $\mu$ A maximum at 115 V 60 Hz meets UL standard 544. Thus the subject will be protected, even in the event of multiple radical failures.

The most important safety impact would probably be the case of a shorted capacitor that is providing the AC grounding on the center tap of the isolation transformer. The result would be direct grounding of the involved coil. This condition would likewise have little impact on subject safety unless there is an accompanying failure in the transducer or connecting wire insulation. With both of these failures, the subject would be directly grounded. The transducer short circuit current is on the order of a few microamperes; therefore, there is negligible danger to the subject from the received signal. However, as long as the subject is grounded, he would be susceptible to shock, should he contact one terminal of an electrical source, the other terminal of which is also grounded. A reasonable amount of prudence must be exercised to avoid this condition.

### III. Determining the gain, G, of each transducer through each of its four channels of electronics

If the location of the transducer is to be determined independent of the angle of tilt, the output voltages resulting from signals induced in each transducer winding must be squared and summed, thus

$$V_T^2 + V_D^2 = V_{Tot}^2 \quad (III-1)$$

Where

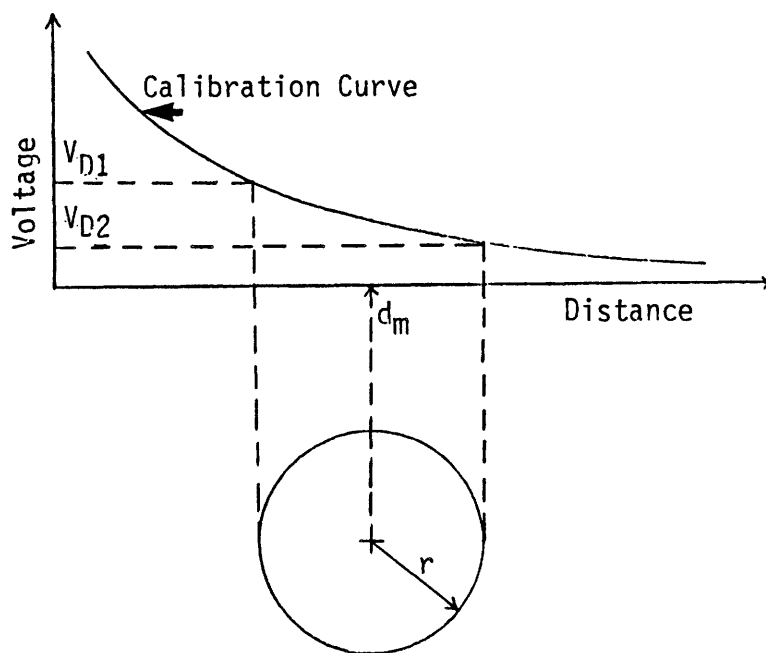
$V_D$  = voltage induced in the translation winding

$V_T$  = voltage induced in the tilt winding

For this method to be successful, the gain through each transducer winding and its two channels of receiver electronics must be equalized. This procedure is as follows.

The transducer is placed in the circle-drawing apparatus and oriented (twisted and tilted) for maximum voltage output from a winding. As illustrated in Fig. III-1, the transducer is then rotated several times through circles centered at mid-field. It is not necessary to know the radius of the circle. The maximum resulting voltage,  $V_{D1}$ , (when the transducer is closest to a transmitter) and the minimum resulting voltage,  $V_{D2}$ , (when the transducer is furthest from a transmitter) are tabulated.

The following equations describe the determination of the gain through a transducer winding and a channel of receiver electronics, G.



**Figure III-1:**

A diagram showing a circle of radius,  $r$ , centered at a distance,  $d_m$  from a transmitter, with voltage outputs,  $V_{D1}$  and  $V_{D2}$  that are produced at minimum and maximum distances from the transmitter.

$$G \times V_{D1} = K / (d_m - r)^p \quad (III-2)$$

$$G \times V_{D2} = K / (d_m + r)^p \quad (III-3)$$

Where

$K$  = the "field strength constant"

$d_m$  = distance between transmitter center and midfield

$p$  = exponent describing decrease of field strength with distance

$r$  = radius of the circle

Algebraic manipulation gives the following nonlinear equation in  $G$ :

$$G \left[ d_m + \left( \frac{K}{G} \right)^{1/p} \left( \frac{(V_{D2})^{1/p} - (V_{D1})^{1/p}}{2} \right) \right]^p - \frac{K}{V_{D2}} = 0$$

Newton's method (see, for example, Gerald, 1978) can be used to solve for  $G$  given  $V_{D1}$ ,  $V_{D2}$ ,  $p$  and  $K$ , all of which are known.

This procedure is repeated for each winding. Each transducer requires four gain equalization factors, one for each of the transmitters for each of the transducer windings. The resulting values of  $G$  are used for gain equalization, which is the first step in the data processing sequence.