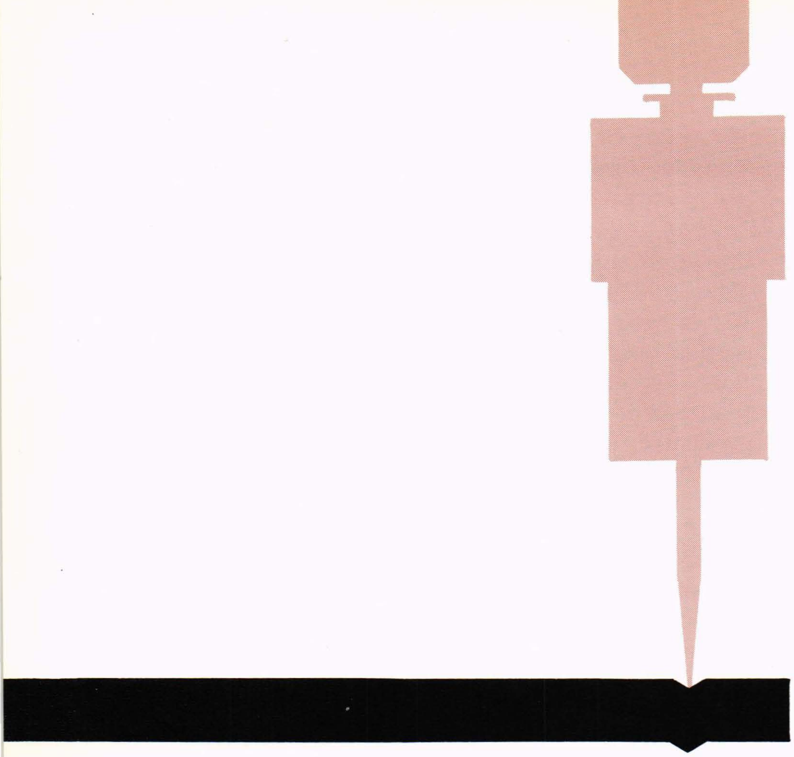

A transducer has been developed for producing micron level indentions in the skin of various animals for the purpose of studying the response of the sensory nervous system. The closed loop system in which this instrument is operated features precise motion control of the stimulating probe and the capability of measuring the force applied to the skin.

J. G. Chubbuck

SMALL-MOTION BIOLOGICAL

Typically, the study of the tactile sensory nervous system involves the mechanical excitation of a small region of the skin by indenting it with a probe while observing the response of some portion of the nervous system to that stimulus. Since this is not a particularly new art, it seems rather surprising that so little has been done in the way of developing suitable stimulation transducers. A popular, if not quite universal, approach has been to use a commercially available vibration generator that was initially intended for shaking watches. Unfortunately the amplitude and force domain in which the highly sensitive tactile sensory system needs to be driven is vastly different from that for which watches are normally vibrated. Some improvement in probe motion control has been realized by attaching a magnetic-type displacement pickoff to the vibration generator so that it may be operated in a closed, rather than open, loop manner. At small displacement amplitudes this configuration characteristically displays an elastic hysteresis (referred to as an "oil can" effect) because of the armature suspension system in the vibration generator. It also exhibits a dead space caused by sliding friction in the pickoff which was attached as an afterthought.

The objective of the effort described here was the development of a better stimulator starting from scratch. A somewhat arbitrarily chosen set of design criteria included as principal features high load force stiffness, a probe suspension system with a maximum achievable ratio of radial-to-axial stiffness and free of nonlinearities, a flat frequency response from zero to 100 cycles per sec, and a displacement control resolution of the order of one micron over a range of 0.1 inch.

Stimulator Transducer

The stimulation transducer design that has evolved is shown in cutaway view in Fig. 1. The displacement-sensing mechanism is a variable capacitance pickoff. It forms one arm of a capacitance bridge driven by a two-megacycle oscillator

STIMULATOR

connected to a demodulator. The oscillator and demodulator, as well as the two fixed arms of the capacitance bridge, are packaged inside the hollow plexiglass cylinder, with lead access from the rear through the hollow central shaft. The capacitance pickoff is formed by the six brass rings imbedded in the surface of the plexiglass cylinder and the ridges of the corrugated aluminum sleeve that are close to the rings. Each sleeve ridge spans the region between the midpoints of two adjacent rings when the sleeve is in its center (rest) position. The sleeve is electrically grounded by the flexible diaphragms that support it. The three sets of two rings and one ridge (connected in parallel for maximum sensitivity) form the two variable arms of the capacitance bridge. An outward displacement of the probe and sleeve assembly increases the capacitance to ground from one ring and equally diminishes that of the other. The opposite phase of bridge unbalance results from an inward sleeve displacement. The measurement system is surprisingly linear over the range of sleeve motion and has a sensitivity of 200 volts per inch.

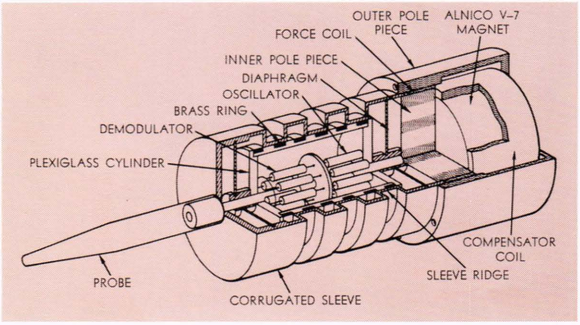

Fig. 1—Stimulator transducer.

The plexiglass probe that transmits stimuli to the specimen screws into a threaded hole in the end cap so as to be readily interchangeable, the end cap being a press fit to the sleeve.

The corrugated sleeve supports the coil form and end cap which are press fits. The annular grooves, formed by this design, enclose the outer edge of the two diaphragms which are clamped tightly in place by the assembly process. The center of each diaphragm is similarly clamped between two brass collars attached to the central shaft. Each diaphragm, which is made from 0.005-inch-thick beryllium copper because of the low mechanical hysteresis of that material, has a single spiral slit in it which removes the oil can effect and allows greater axial displacement. This construction results effectively in a single wide spoke which spirals once around the shaft and which has a very low spring constant axially although it is quite rigid radially. The importance of the high radial rigidity of the suspension system is that it allows close spacing between the sleeve ridges and the brass rings without danger of touching, thus maximizing linearity and sensitivity. It also constrains the probe to pure motion along its longitudinal axis—the only component of displacement the pickoff can sense. Reaction forces between the probe tip and the specimen are not necessarily directed along the probe axis.

The force coil is suspended at the rear of the sleeve in the air gap of a compensated speaker motor. The inner and outer pole pieces of Hyperco material are operated well below saturation. They are energized by a cylindrical permanent magnet of Alnico V-7 material chosen for its high energy product. The compensation coil around the magnet is operated in series opposition with the force coil to minimize variations in the air gap field intensity caused by the force coil current as well as to make the speaker motor present a more nearly noninductive load to its driver amplifier.

The stimulator transducer is approximately 3½ inches long, excluding the plexiglass probe which can be of various lengths, and two inches in diameter.

Figure 2 is a photograph of the complete transducer and shows a ball and socket mounting system which allows some range of variation of the orientation of the probe axis. For micron level displacements to be meaningful, the stimulator must be mounted to some extremely rigid supporting member.

Displacement Control Loop

The transducer is the principal component of the displacement control loop which also contains a mixing operational amplifier with an input command gain of K_c and a feedback gain of K_f and a power amplifier having a gain of K_a amperes per volt as shown in Fig. 3. The output of the displacement pickoff, x_m, is fed back to the operational amplifier, and thus modifies the input voltage waveform, x_c, as a command of probe displacement. The principal dynamic characteristic of this loop is the double integration, $(1/s^2)$, between speaker motor force, F_T, and sleeve displacement, x. A purely proportional loop closure would, of course, result in a highly underdamped system. The lead characteristic achieved by the operational amplifier feedback network, $(\alpha\tau s+1)/(\tau s+1)$, raises the system damping (error velocity damping) to approximately 0.7 critical. The loop gain is high enough to achieve a 100-cycle-per-sec bandpass and a high load force stiffness. The load force stiffness must be high if the specimen reaction force, f, is not to affect the output displacement response to the input commands. The notion of overpowering the dynamic resistance of the specimen results from the assumption that this will not, in general, be known and, therefore, should be made negligible by the very high load force stiffness of the driver. The force, F_d, shown in Fig. 3 is the elastic restraint of the diaphragms having a spring constant, k, while the force of gravity on the sleeve when oriented at an angle θ above the horizontal is shown as $Mg \sin\theta$. The pickoff sensitivity is identified as K_p.

Reaction Force Readout

So far we have considered tactile stimulation to mean a controlled displacement of the probe in contact with the skin. There are those, however, who feel that applied force would be a more appropriate variable. Certainly these two entities are not independent but are related by the dynamic properties of the skin and the underlying tissue. The writer is in no position to formulate an opinion as to the merits of controlling applied forces rather than displacements, but it seems to make sense to design a stimulator transducer that reads out specimen reaction force as well as displacement, and allows the user to choose either one as the controlled variable by using it in the feedback loop. Whichever variable is controlled, both may be recorded. It is suggested that simultaneous recordings of displacement and force provide an improved measurement of the dynamic properties of the skin which are believed to be significant to the overall tactile sensory system behavior.

The use of a direct force-sensing transducer mounted at the output end of the displacement pickoff is, of course, a natural one but it encounters some rather stringent requirements. The force pickoff must not add materially to the sleeve mass (23.7 grams) and must not require displacement to read out force since this would contribute an error to the displacement pickoff output. There are miniature force sensors that operate in the frequency region of a few cycles per second and up, but the need to include static forces in the measurement led to a method for computing specimen reaction forces from other available system vari-

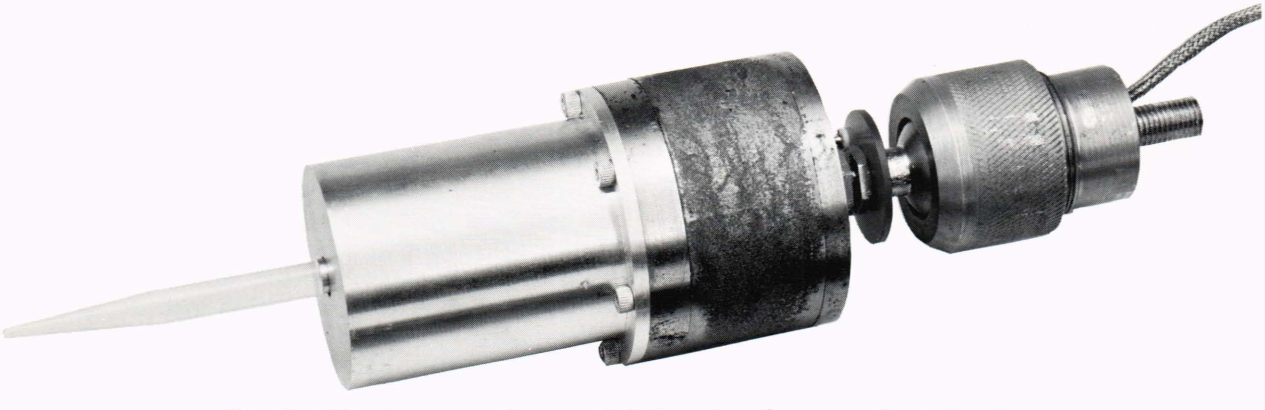

Fig. 2—Stimulator transducer with ball and socket mounting arrangement.

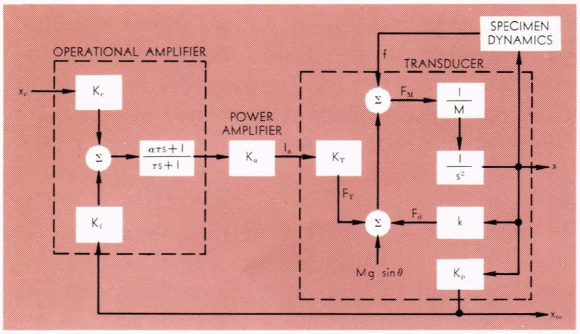

Fig. 3—System dynamic configuration (displacement mode).

ables. The technique is to compute the sum of all forces acting on the moving mass (sleeve) except for the reaction force of the specimen. The value of the sum thus computed represents the force output of the probe.

Computation of Reaction Force

The block diagram representation of the stimulator transducer shown in Fig. 3 depicts all of the forces acting on the sleeve assembly. The force output of the speaker motor is denoted by F_T, F_M is the force for acceleration of the mass, M, F_d is the diaphragm restraining force, and f is the reaction force between the specimen and the probe. Taking the sleeve as a free body it is evident that the sum of these forces should, at all times, be zero, which leads to the relationship,

$$f = F_T - F_M - F_d - Mg \sin\theta.$$

The gravity term is a steady-state bias that must be included in the force computation and may be used to absorb all time invariant biases occurring in the force computing circuitry. The above expression for output force may be written in terms of measured values of system variables,

$$f_m = K_T\, I_a - M\left(\frac{d^2x_m}{dt^2}\right) - kx_m - Mg \sin\theta.$$

In this expression K_T is the force per unit current, I_a is the current of the speaker motor, k is the diaphragm spring constant, and x_m is the displacement pickoff output.

Figure 4 shows, in block diagram form, the addition of the force computation as well as showing the stimulator loop closed as a force control system. The circles containing constants imply input gains to the operational amplifier which performs the summation of computed force components. The computed values of F_M, F_T, and F_d are indicated by F_{Mm}, F_{Tm}, and F_{dm}, respectively. The double differentiation amplifier is three AC gain stages (for isolation) separated by derivative coupling networks that conform to the dynamic characteristic shown in transform notation, $s^2/(0.000795\ s+1)^2$.

Since the reaction force computer must measure the difference in terms that at high frequency will be large compared to their difference, $F_T - F_M$, the adjustment of computer gains must be done rather accurately. Fortunately there exists a convenient alignment procedure for doing so. With the loop closed in the displacement control mode and the input, x_c, grounded, making the displacement pickoff output very close to null, the gravity balance is adjusted to give zero force indication. The input is then driven at a relatively large amplitude but very low frequency so that the mass reaction force, F_M, is negligible while the diaphragm spring compensation gain, k/K_p, shown in Fig. 4 is adjusted for best force measurement null over the range of travel. The system is next driven at small amplitude and high frequency where the predominant force component is the mass reaction, F_M, and the gain of the differentiation amplifier is adjusted for the best force null. All adjustments are, of course, made with the probe free of any form of physical contact. The gravity balance portion of alignment must be repeated after any change in orientation of the stimulus axis.

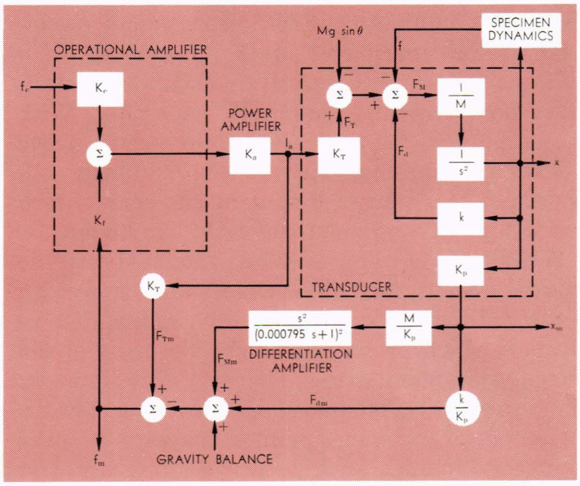

Fig. 4—System dynamic configuration (force control mode).

It is interesting to note that the displacement position of the system when not in contact with a specimen is completely undefined in the force control mode and that it seeks one of the two extremes of displacement depending on the sign of the prevailing system misalignment. In use, however, a slight outward force bias would be used to hold the probe in contact with the specimen.

Experimental Results

The bandwidth of a doubly integrating closed loop is given as the square root of the loop gain divided by 2π. This suggests that any desired bandwidth is obtainable by supplying sufficient gain within the loop. However, there is an upper limit of usable bandwidth which is determined by the maximum acceleration that can be applied to the moving mass. In the stimulator transducer that has been reduced to practice, a saturation drive current, I_a, of 0.5 ampere results in a force, F_T, of approximately 300 grams on a sleeve assembly having a mass of 23.7 grams. Thus, the system has an acceleration limit of approximately 5000 inches/sec^2.

Selection of an appropriate loop gain (and thereby a bandwidth) that is compatible with the acceleration limit is accomplished by arbitrarily choosing a minimum usable displacement amplitude at the upper end of the pass band. Ten milli-inches has been tentatively chosen as a minimum high-frequency amplitude capability. With this amplitude, the peak acceleration of the sleeve reaches the limiting value at approximately 110 cycles per sec. Thus a loop gain has been chosen that results in a nominal 100-cycle bandwidth.

Because of the rapid response rate of the tactile sensory system the 100-cycle-per-sec bandwidth is not entirely adequate. A sleeve redesign is in progress which promises to halve the mass of the present aluminum sleeve. The new sleeve is to be made primarily of plexiglass with the passive capacitor pickoff rings painted on with a silver conductive paint. Such a sleeve mass decrease would result in a bandwidth increase of about 40%.

Resolution is normally defined as the smallest incremental change in the input command that the system will reproduce, with reasonable fidelity, in its output. The capacitance variation of the pickoff bridge is certainly continuous as is the speaker motor current to force relationship. The single spoke diaphragm sleeve suspension system was specifically chosen to minimize dead space and hysteresis in its force-to-displacement relationship. Systems that require one surface to slide over another are subject to force dead space (sometimes called "stiction"). The sleeve suspension has no sliding surfaces and relies on the elastic property of the beryllium copper diaphragms which have extremely small hysteresis effects over the small stress range to which they are subjected. In the case of the stimulator there seems to be no measurable lower limit to resolution defined in this way. In a practical sense, therefore, resolution is determined by such considerations as system noise and power supply stability. For the present stimulator configuration, the principal source of noise was the vibrations present in the environment in which it was tested. Figure 5 shows a recording of output response to a two-cycle-per-sec triangular waveform command in which the peak-to-peak amplitude is two microns. The reader will observe that this response is at least a factor of 10 above the system noise level. It is important to keep in mind at this point the difference between resolution and accuracy. A one-micron resolution implies that the system will respond rather faithfully to an incremental change of one micron in the input command. It does not mean that the probe can be commanded to assume some absolute displacement position anywhere within its region of travel to an accuracy of one micron. The displacement pickoff is not nearly that linear. Position control accuracy is also diminished by the specimen reaction force in a system such as this which has a finite load force stiffness (1.2 grams per micron of displacement error).

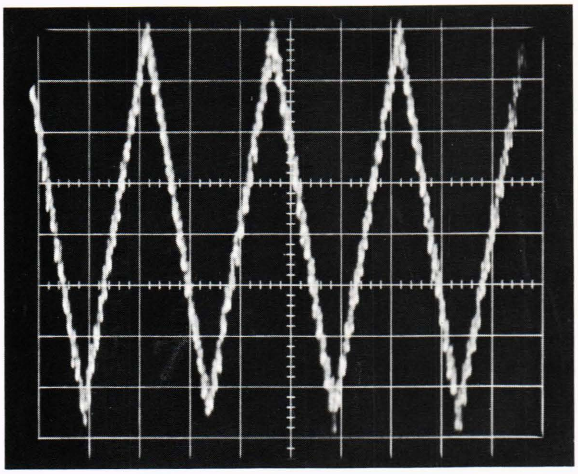

Fig. 5—Displacement output response to a 2.0 cycle per sec triangular wave command of 2.0 microns peak-to-peak. (Scale: 0.25 micron per division).

As previously shown, reaction forces are computed from other measurable system variables. The accuracy of the reaction force readouts is, therefore, limited by the precision with which these variables are measured and the accuracy with which the computation is performed.

The accuracy of force computation is influenced by both static and dynamic accuracy considerations. The principal sources of static force errors are changes in air gap magnetic field caused by the presence of the force coil current and nonlinearity of the diaphragm spring constant.

The demagnetization of the air gap by the force coil current is largely compensated for by passing this current through the series (opposed) compensation coil. The completeness of compensation is limited, however, by the fact that the coefficient of coupling of the force coil and the compensation coil varies with the displacement of the sleeve. The force coil current also induces unequal fringing fields on the ends of the speaker motor flux gap, which cannot be corrected by the compensating coil, and this causes residual nonlinearities.

The beryllium copper diaphragms, although relatively free of dead space and hysteresis, become nonlinear at large values of displacement from the center position. In the center of the displacement region the single spoke diaphragm may be considered as a beam subjected to bending stress only. At larger values of displacement, where it no longer lies in a plane, torsional strain becomes significant resulting in an increase in the diaphragm spring constant. When the diaphragm spring compensation term, kx_m, of the reaction force computation is properly adjusted for small displacements, some error must be accepted at large displacement.

The static force measurement accuracy of the present stimulator configuration, when scaled to read out forces between zero and ±40 grams, is of the order of 1% (0.4 gram uncertainty)—principally caused by the increase in the diaphragm spring constant.

In the area of dynamic force computation accuracy, two error sources have been observed—both of which should have been quite obvious before they were found experimentally. The region inside the corrugated sleeve and off the probe end of the plexiglass cylinder forms a "dash pot," which operating in air, adds a measure of viscous damping and frequency sensitive spring restraint. In the next model this region will be well vented to the exterior of the sleeve.

The other significant dynamic force measurement error is caused by the phase lag in the passive network of the double differentiating amplifier. At high frequency the force computer takes the difference between two large quantities, F_T and $M\ d^2x/dt^2$. A small phase difference in these two quantities results in large difference errors. This error can be made acceptably small by locating the corner frequency of the differentiator one octave higher than the region of interest (zero to 100 cycles per sec) while simultaneously adding a phase roll-off characteristic to the F_T variable which closely matches that of the differentiator up to 100 cycles per sec. The next model of the stimulator will concentrate on improving force readout accuracy, which in the present model is only about 5% in the dynamic sense.

Other Interests

During the course of development of the neural stimulator other potential uses of the basic principle have been suggested—two of which may be of interest.

The contraction activity of muscle tissue is sometimes studied by detaching a small muscle spindle at one end and connecting it to some type of transducer that will sense tension or contraction that results when the tissue is excited. Since the stimulator system may be operated as a pulling as well as a pushing mechanism, it has been suggested that a somewhat larger and more powerful model with a longer travel capability be developed to be used as a "muscle puller." This seems to require nothing more than scaling up the size of the present design and achieving a diaphragm suspension system with a longer travel.

Both the force control and displacement control loop closures are of interest, although it is expected that input driving functions will be little more than static commands of tension or stretch. In this case the device should be thought of more as a measuring instrument than as an excitation means. In the displacement closure mode the high load force stiffness characteristic would inhibit changes in length of the tissue while the force computer would indicate the tensile forces resulting from an attempt to contract. Conversely, the force control mode would allow observation of muscle contraction against a preassigned constant tensile stress.

The other potential use of the stimulator system would involve extending the technique to a multiplicity of axes (perhaps as many as five) to form a micromanipulation system. The principal significant features would be high resolution motion control, large dynamic range of displacement control, sensing of fractional gram level reaction forces, and high load force stiffness. Probably the minute reaction forces would be greatly amplified and fed back to the manual control transmitter to restore the operator's sense of feel of the manipulative process. An angular version of the stimulator displacement control configuration is being considered for two axes of a micromanipulator that would operate in spherical polar coordinates. The radial axis of the manipulator, like the muscle stretcher, requires a diaphragm suspension system with considerably longer travel.

Although the work on the muscle stretcher is currently being actively pursued, the micromanipulator suggestion has as yet not aroused sufficient outside interest to warrant any follow-up action.