MAGNETOINDUCTIVE SKIN FOR ROBOTS

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A flexible tactile imaging skin for robots based on magnetoinductive technology is proposed. This skin would be inexpensive and suitable for use either as a sophisticated imaging device or as a simple on/off tactile sensor. In the proposed design the skin would consist of a thin flexible magnetoinductive array with the sensor elements .5 mm apart covered on each of its two sides by a sheet of rubber and a row of flat wires etched on a Kapton film. I/O's should be easily accessible and the system's electronics should be simple. It would be able to be trimmed to size. The skin is expected to bend around a 25.4 mm radius. Linear pressure and compression relationships are expected over a 8 bit dynamic range. Cross talk between sensor elements should be nonexistant; and the system should be low power (.25 W/cm^2) and high speed. The array would be electronically tunable over a 10/1 range in pressure and spatial sensitivity.

I. Introduction

The development of a practical, high performance, flexible, tactile sensor based on magnetoinductive principles appears feasible. Designed initially as an imaging skin with an imbedded array of sensor elements, this skin would be reconfigurable both electronically and physically to perform a wide range of tactile and force feedback tasks. In this paper the design and expected performance of the skin is described in detail. This is followed by a discussion of the ways the skin can be reconfigured to perform sensory tasks ranging from an imaging skin to a single element microminiature pressure or force sensor.

II. Design Goals

The overall design goal is to explore the practical performance limits of magnetoinductive skins for robots. As an interim measure it is useful to create a functional specification for the first prototype, as follows:

Element Spacing and Skin Thickness

The magnetoinductive sensing elements would be .5 mm apart. The skin area could be as great as 4 in X 4 in (10 cm x 10 cm) since Metglas* comes in tape form as wide as 10 cm. The skin could be made as thin as 3 mm. As explained in the section on spatial sensitivity below, the rubber layers could be made as thick as desired; but with the tradeoff of decreased spatial sensitivity. The .5 mm spacing was chosen as a limit because this exceeds the resolution needed for object imaging and edge determination.

Dynamic Range

A dynamic range of 10 bits per element is desired i.e., maximum detectable pressure divided by minimum detectable pressure = 2^{10} or 10 log 2^{10} ≈ 30 dB. This requirement is because electronics is normally noise limited to 30 dB dynamic range.

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*Metglas is a tradename of Allied Corporation, 6 Eastermans Road, Parsippany, NJ 07054.
In this paper, certain tradenames and products are identified in order to adequately specify the procedures and equipment used. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessarily the best available for the purpose.

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Sensitivity

a. Force Sensitivity

A threshold pressure of 3 N/m^2 would be detectable using .5 mm thick open celled sponge rubber between the magnetoinductive sensor elements and the flat wires generating the field (dynamic range of 3 N/m^2 to 3000 N/m^2). By using a stiffer rubber the threshold pressure would be increased to 5.0 N/m^2 with a corresponding dynamic range of 50 N/m^2 to 5×10^4 N/m^2.

b. Spatial Sensitivity

The skin should be able to detect an encounter with an object when it has been compressed .025 mm. This assumes a skin thickness of 3 mm. Making the skin thicker would cause a proportionate decrease in spatial sensitivity. This functional requirement means that burrs and dimensional accuracy could be checked to normal manufacturing tolerances.

Power Dissipation

Five hundred (500) mA and 25 watts are the maximum allowed current and power desired in the 10 cm x 10 cm prototype. This requirement would permit continuous operation without overheating.

Cross Talk

Less than 5% magnetic field intensity cross talk between adjacent elements is desired. This requirement would permit the simplification of software in the imaging process.

Durability

The system must be able to withstand 10,000 cycles of 33% compression of the rubber with 10% or less plastic deformation. This requirement is necessary so that the skin would be rugged and durable.

Conformalness And Flexibility

The system should be able to be flexed about a 3 cm radius with 5% or less degradation in signal sensitivity or dynamic range. The 3 cm value is given because most curved gripping surfaces have radii in excess of this value.

Temperature

The system should be able to perform at temperatures between -10°C to +60°C with 5% or less degradation in signal sensitivity or dynamic range. The wide temperature range is intended to permit the sensor to be used in almost any environment.

Electronics

The sensor design must use simple electronics. Bridge circuitry should be self compensating. That is, reference units must experience the same environmental disturbances (e.g. stray magnetic fields, temperature effects, mechanical strains) as the sensor elements being measured. Signal output should bear a direct relationship to the force on the sensor rather than being a function of the rate of change of force with respect to time (a derivative relationship).

I/o's

I/o's must be accessible by standard board connectors despite the sensor array having a high sensor element density.

Reconfiguration/modularity/trimming

The sensor array must be easily reconfigured electronically. Its active sensor element density should be reconfigurable to any spacing .5 mm or greater (for example 2 mm) as long as the increments are in .5 mm multiples. Similarly, its active sensor element pattern should be electronically changeable as should the scan order of the sensor elements. The skin array should be made in standard sizes (modules) so that users could tailor their own sensor arrays to whatever size desired. Still the sensor modules would have to be designed such that they could be cut and trimmed to size with all the remaining sensor elements functional.

III. Construction

The proposed construction of magnetoinductive robot skin is shown in Fig. 1a. The method by which the field from the flat wires would excite the sensors is shown in Fig. 1b.

A. General Construction

The sensor array film would have a .5 mm thick sheet of compressible rubber glued to its top and bottom. A .025 mm thick sheet of Kapton** with .013 mm

**Kapton is a tradename for a polyimide type of film produced by DuPont Corp., Polymer Products Dept., Chestnut Run, Wilmington, DE 19898 thick, .13 mm wide copper lines etched on it would be wrapped around the sensor array film and rubber sheets such that the copper lines would be perpendicular to the sensor elements. A .5 mm thick sheet of rubber would be added top and bottom. Finally, the shielding material which is typically 50 um thick would be wrapped around the entire assembly like a sandwich. The shielding should be a single sheet which is glued to both the top and the bottom of the skin and which passes over one edge of the skin enroute from top to bottom. The grooves in the compressible layer of rubber (that between the flat lines and the sensor elements) would probably be chemically etched. Since the rubber would be purchased in sheets .5 mm thick and since chemical etching normally etches transversely under the mask at the same rate it etches down into the rubber, we can expect "V" shaped grooves as is illustrated in Fig. 1a. This means that if the narrow side of a groove were on the order of .25 mm, the wide side would be on the order of 1.25 mm, thus the small rubber blocks would be shaped like truncated pyramids.

B. Sensor Array Construction

A piece of magnetized Metglas tape would be fixed to a smooth surface evenly and without stress. This 25.4 um thick Metglas tape would then be chemically levelled, removing approximately 7.7 um of the material in the process. Grooves would be etched parallel to the direction of magnetization. These grooves would be 5 um deep and .2 mm wide (see Fig. 2, Fig. 3 and Fig. 4). Next the entire Metglas tape would be covered with a 2 um thick coating of flexible insulation. The next step in the process would be to fit a second mask and etch vias in the insulation so that the flat coil end connections could be made. We next would cover the entire tape with a 4 um thick copper coating. Using a third mask we would be able to etch the top half of the copper coils of the sensor array.[+] We would next add a 2 um coating of insulation, leaving some vias for the input/output connections. We would then add a 4 um layer of copper. Using another mask we next would etch our output connections. We would then remove the unfinished skin from the fixture, turn it over, reregister it and repeat the process described above except that a separate layer would not be necessary for the inputs as this would be a part of the pattern of the coils layer. Next a layer of glue .001 in (25.4 um) thick and a film of Kapton also .001 in (25.4 um) thick would be added to each side of the sensor array and the entire sandwich baked into a tough flexible circuit.

C. Input/output Connections

Because of the dense packing of sensor elements and the many input/output lines, it would be desirable to have the I/o lines run the length of the Metglas tape away from the area of the sensor array. They could then be spread out and patched into a standard connector using hybrid technology (Fig. 5).

The individual input wires (Fig. 6) would be a part of a multilayer flexible circuit board and could transmit the current from a remote source. The array of wires would be folded so that the wires encircle the sensor elements, passing above and beneath. The flat wires in the vicinity of the sensor array would be .13 mm wide and 13 um thick etched on a 30 um thick film of Kapton so as to keep the skin as flexible as possible. Once past the other side of the sensor array, the individual flat wires would terminate in a common return line which would return to the power source. Thicker, flexible circuit board and wider lines could be used away from the sensor array.

IV. Data Acquisition

Fig. 7 shows a strategy for achieving a raster scan and extracting maximum sensitivity from the magnetoinductive elements. The magnetoinductive elements would be arranged in rows and the flat wires above them arranged in columns. When a flat wire would be excited by a sine or square wave current it would emit an

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[+] It is a rule of thumb among hybrid fabricators that lines and spaces should be a minimum width of 4 to 5 times the thickness of the material in which they are being etched. For example, a 4 um thick copper film can have lines and/or spaces as narrow as 16 um to 20 um, (we would use 20 um). Where the individual coils join top and bottom we would use a safety factor of 1.5 and hence these junctions would be along an area 30 um long and 20 um wide. It is a second rule of thumb that the maximum distance photolithography can be used to see over a 90° edge is 5 um. Thus, to be on the safe side we would etch only a 5 um groove in the Metglas. This groove would be at an approximate 45° angle.

a.c. electromagnetic field which would be transmitted to the sensor elements below. The sensor element in each column, directly below the flat wire is the element(s) of interest. The magnetic component of the electromagnetic field would react with the Metglas core of the magnetoinductive element, enabling this element to act like a step up transformer and produce a voltage. The magnetic field at the sensor element would be (neglecting shielding reflections):

$$H = \frac{I}{2\pi S}\left[\tan^{-1}\left(\frac{b+\frac{S}{2}}{R}\right) - \tan^{-1}\left(\frac{b-\frac{S}{2}}{R}\right)\right] \quad (1)$$

where:

H = magnetic field in amps/meter.
S = width of conductive strip in meters.
R = distance of conductive strip above (or below) sensor elements in meters.
b = distance that the point of measurement on the sensor element is displaced from the center line of the sensor element. This assumes the sensor elements are directly beneath the flat wires.
I = current in amps.

The voltage generated by each element would be $V = N\frac{d\Phi}{dt}$. A switching circuit would enable only a single row to conduct current, thus current would be able to enter the top side of the coils of each element in that row. However, the bottom side of the coils of each sensor element would be connected with the bottom side of the coils of the sensor element(s) in the adjacent row(s) on a column by column basis. Each of these columns would terminate on one side of a differential operational amplifier. Since we would know which flat wire is conducting current, because only one row of the sensor elements is permitted to conduct current and since each element in that row is connected directly to a differential operational amplifier, we could isolate the performance of the element in that row directly below the flat wire and measure its voltage output. Thus we could raster scan the entire array on an element by element basis.

The skin would be constructed with each sensor element having a flat wire directly above and below it thus b = o and the ratio of magnetic fields reduces to:

$$\frac{H(R)}{H(R_o)} = \frac{\tan^{-1}\left(\frac{S}{2R}\right)}{\tan^{-1}\left(\frac{S}{2R_o}\right)} \approx \frac{R_o}{R} \quad (2)$$

R_o = distance of the conductive strip above and below the sensor element in mm with no pressure applied (typically .5mm).

R = distance in mm with pressure applied (typically from .333 mm to .5 mm).

S = width of flat wire (typically .13 mm).

The maximum error introduced in equation (2) by using the small angle approximation is 5%.

V. Expected Performance

The sensor array will be addressed first. Following this the flat wire expected performance will be calculated followed in turn by rubber force analysis, system resolution, current and power requirements, cross talk between elements, temperature effects, data rates, and conformalness and mechanical properties.

A. Sensor Elements

1. Signal output

The expected signal output from each sensor element is given by the expression:

$$V = N\frac{d\Phi}{dt} \quad (3)$$

V = signal output in volts.
N = number of turns = 9.
Φ = magnetic flux in webers in the Metglas core of the sensor element.

Φ , in turn, is given by the expression:

$$\Phi = \int_s \vec{B}\cdot d\vec{s} = \mu_o \mu_r \int_s \vec{H}\cdot d\vec{s}$$
$$V = N\mu_o\mu_r \int_s \frac{d\vec{H}}{dt}\cdot d\vec{s} \quad (4)$$

$u_o = 4\pi 10^{-7}$ A/m.

u_r = relative permeability (assumed constant).

H = magnetic field in A/m.

s = cross sectional area of element core in m^2.

The x component of the H field is the component that passes through the coils of each of the constant width sensor elements. Therefore:

$$V = N u_o u_r W \int_{z_1}^{z_2} \frac{dH_x}{dt}\, dz \qquad (5)$$

where:

W = width of sensor element core.

As shown in figure 1b the magnetic field which would excite the sensor element would eminate from the flat wire directly above and below that element. This field would penetrate the sensor element from the its surface (along the Z direction). But since the core itself is a conductor, H_x would be attenuated as it penetrates. H_x is of the form:++

$$H_x(z,t) = H_{xo} e^{-z/\delta} \cos(\omega t - z/\delta) \qquad (6)$$

$$V = N u_o u_r W H_{xo} \frac{d}{dt} \int_{z_1}^{z_2} e^{-z/\delta} \cos(\omega t - z/\delta) \qquad (7)$$

We make the following substitution to simplify the integration:

cos (wt-Z/δ) = cos wt cos Z/δ + Sin wt Sin Z/δ
and operate on each of the 2 terms separately.

If we chose H_{xo} as the maximum value of H at the top of the Metglas core, then Z_1 = 0, Z_2 = 10 um (the core thickness).

$$V = N u_o u_r W H_{xo} \pi f \delta \left\{ \sin\omega t \left[e^{-\frac{z_2}{\delta}} \left(\cos\frac{z_2}{\delta} - \sin\frac{z_2}{\delta} \right) - 1 \right] - \cos\omega t \left[e^{-\frac{z_2}{\delta}} \left(\sin\frac{z_2}{\delta} + \cos\frac{z_2}{\delta} \right) - 1 \right] \right\} \qquad (8)$$

N = number of turns (9)

u_o = free space permeability 4 (10^{-7}) H/m

u_r = relative permeability

W = core width (304.8 um)

H_{xo} = maximum strength of magnetic field at top surface of core

f = magnetic field frequency

δ = core skin depth in meters

Examination of equation (8) suggests the following:

1. The signal output would be directly proportional to the number of turns N, the relative permeability of the Metglas u_r, the width of the core of each element w, the strength of the magnetic field incident on the surface of the core H_{xo}, the frequency of the magnetic field f, and the skin depth of the core δ . However u_r, f and δ are interrelated and increasing f would lower u_r and δ .

2. The signal output would be two sinusoidal wave forms, each at the same frequency; but of different amplitudes and out of phase with each other (Fig. 8).

The frequency of the resultant signal output would clearly be that of V_1 and V_2. The maximum amplitude of this signal could be determined as follows:

$$\frac{dV}{d\theta} = 0 \quad \text{at } V_{MAX} \text{ or } V_{MIN} \qquad \theta = \omega t \qquad (9)$$

solve for θ_{max}.

Substitute θ_{max} back into V and solve for V_{max}.

$$\frac{dV}{d\theta} = N u_o u_r W H_{xo} \pi f \delta \left\{ \left[e^{-z/\delta} \left(\cos\frac{z}{\delta} - \sin\frac{z}{\delta} \right) \right]_{z_1}^{z_2} \cos\theta + \left[e^{-z/\delta} \left(\sin\frac{z}{\delta} + \cos\frac{z}{\delta} \right) \right]_{z_1}^{z_2} \sin\theta \right\} = 0 \;; \text{Let } z_1 = 0,\ z_2 = z \qquad (10)$$

$$\frac{e^{-z/\delta} \left(\cos\frac{z}{\delta} - \sin\frac{z}{\delta} \right) - 1}{e^{-z/\delta} \left(\sin\frac{z}{\delta} + \cos\frac{z}{\delta} \right) - 1} = \tan\theta_{max}$$

We can now select a Metglas material and an operating frequency. We choose Metglas alloy 2605S-3 (Fig. 9), because it has a flat frequency response to 100 kHz, because it has a high permeability $u_o u_r$ and because it has a high saturation magnetization (1.58 tesla). We choose 70 kHz because it is a high frequency; but is well below the 100 kHz cutoff.

++Page 402, Engineering Electromagnetics, William H. Hayt, Jr., Fourth Edition, 1981. McGraw Hill, Inc.

We first calculate the signal output per sensor element for a 50 mA current through the flat wires. This is the maximum current that can be handled by standard multigate multiplexers.

Using equation (1) we calculate H at the surface of the sensor core = 15.6 A/m (.2 Oe). We must next estimate the of the Metglas at 70 kHz. We know $u_o u_r$ H = B. We also know u_o and we have a calculated value for H. Looking at the top graph of Fig. 9, we have the relationship between u_z and B for Metglas 2605S-3 as a function of frequency. Also since u_z has units of Gauss/Oe we know u_z represents $u_o u_r$ in gaussian units. Therefore we should be able to use curve fitting techniques to assume a value for B, read u_z and then plug this u_z back into the u_z H = B equation to see how the calculated B relates to the assumed B. We can then adjust our assumed B and repeat the process described above until this assumed B and the calculated B are approximately equal. We then have our best $u_o u_r$ value in gaussian units. This can be converted to MKS units and δ (skin depth) can be calculated+++ from:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (11)$$

δ = skin depth in meters
u = $u_o u_r$ (permeability in W/m^2).
u_o = $4\pi 10^{-7}$H/M
u_r = relative permeability of Metglas
σ = $8(10^5)$ MHOS/meter conductivity of 2605S-3 Metglas, (Fig. 9)
f = frequency

For the 50 mA case the curve fit occurs at B $\approx$ 3,600 Gauss, u_z = 18,000, f = 70 kHz. (We will use gaussian units while working with the graph on Fig. 9 then convert back to MKS units before we calculate skin depth). Since u_z has units of Gauss/Oe we know u_z H = B and $u_z = u_o u_r$. We can now convert u_z back to MKS units and calculate the skin depth δ. u_z = $2.3(10^2)$ Wb/Am and calculates to 15.9 (10^{-6})m. Knowing the skin depth and using equation (13) we can calculate θ_{max} = 1.29 rad. We can next use equation (11) and solve for V. (The reader is reminded that θ_{max} = wt in equation (11)). The calculations indicate that:

V = 2.6 mV. If we compress the skin 25% we calculate V = 3.5 mV and V = .87 mV. But our flat wires would impinge upon the sensor element core from two sides so: V = 1.7 mV and if the electronics can discriminate 4uV, we have a signal resolution of 425/1 or 8 bits.

It may be convenient to make the drive electronics more compact by limiting the current in the flat wires to 25 mA. This would result in a slight loss in sensitivity and dynamic range. In this case: V = 740 uV, and the dynamic range = 740/4 = 185/1 or 7 bits.

On the other hand, it may be important to get the maximum performance out of the skin by using a high current in the flat wires even if heavy duty current drivers must be used.* A flat wire current of .18 amps can be used without fear of saturating the Metglas core. It is difficult to curve fit with accuracy in this case; but it does seem clear that we would have $u_o u_r > 19{,}000$ gauss/Oe (2.388×10^{-2} Wb/Am and $u_o u_r$ H_{xo} = .8 tesla.
With these values we can follow the procedures outlined above to yield $\Delta V \approx$ 4mV. This gives a 9 bit resolution.

From the discussion above it is clear that the sensitivity of the sensor elements could be tuned electronically by changing the current in the flat wires. A variation of 4 bits should be easily obtainable.

2. Shielding

Shielding would be required for magnetic fields from D.C. to 70 KHz. RF shielding would be required mainly to prevent the skin from sensing reflections off metal objects with which it would come in contact (Fig. 10). Analysis indicates reflection off the shielding back to the sensor element would not be a problem.** The same shielding would protect against low frequency magnetic fields such as

+++Ibid; p400.

*This is entirely practical since the current drivers for the flat lines would be remote from the skin. The signal electronics would be uneffected.

**The author has a longer version of this paper which includes shielding analysis.

the earth's field. A 60 um sheet of Mu metal would suffice. It would be important to make the top and bottom shielding a single continuous sheet to allow the stray magnetic flux to flow around the skin and continue on its path.

3. Line And Coupling Losses

We will now estimate the signal losses that would occur through line losses, switching circuit resistances and coupling to operational amplifiers.

Since only a single sensor element would be permitted to conduct current at a time, the maximum line loss for the largest possible skin (100 mm wide) would be approximately 50Ω total. This would include the resistance of the 9 coils, the lead wire to the coils, the I/o's and the multiplexer/demultiplexer channels.

We could expect a total line loss of approximately 50 ohms. Referring back to Fig. 7 we note:***

$$V_o = \frac{R_2}{R_1}(V_1 - V_2) \qquad (12)$$

where $R_1/R_2 = R_3/R_4$, V_1 = signal output

V_2 = standard reference signal.

If we set $R_2 = 1\ M\Omega$, $R_1 = 1\ K\Omega$

$R_4 = 1\ M\Omega$, $R_3 = 1\ K\Omega$

We would get a gain of 1,000. At the same time our line loss of 50Ω would be compared to a loss of $R_3 + R_4$ or $R_1 + R_2$ or $1.001 \times 10^6\Omega$. Thus virtually all of the signal would be dropped across the op amp input resistor.

B. Flat Wires

Section VA.1 above shows that the maximum current in the flat wires would be .18 amps. If a flat wire configuration of .13 mm wide and .013 mm thick were adopted (as in Fig. 6), we would get, at most, a resistance of 4Ω total including the I/o's to the flat wires. This would result in line losses of .72V and .13 watts.

***Page 574 Micro Electronics, Jacob Millman, 1979. McGraw-Hill, Inc.

C. Rubber Force Analysis

The rubber structures (Fig. 11) would play a key role in linking the force encountered by the robot gripper and inductance changes in the sensor elements. Rubber acts like an incompressible fluid in which volume must be conserved. However, unlike an incompressible fluid which passes pressure to the walls of its container, rubber experiences internal shear stresses. For the model shown in Fig. 11b, the rubber is free to change its shape (no confining side walls) so that all force applied to the top of the rubber block goes into increasing the internal stresses in the rubber. Accordingly, the following equation may be applied:+

$$\frac{G}{\lambda^2 - 1/\lambda} = K_{oust} \qquad (13)$$

G = shear stress (psi)
$\lambda = h/h_o$ where
h = rubber thickness under compression
h_o = rubber thickness before compression

In the tactile sensor array the rubber could be compressed as much as 1/3 without degradation. The discussion that follows examines the relationship between the deformation of the rubber and the force per unit area causing the deformation. A linear relationship is desired.

Since the rubber of the skin has no confining side walls, G (shear stress) is directly proportional to downward tactile force per unit area.

G = KF/A; where F/A = Force per unit area.

Thus $K_{oust}(\lambda^2 - 1/\lambda) = KF/A$; and it is clear that the force and hence the pressure F/A is a function of λ.

The linearity of this relationship will now be explored. Expanding in a Taylor's series about λ_o we have,

$$\frac{F(\lambda)}{A} = \frac{K_{oust}}{K}\left(\lambda_o^2 - \frac{1}{\lambda_o}\right) + \frac{K_{oust}}{K}\frac{\partial}{\partial\lambda}\left(\lambda^2 - \frac{1}{\lambda}\right)\Big|_{\lambda=\lambda_o}(\lambda - \lambda_o) + \frac{K_{oust}}{K}R_m \qquad (14)$$

R_m = remainder term.

+Louis J. Zapas NBS, private communication

But $\frac{F(\lambda)}{A} = \frac{K_{ovs}\tau}{K}(\lambda^2 - 1/\lambda)$

So $$(\lambda^2 - \tfrac{1}{\lambda}) = (\lambda_o^2 - 1/\lambda_o) + \frac{\partial}{\partial\lambda}(\lambda^2 - 1/\lambda)\Big|_{\lambda=\lambda_o}(\lambda - \lambda_o) \quad (15)$$

The first two terms represent the region of linearity and R_m is the deviation from linear.

We know $\lambda_o = \frac{h_o}{h_o} = 1.$

$$\text{AND } \lambda = \frac{h}{h_o} = 1 - \delta \qquad \text{WHERE } \delta = \frac{\Delta h}{h_o} \quad (16)$$

Substituting the conditions of equation (23) into equation (22) and solving for R_m we get

$$1 + \delta + \delta^2 - \frac{1}{1-\delta} = R_m \quad (17)$$

Recalling $\delta_{max} = 1/3$, R_n max % deviation from linear = 5.6%. Since the sensor elements measure λ, the signal processing can assume a linear relationship between $F(\lambda)/A$ and Δh be at most 5.6% in error through 1/3 deformation of the rubber.

D. System Resolution and Sensitivity

System resolution for this skin would include spatial resolution, force resolution and pixel resolution. System sensitivity, however, would apply only in a spatial and force sense for each pixel.

a. Spatial resolution and sensitivity. Assuming a dynamic range of 8 bits per sensor element, we would have achieved 8 bits of signal amplitude when the rubber near the sensor element (Fig. 11a) was compressed 25% of its total height (25% X .5 mm)(2) or .250 mm. If the skin were to have a tread thickness of 1.6 mm, this too would compress 25% or .4mm. Thus we would have a total spatial sensitivity of $.650\ \text{mm}/2^8$ = 2.539 um. Thus each pixel could resolve deformations of 2.539 um or greater on the tread above it. Increasing the thickness of the tread would degrade pixel spatial resolution and sensitivity though it would improve the ability of the rubber to conform around an object.

b. Force resolution and sensitivity tests have indicated that open celled sponge rubber can be ground to a thickness of .5 mm and can be repeatedly compressed 1/3 of its unstressed thickness without physical degradation. This 1/3 compression is a linear force-compression relationship to within 10% variance. The same tests on the sponge rubber indicate that a 1 mm thick sample compresses .125 mm in its linear region for each pressure increment of 1370 N/m^2. Thus each pixel would be able to detect pressures ranging from 27.8 N/m^2 to 7,124 N/m^2. This is calculated by setting up the ratio of 2.539 (10^{-6})m [spatial sensitivity] X $\frac{1370\ N/m^2}{.125(10^{-3})m}$ = 2.88 N/m^2 [force sensitivity].
The 8 bit dynamic range yields the 7,124 N/m^2 value.

The force resolution, sensitivity and dynamic range could be changed by using a stiffer rubber and/or greater distance between. If rubber of 65 durometer hardness were used and grooves put in it as per Fig. 11, the operating range of the skin would be approximately 260.6 N/m^2 to 6.67 x 10^4 N/m^2 with 260.6 N/m^2 being the threshold value. These value are calculated assuming 2.1 mm compressible rubber thickness (1.0 mm near the sensor elements and 1.6 mm tread thickness). The grooves as shown in Fig. 11 leave blocks of rubber .25 mm X .25 mm X 2.1 mm. The equation

$$\alpha = \alpha_{55} \frac{E_{55}}{E} \frac{(h\beta)^{2/3}}{\sqrt{A}} \quad (18)^{++}$$

Relates rubber compression to stress and the geometry of the rubber assuming no sidewall constraints.

α = percentage of rubber deflection used in the skin.
α_{55} = percentage of deflection of 1 inch cube of 55 durometer rubber used as a standard.
E_{55} = compression modulus of elasticity in psi of 1 inch cube of rubber used as a standard.
E = compression modulus of elasticity in psi in rubber used in skin.
h = compressable rubber thickness (inches).
β = ratio of length to width of rubber blocks used in skin.

++Pages 223,4 Design of Machine Elements, MF Spotts fifth edition, 1978. Prentice-Hall, Inc.

A = area of rubber block normal to force inches^2).

For the skin, α = 25% maximum, h = .083 in, β = 1, A = .0001 in^2.

$$\alpha_{25\%} = \alpha_{55} \frac{105}{145} \frac{[(.083)(1)]^{2/3}}{\sqrt{.0001 in^2}}$$

α_{55} = 1.814% corresponding to a load of 6.67 x 10^4 N/m^2 (10 psi) (shown in a graph in Spotts page 224). Thus the maximum load the skin can oppose and still be in the linear region (25% compression) is 6.67 x 10^4 N/m^2. With a dynamic range of 8 bits, the minimum detectable load per pixel would be 260.6 N/m^2. The force range could be moved into a much stiffer region simply by cutting less grooves in the compressible rubber (Fig. 11).

E. Current And Power Requirements

a. Sensor Elements

From section VA4 above we have estimated total line resistance across the sensor elements as 50Ω. This would include going through the multiplexer on one end of the system (Fig. 7). This 50Ω resistance would feed into the op amp port marked V_1 of Fig. 7. Since it would be desirable to use a differential gain of 1,000 for this circuit, we would typically set R_1, R_3 =1kΩ and R_2, R_4 = 1MΩ. $V_o = R_2 (V_1 - V_2)$ from eq. 19 when $R_1/R_2 = R_3/R_4$.
Thus the input impedance of each port of the op amp would be approximately 1M and the voltage line loss over the 50Ω negligible. From section VA above we know the coils in each sensor element would generate a voltage of approximately 2.6 mV. Thus we would expect a current of $\frac{2.6mV}{}$ at 2.6(10^{-9}) amps amounting to a power loss of 2.6(10^{-9}) amps 2.6(10^{-2}volts) = 6.7 (10^{-11}) watts -negligible.

b. Flat wires

Current and power losses across the flat wires were estimated above in section V.B as .25 amps and .25 watts respectively. Thus there would be very little power loss and heating effects in the skin area itself. Most of the heating effects would occur in the electronics driver and signal processing circuitry.

F. Cross Talk Between Elements

Since only one element at a time is enabled, there should be no cross talk.

G. Temperature Effects

It is expected that the Metglas cores of the sensor elements would be most affected by temperature variations. Manufacturer's data indicates that Metglas 2605S-3 can be operated from -50°C to 150°C. Manufacturer's data also states that Metglas 2605S-3 is superior to ferrites in that it can be used over a wide temperature range without cracking or showing large reductions in useable flux density. Product graphs indicate saturation inductance would drop $<$ .4 Tesla in 15.8 Tesla between C = 0° to 40°, the normal maximum operating range of the skin. This would be a 2.5% drop and should be representative of the expected performance of the skin as a whole.

H. Data Rates

In most cases the skin area would not exceed 100 mm X 100 mm in area and would have 40,000 pixels at most. With so many pixels it would seem most appropriate to use intelligent scanning. For example, if the scanning rate were 70 KHz, the computer algorithm might initially scan 1 out of 10 pixels in each row and column or 400 pixels. Thus the general outline of the part could be established in 5.7 millisec. Following this initial scan, the computer algorithm could restrict its scan area to that area with which the object has contact. A full image of this area could be obtained with a resolution greater than that obtained on a commercial 19 in diagonal television screen which has 512 lines by 512 lines. If this area remains too large, the computer algorithm could determine some representative points in the image area and monitor these, looking for slip, torque or forces.

I. Conformalness And Mechanical Properties

The flexible skin must not break, degrade in performance or have physical separations in its various layers because of mechanical stresses and strains. Also it must not have unwanted magnetostriction.

a. Resistance To Breakage

The most vulnerable points on the sensor array film would be the copper lines that connect the sensor elements of each column (Fig. 2) or row. These copper lines would be expected to stretch elastically at least 5%. However, the entire sensor array film would have a 25.4 um (.001 in) sheet of Kapton on its top and bottom. At 5% elongation manufacturer's data indicates the stress set up in each sheet of Kapton would be 78×10^6 pascals (13,000 psi). Thus even a narrow sensor array film 1.125 cm (.5 in) wide would resist 57.8 N (13 lbs). Also, since the sensor array film would be placed in the center of a sandwich of rubber, Kapton film (for the flat wires) and shielding material (Fig. 2), the strength for the entire 1.25 cm wide section of skin would be 222 N (50 lbs). This is more than adequate for the vast majority of applications. If more strength were needed 25.4 um thick strips of Metglas film could be added. These would strengthen the skin by $>$ 175 N (39 lbs) per centimeter of width.

Bending would not appear to be a problem. Metglas ribbons 30 um thick have been bent to a 6 mm (.25 in) radius with no ill effects.

b. Sensor Performance Under Stress

The performance of the sensor elements would be relatively unaffected by the stress and strain caused by skin flexure.

Metglas has a permanent magnetic bias along a linear axis, termed the easy axis (Fig. 12). That is, the material itself is a permanent magnet. If a wire coil is wrapped around a Metglass 2605S-3 core such that the axis of the center of the coil is perpendicular to the easy axis of the Metglass, and an a.c. current is passed through that coil, a highly sensitive strain gauge (or force feedback sensor) results (Fig. 12a).+++ This is precisely what we would wish to avoid. In the strain gauge configuration, the a.c. current in the coils would cause the magnetic domains to rotate (dashed lines Fig. 12a). Tensile strains on the Metglas perpendicular to the easy axis would inhibit the rotation of these domains (compressional strains would aid rotation). This perturbation in magnetic domain rotation caused by strains would result in a corresponding perturbation in the voltage output of the sensor element. Reorienting the sensor elements such that the easy axis is parallel to the coil axis (Fig. 12b) would minimize the problem. An a.c. current through its coils would cause the magnetic domains to flip back and forth on the easy axis; but this would not result in a perturbation in the voltage output of the sensor elements. For the skin, the magnetic field imposed on the Metglas of the sensor elements from the flat wire directly above it would be analogous to the situation shown in Fig. 12b. Thus the skin would be minimally affected by bending and flexing stresses.

c. Magnetostriction

It has been shown that when the magnetic domains rotate, the Metglas expands in the direction of the magnetic domains and contracts in the direction perpendicular to the domains (volume is conserved). Manufacturer's data shows a saturation coefficient of magnetostriction of 27×10^{-6}. With the configuration of Fig. 12b, the magnetostriction takes place only across the width of the Metglas core (.3 mm) or (.012 in). Thus the magnetostriction would be only 8.1×10^{-9} m (3.19×10^{-7} in), an insignificant amount.

d. Physical Separation of Layers

Physical separation of layers within the skin would not seem to present a problem (Fig. 3,4). The layers would not be applied at high temperatures so thermal separation should not be a problem. The Kapton layers would absorb most of the physical stress and thus spare the more ductile copper. The copper is applied on a relatively soft, flexible insulation layers which further protects it. Also, since the copper is at the center of the skin (Fig. 3,4) skin bending should not cause difficulty.

VI. Modularity and trimming

The skin would come in standard widths and lengths and these modules could be glued together on a gripper finger to form the total sensor array. In certain circumstances trimming one or more of the skin modules would be the preferred solution. Either or both solutions would be possible.

Assume we have a standard series of modules of 1 in (2.54 cm) wide modules

+++Mitchell, E.E. and Vranish, J.M. Magnetoelastic Force Feedback Sensors for Robots and Machine Tools; Proceedings, 12th Industrial Robots, June 9th-11th 1982, Paris, France pg. 131.

with lengths of 1 in (2.54 cm), 2 in (5.08 cm) and 4 in (10.16 cm). The same lengths would be available for 2 in and 4 in wide modules. All modules would come in both left and right hand versions. A left hand version has the reference column on the left side of the skin and could be created by turning a right hand version over and gluing the tread to the bottom rather than the top of the skin. This would permit gluing the reference columns back to back and trimming irregular shapes (such as section B-B Fig. 13a) on the outside of each module. For two modules glued side by side, there would be a dead zone down the seam on the order of 2 mm. In most circumstances this would be an insignificant factor. If no seam were desired, a wide module could be used and trimmed to size.

Trimming both columns and rows would be permitted. In trimming columns, one would trim off the columns on the side opposite the reference column (Fig. 13). An entire column(s) or portion of a column(s) could be cut out (section A-A Fig. 13) without disturbing the flow of current through the inputs to the remaining sensor elements. Trimming rows would be accomplished by cutting away tread, shielding and rubber down to the flexible flat wire layers (Fig. 14 section A-A). This would be for the rows opposite the end of the module nearest the I/o's. The same technique would be used in trimming an irregular pattern (such as the diagonal section B-B, Fig. 13a).

VII. Applications

The magnetoinductive skin would provide a range of options to solve tactile and force feedback type problems. A few examples are given below.

A. High element density imaging skin

This would be a pad on a robot gripper finger in which the robot would require a great deal of tactile information such as: What part is being grasped? With how much force? Where on the gripper pad is it being held? Where on the part? The slip vector would also need to be measured. The gripper finger could be flat or irregularly shaped.

The high element density imaging skin could also be used as part of an inspection station which could perform inspections on finished parts, checking for burrs and verifying dimensional integrity. In the conceptual drawing shown in Fig. 15, an irregularly shaped part could be positioned in a quality inspection vice in which the jaws would each be covered with an imaging skin backed by a layer of compliant rubber. The robot would place the part in the vice. The vice jaws would close on the part with the skin partially complying around the part contours. The distance between the steel jaw faces would be known to a greater degree of accuracy than the tolerances of the part. It would also be known which skin pixels on vice jaw A would be directly opposite those on vice jaw B. The calibration technique shown in Fig. 15b would provide the data to determine how each set of pixels (one on jaw A and its opposite member on jaw B) senses the closing of the jaws and the compression of the rubber. As indicated in section VID above, we could expect to detect a 2.54 um spatial compression on the face of the rubber above a sensor element if the skin is 1.6 mm thick. But we only need to locate tolerances of .001 in (25.4 um). Thus we could make the rubber behind the skin 8 mm (.3 in) thick on each jaw. The system would be able to measure dimensions W_1 through W_n as shown in Fig. 15a. But the system would also be able to measure many points in the Y direction and we would, in fact, see a three dimensional pattern. Dimensional tolerances, surface deformaties and burrs would be detected wherever the part was in contact with the skin. The inspection would be done with the speed of electronic scanning. The robot could turn the part and two more surfaces tested until all three side pairs were examined. The exact placement of the part in the vice would not be important. This technique would not check all the points on the part; but would be a rapid and accurate way to check many of them. It would also give a good indication as to the general part quality.

B. Robot gripper pad

This would be a common application in which the robot would need information such as: how hard is the part being grasped? And is the part located squarely on the gripper pads? For this level of information a fairly large center to center spacing of sensor elements, such as 1 cm, would suffice. An analog output would be needed from each sensor element.

Robot grippers currently use strain gauges to measure grasping force and use rubber pads to hold objects. The robot does not have tactile information as to where the part is located on the gripper fingers. In using strain gauges, a cantilever bar, normally of steel, is designed and fabricated for each finger. Strain gauges are mounted on the cantilever bar and the subassembly is bolted into the robot gripper. Wheatstone bridge circuitry is typically used to discriminate the signal. The discriminated signal is then typically amplified, sent to an A/D converter and then on to the computer.

The magnetoinductive skin could be used to do the same job as the strain gauges with much less effort. The skin would be glued to the gripper finger in place of the rubber pad. The sensor element spacing could easily be set by wiring only the appropriate I/o's to the multiplexer and demultiplexer (fig. 7). Any sensor element spacing or pattern could be set. The circuitry shown in Fig. 7, would suffice with the results being fed directly into an A/D and then on to a computer. Each sensor element signal would represent an increment of force so the sum of the sensor element signals would represent the total force on the fingers. With 8 bit resolution per sensor element, the resolution for the total force on the fingers would be comparable with that achieved by strain gauges.

C. Microminiature pressure sensor

In this application a standard 1 in (2.54 cm) X 1 in (2.54 cm) X 1/8 in (3.2 mm) thick skin module could be trimmed to a much smaller size, say 1/2 in (12.7 mm) X 1/8 in (6.4 cm) X 1/8 in (3.2 mm). The central row could be excited by a 70 KHz source and two columns could be selected as outputs, the reference column and, probably, the center column of the 1/4 in wide segment of skin. These outputs could be connected to the legs of the differential operational amplifier as shown in Fig. 7. No multiplexers or demultiplexers would be needed. Also, no wheatstone bridge circuitry would be needed. The results would be a single element flexible pressure sensor with 9 bits of resolution.

D. On/off sensors

Any of the sensors from B through D could be turned into an on/off sensor simply by adding a Schmidt trigger behind the preamp shown in Fig. 7.

VI. Summary and Conclusions

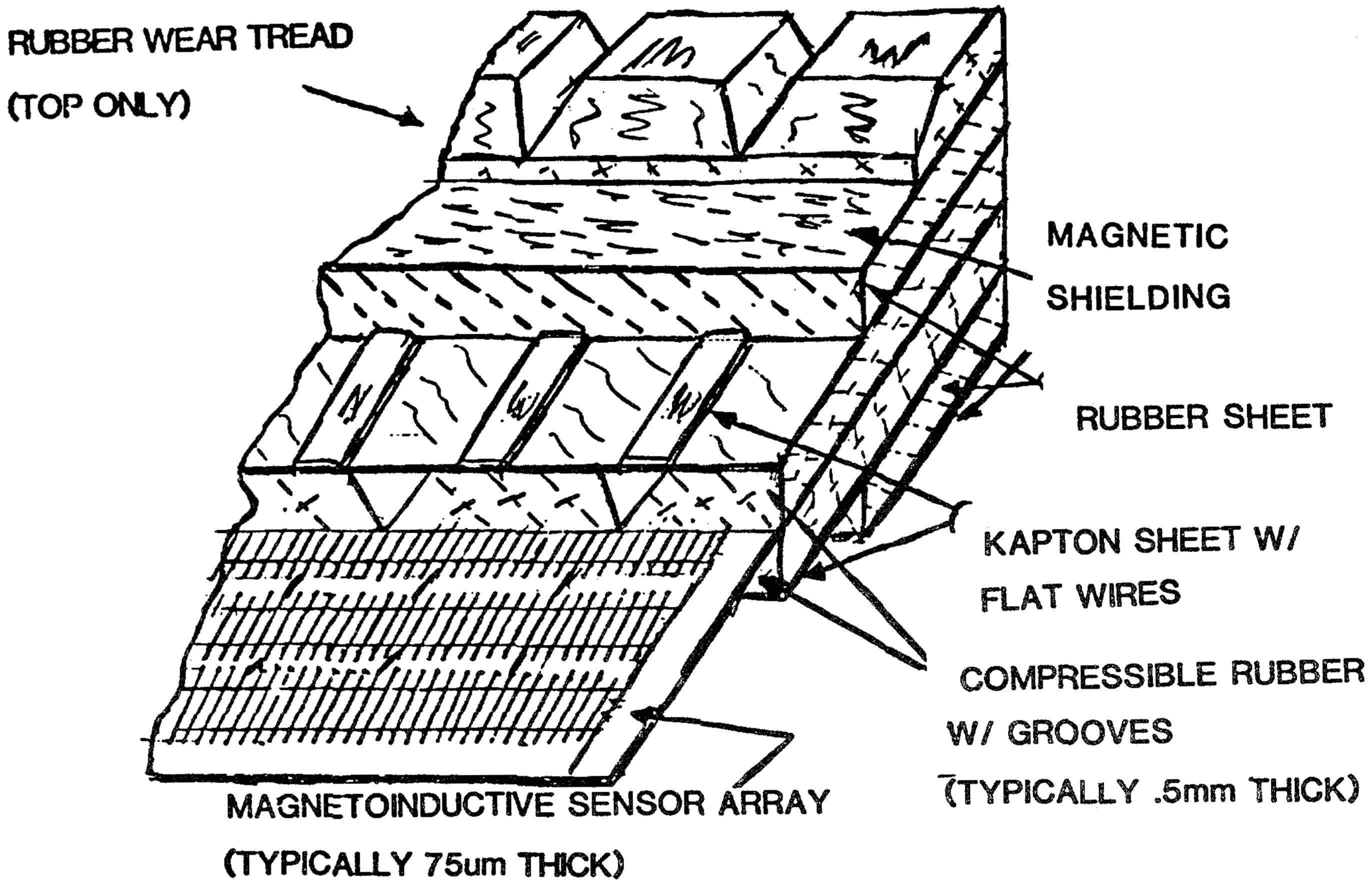
A flexible sensor array could be made of metallic glass used in an anti-magnetoelastic mode. This sensor array would form the basis for a wide variety of tactile sensors ranging from a simple microminiature pressure sensor to a high performance imaging skin. Signal output would be directly proportional to pressure (force) not based on rate of change of force with respect to time; thus signal processing would be simplified. Sensitivity could be varied electronically by a factor of 10. The electronics would be simple. Internal heat and external temperature changes would not present a problem. Stray magnetic fields and bending streses would also be easily managed. Despite the high density of the sensor elements, I/o's would be easy to access using standard connectors. Construction of the skin would be based on using photolithography techniques, masks and acid etching so the skin could be mass produced in a cost effective manner.

As an imaging skin, the sensor array would be high performance. It would have .5 mm between elements and 8 bits of resolution per element. A skin with a tread 1.6 mm thick would be able to detect movements of 3 um on the tread surface. If the skin were set up for force sensitivity (sponge rubber above and below the sensor elements) this would translate to a force sensitivity of 260 N/m^2 (soft enough to hold an egg).

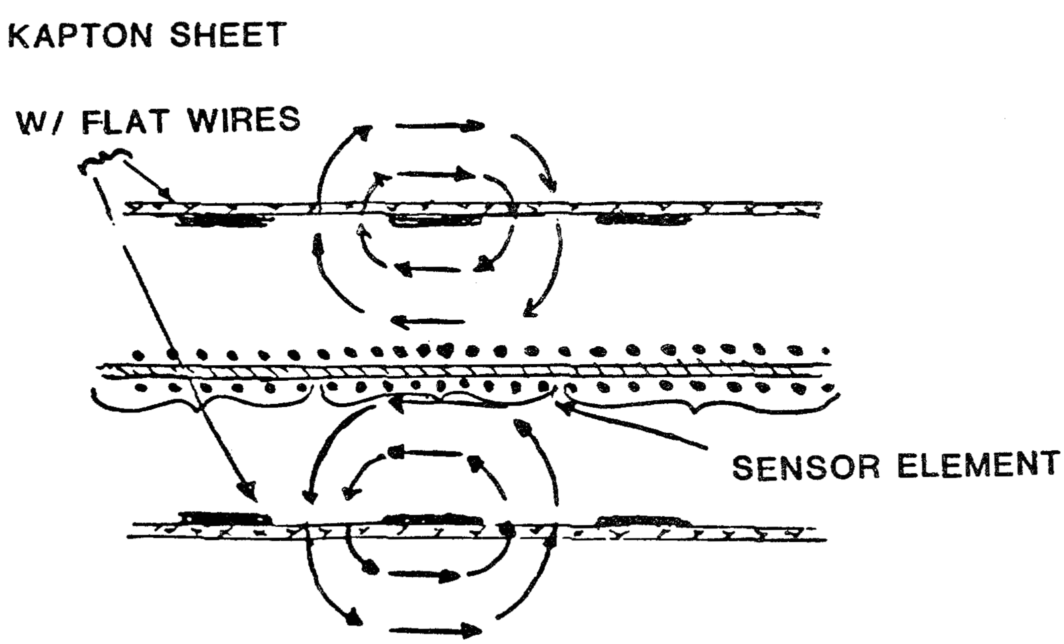
As a simple robot gripper pad, the array could be programmed for whatever sensor element density desired. The scan pattern and rate could also be preprogrammed. This would satisfy most robot tactile requirements without the extensive computer processing required in image interpretation.

As a microminiature pressure sensor, a trimmed down portion of the array could perform tasks normally done by strain gauges or pressure sensors. It could be made nearly as compact as required 1 cm X .5 cm X .3 cm (thick), its bridge and reference circuitry would be self contained in large part, its resolution would be 9 bits and it would be flexible.

The skin would come in modules and could be physically trimmed without affecting the performance of the remaining elements; thus nearly any size or shape skin could be assembled by the user.



a. SKIN CROSS SECTION



b.HOW A MAGNETIC FIELD FROM A FLAT WIRE
EXCITES A SENSOR

FIG. 1 MAGNETOINDUCTIVE SKIN

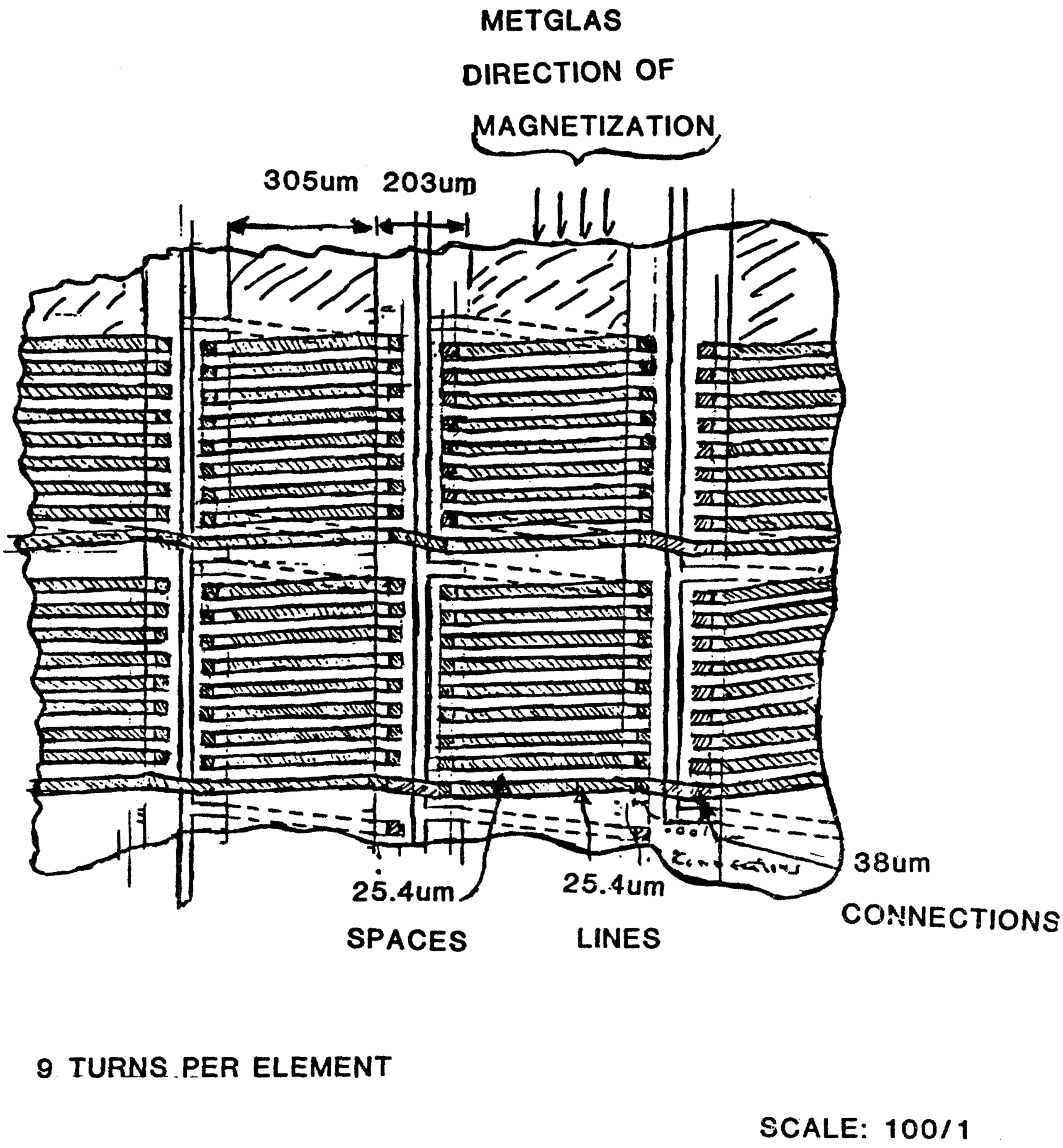


FIG 2. PHYSICAL LAYOUT OF SENSOR ELEMENTS

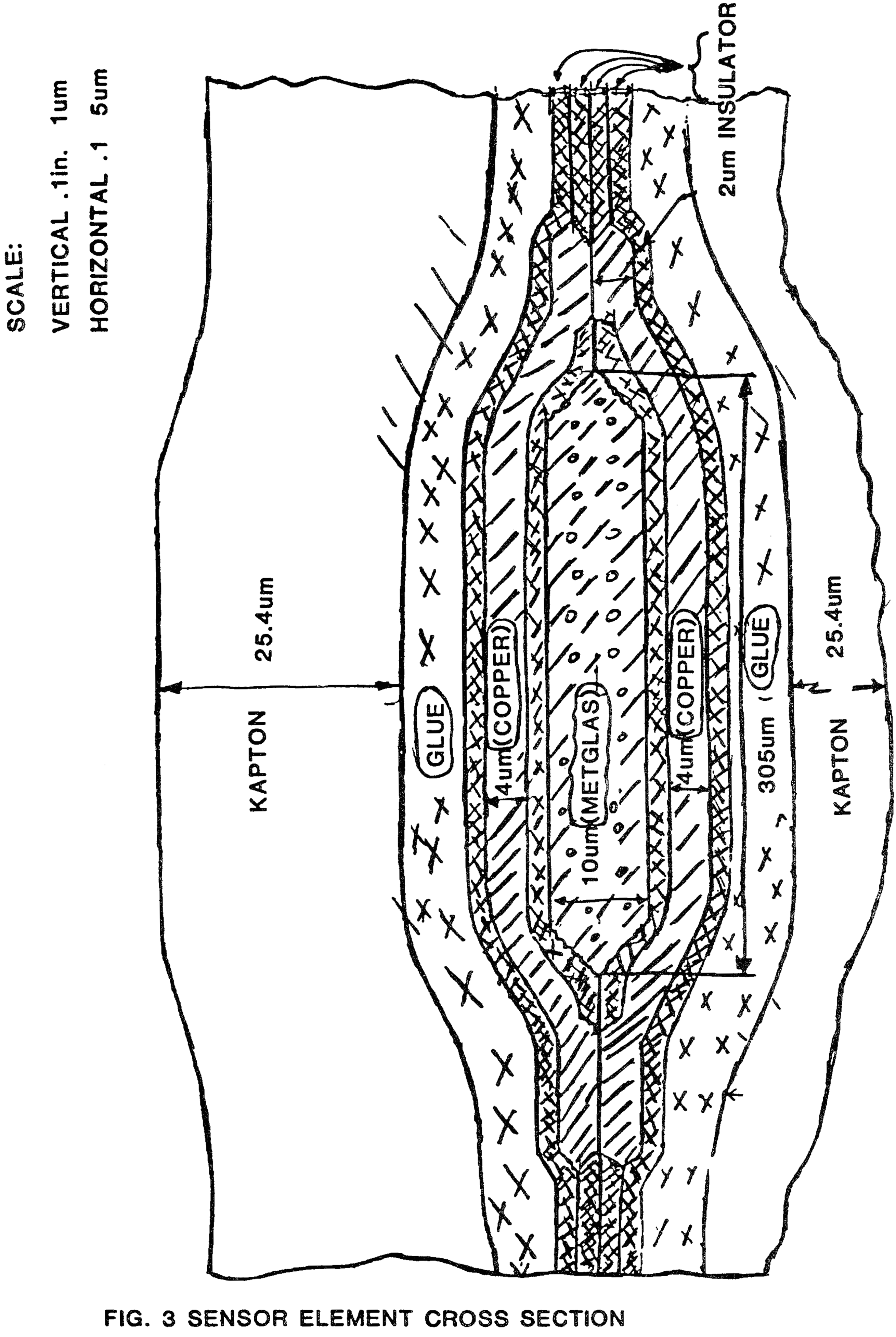


FIG. 3 SENSOR ELEMENT CROSS SECTION

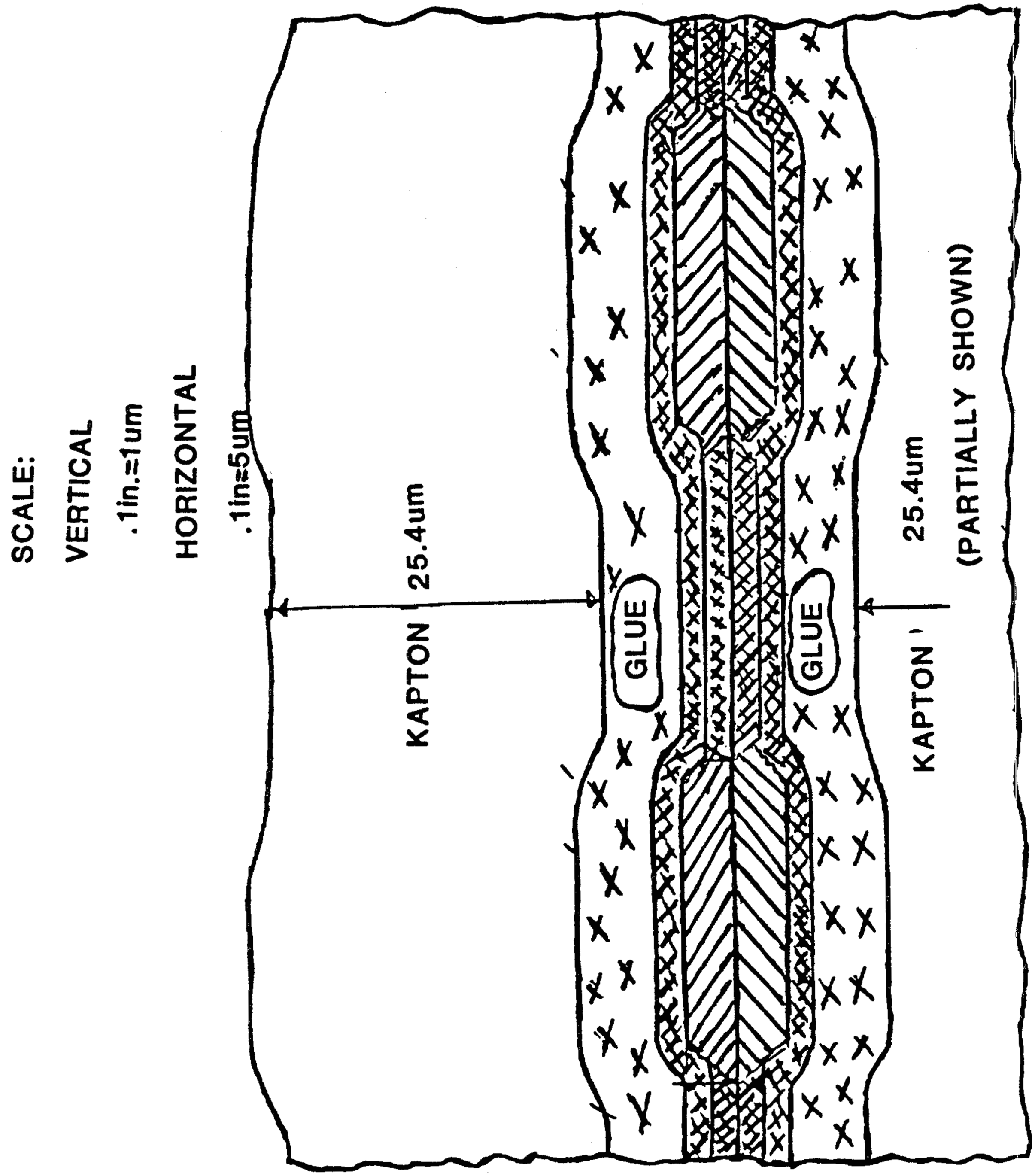
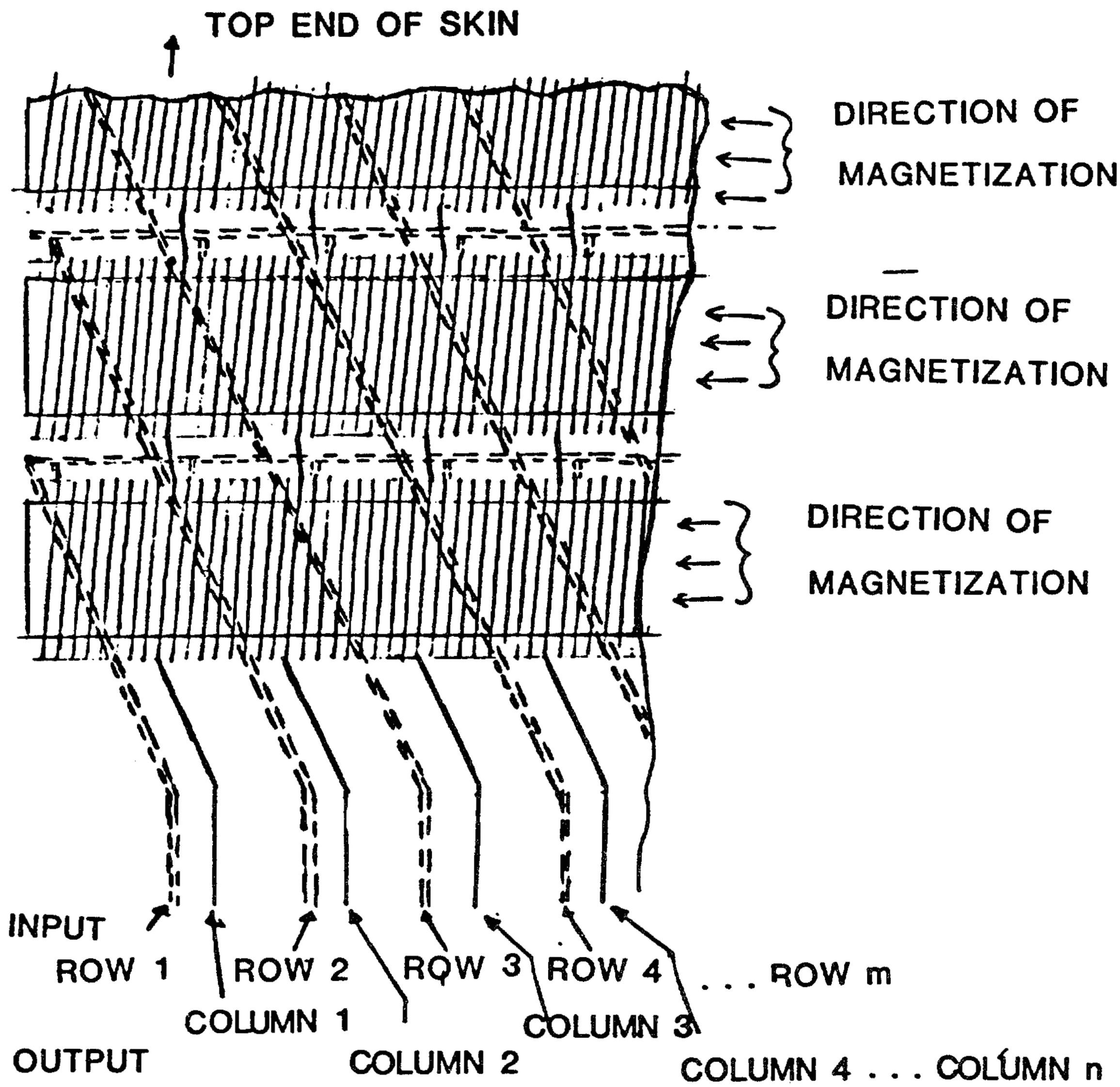


FIG. 4 END CONNECTIONS



mxn SENSOR ARRAY

FIG. 5 INPUT/OUTPUT LINES

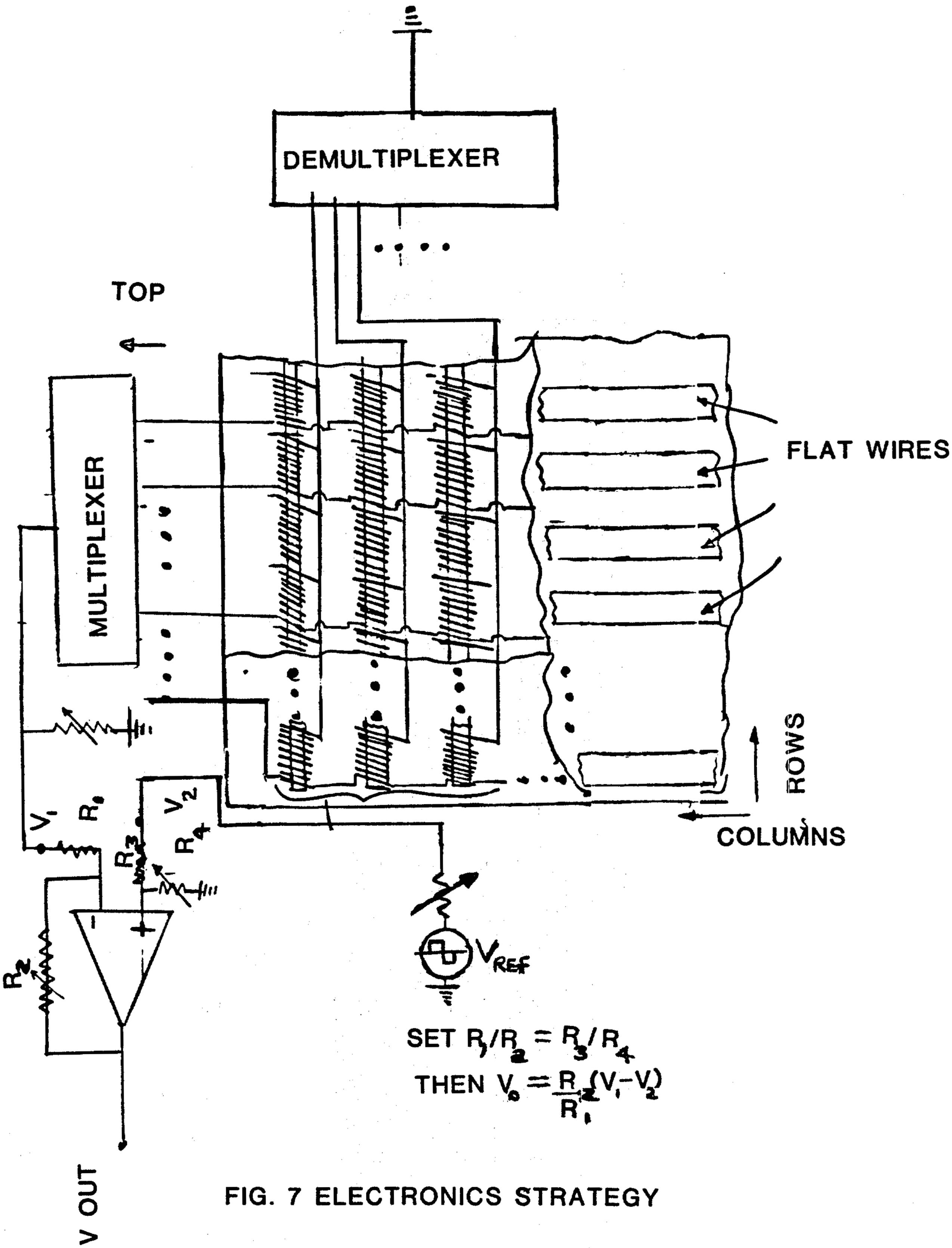


FIG. 7 ELECTRONICS STRATEGY

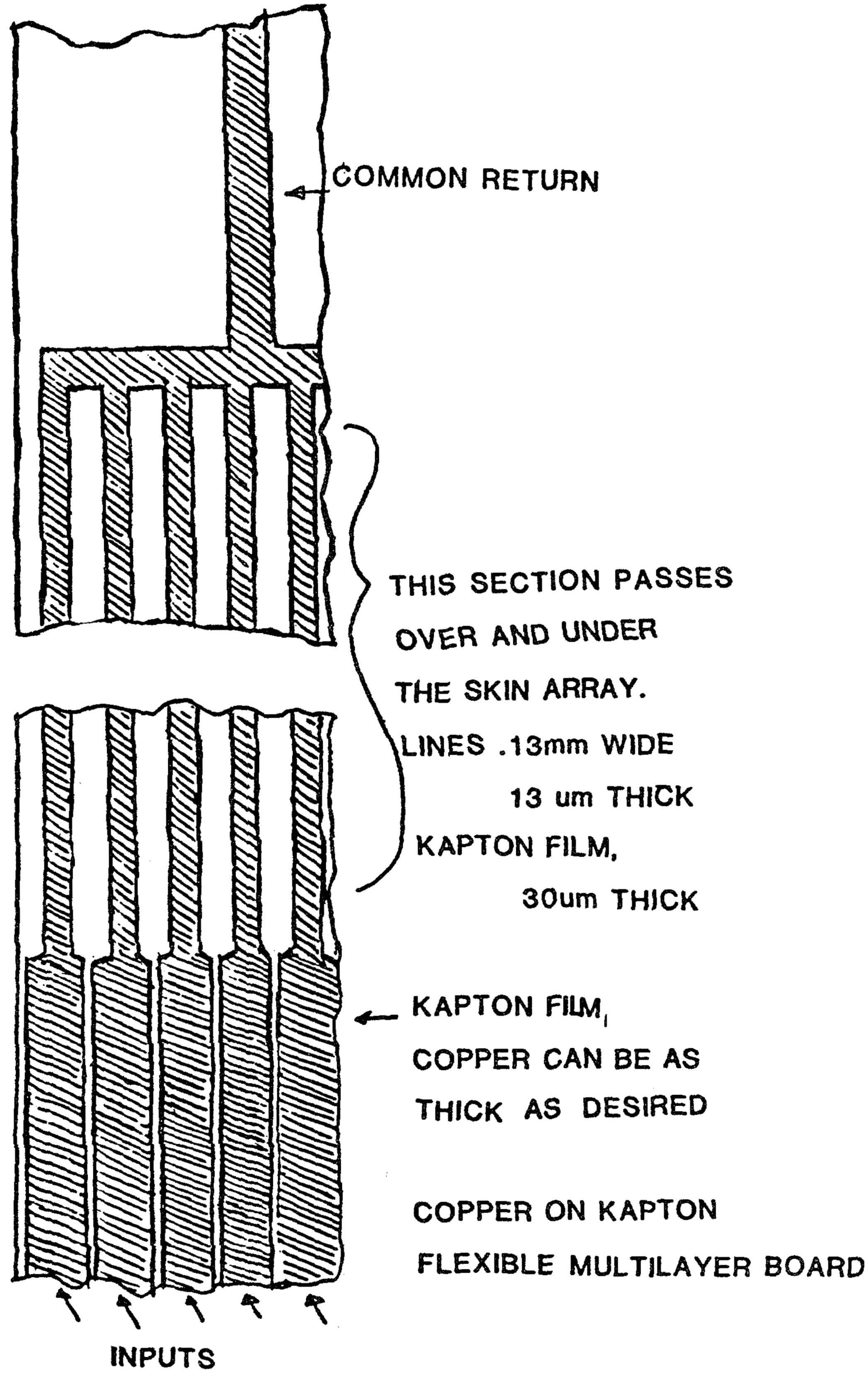


FIG. 6 FLAT WIRE INPUT/OUTPUT LINES

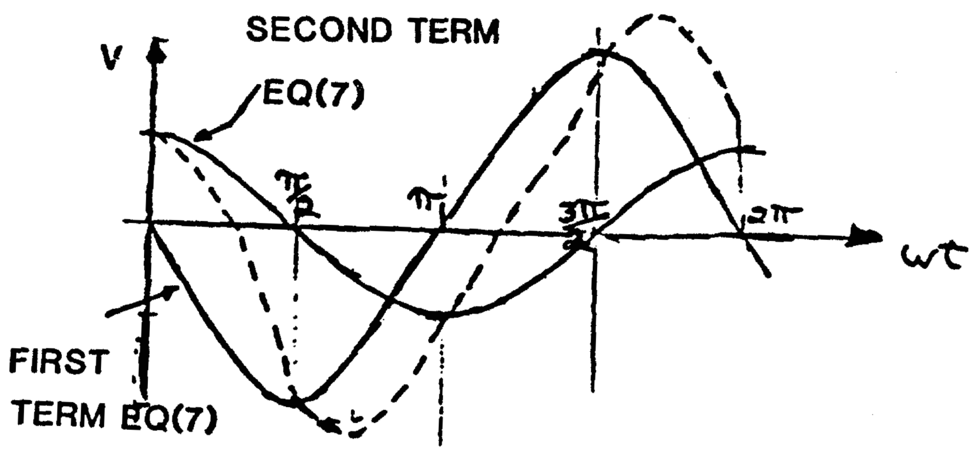
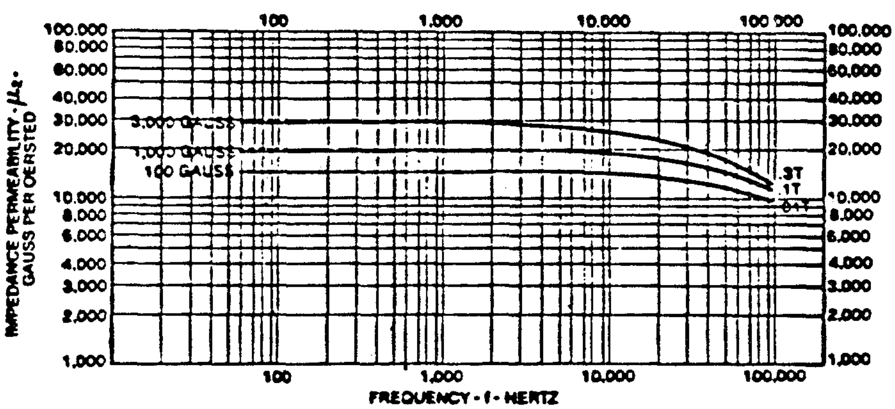


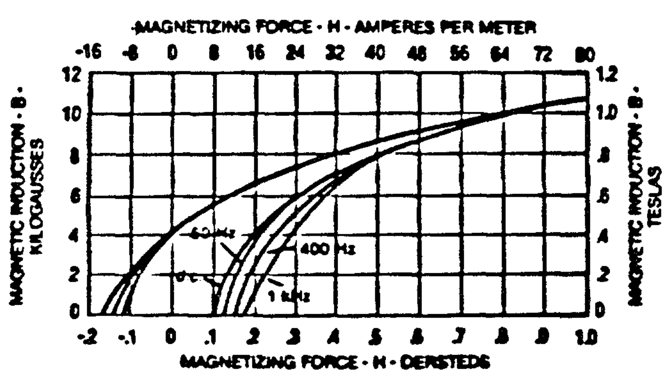
FIG. 8 OUTPUT SIGNAL WAVE FORMS

	Symbol	As Cast	Annealed
Magnetic Properties*			
Saturation Magnetization	B_s	15.4 kG	15.8 kG
Coercive Force	H_c	0.20 Oe	0.10 Oe
Residual Induction	B_r	3.0 kG	4.0 kG
Induction at 1 oersted	B_1	5.0 kG	11.0 kG
Curie Temperature	T_c	405°C	
Saturation Magnetostriction	λ_s	27×10^{-6}	
Physical Properties			
Density	δ	7.28 g/cm³	
Stack Factor	S	>0.75	
Crystallization Temp	T_x	515°C	
Continuous Service Temperature Range		−50°C to 150°C	
Electrical Properties			
Resistivity	ρ	125 μΩ-cm	

*All Values Typical

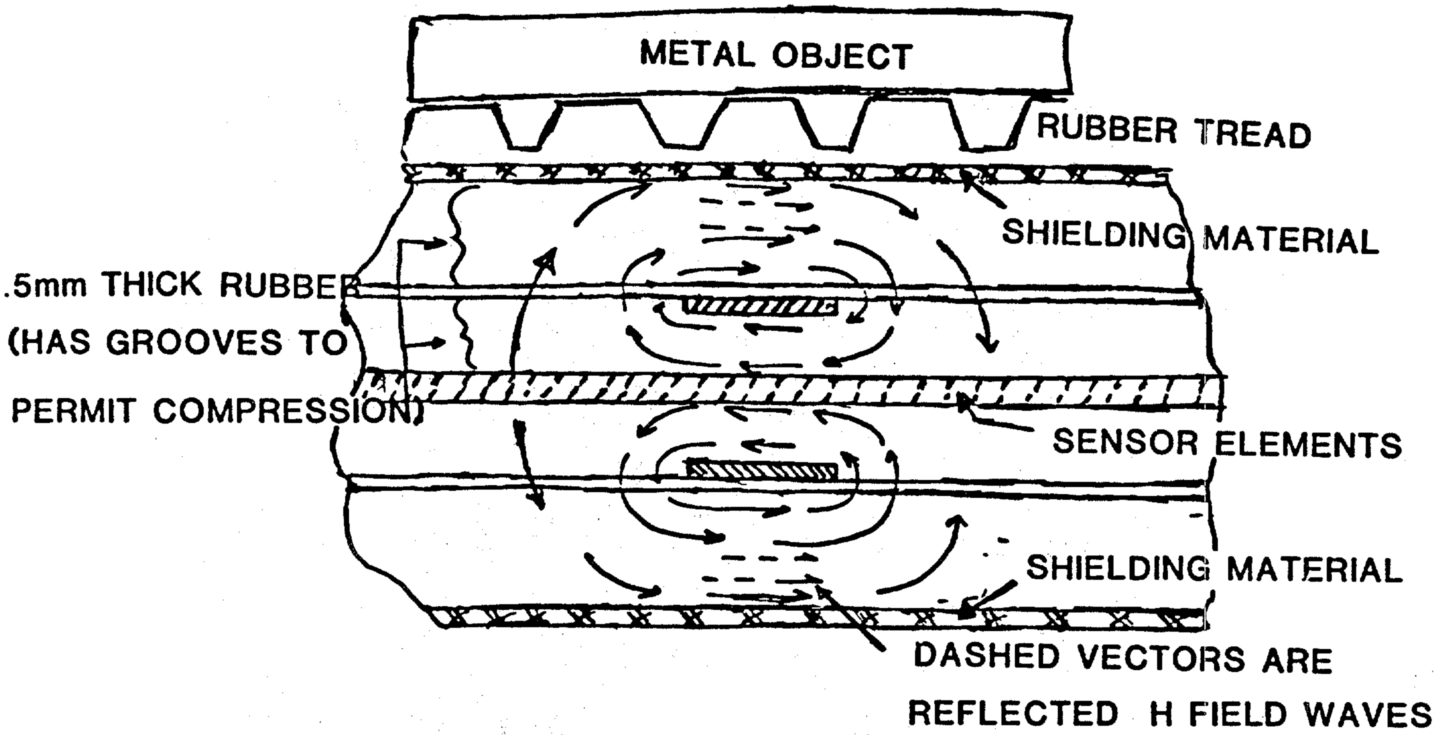


Typical Impedance Permeability Current METGLAS Alloy:

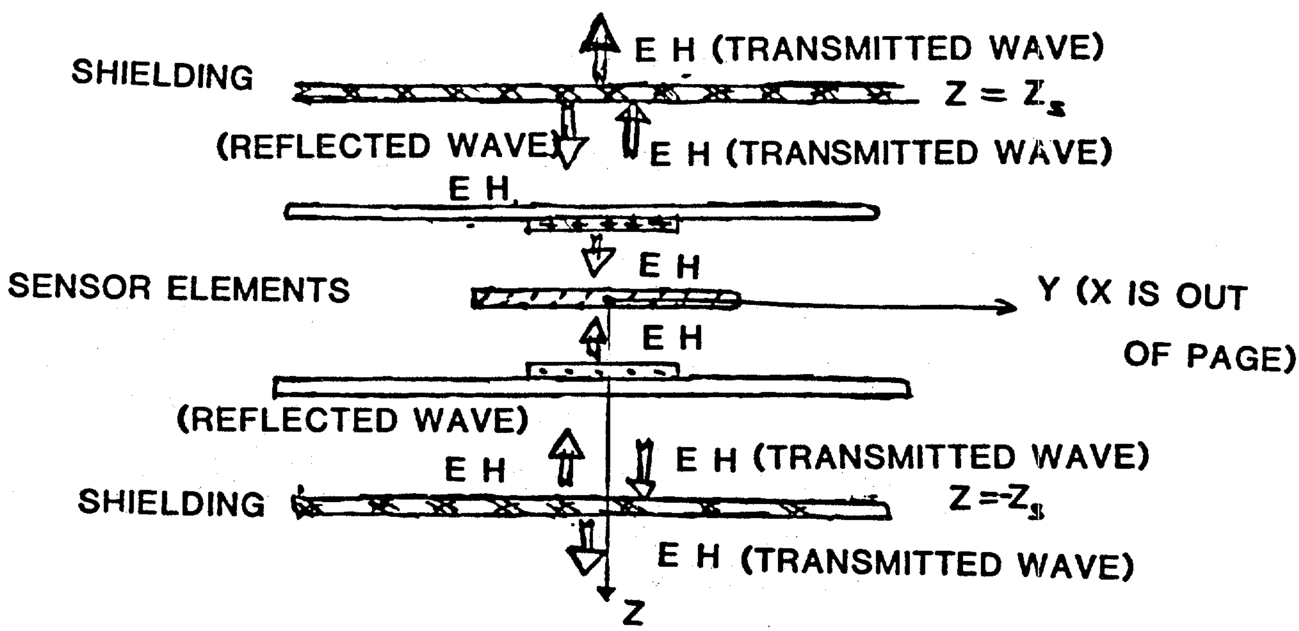


Typical Hysteresis Loops
METGLAS Alloy 2605S-3
Upper two quadrants with
ac sine current excitation.

FIG. 9 MANUFACTURERS'S DATA

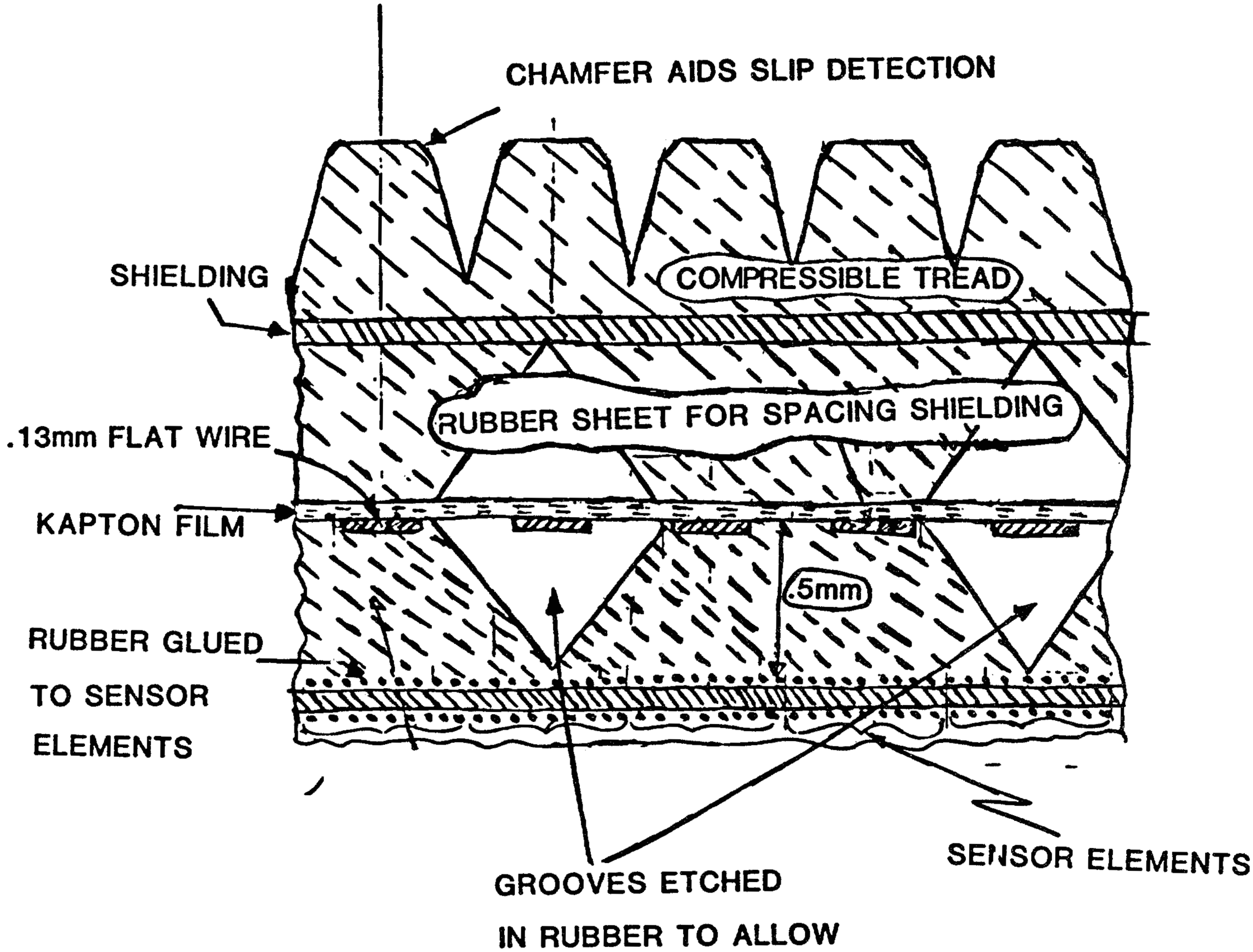


a. PHYSICAL CONSTRUCTION

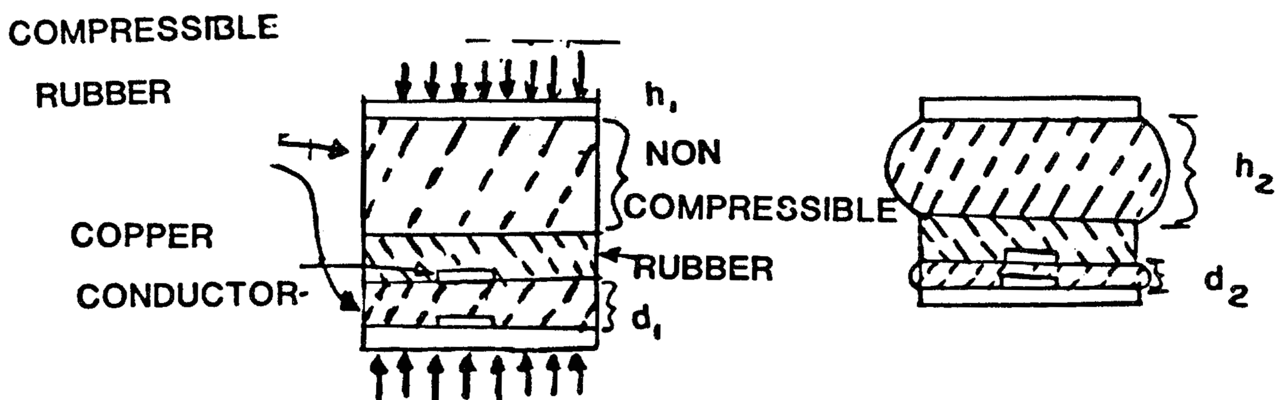


b. ELECTROMAGNETIC MODEL

FIG. 10 SHIELDING



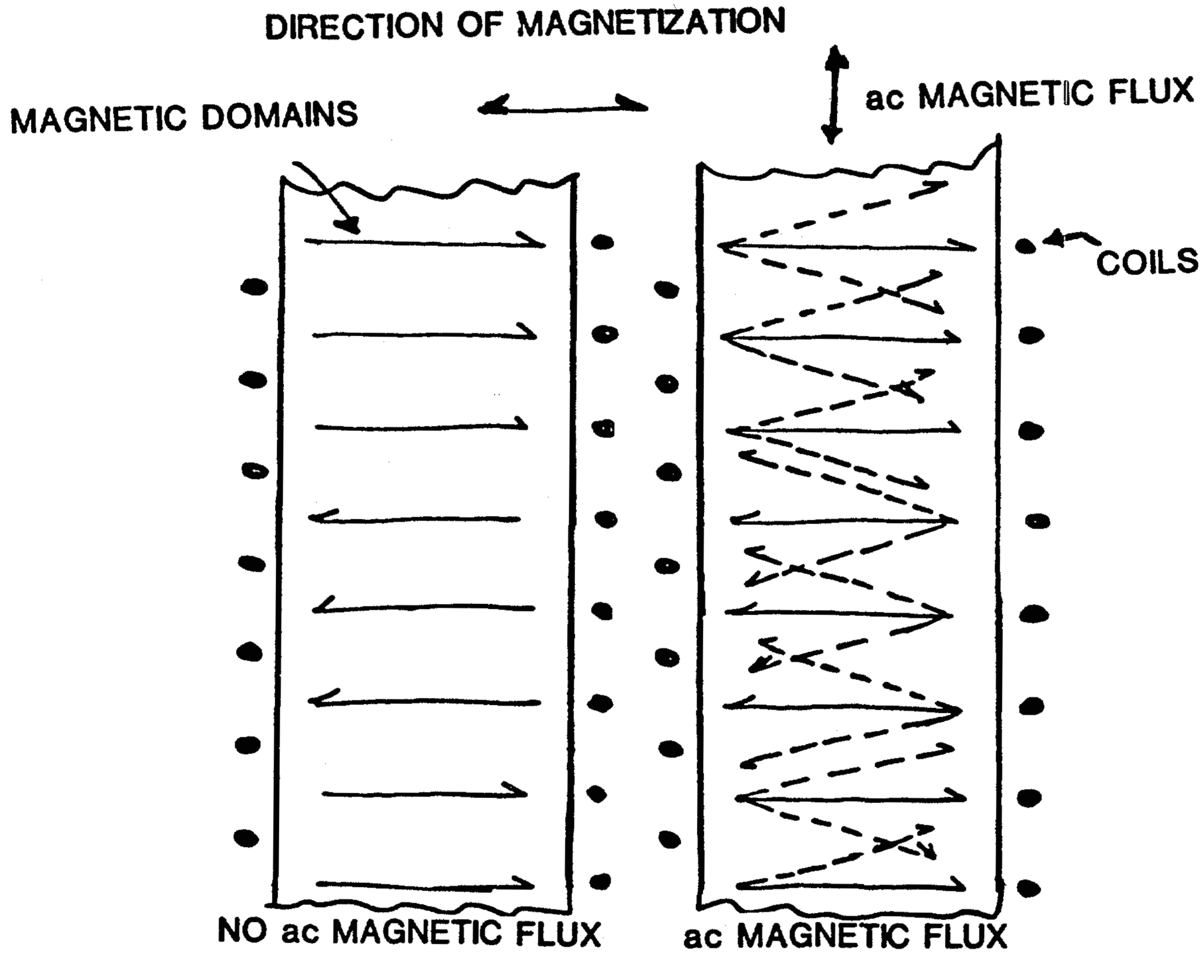
a. CROSS SECTION BLOW UP



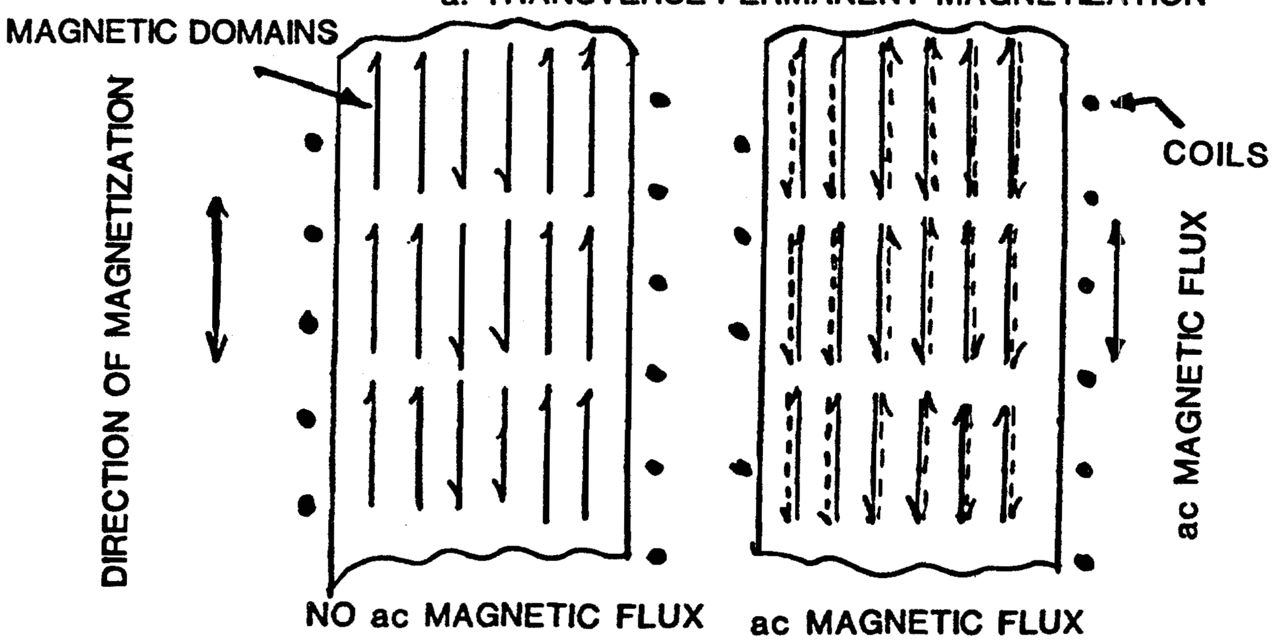
$$\frac{d_1}{d_2} = \frac{h_1}{h_2}$$

b. MODEL BASED ON RECTANGULAR BLOCK SPRING IN COMPRESSION

FIG. 11 TREAD AND RUBBER DETAILS

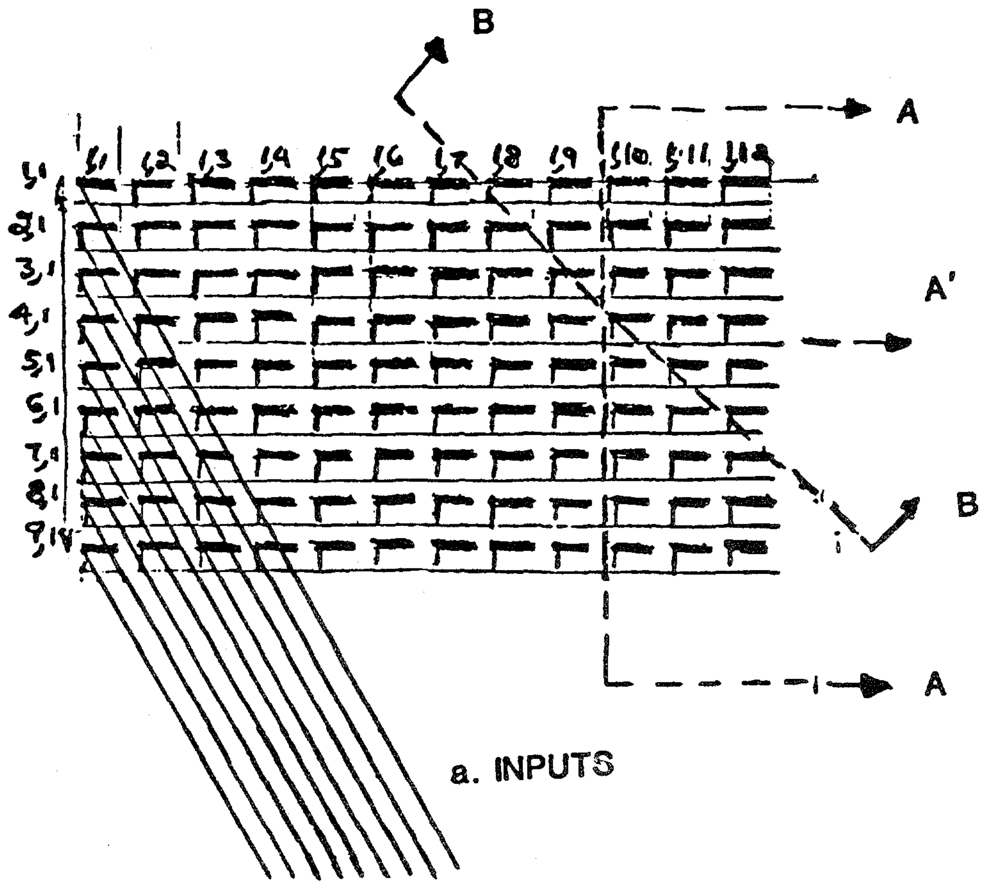


a. TRANSVERSE PERMANENT MAGNETIZATION

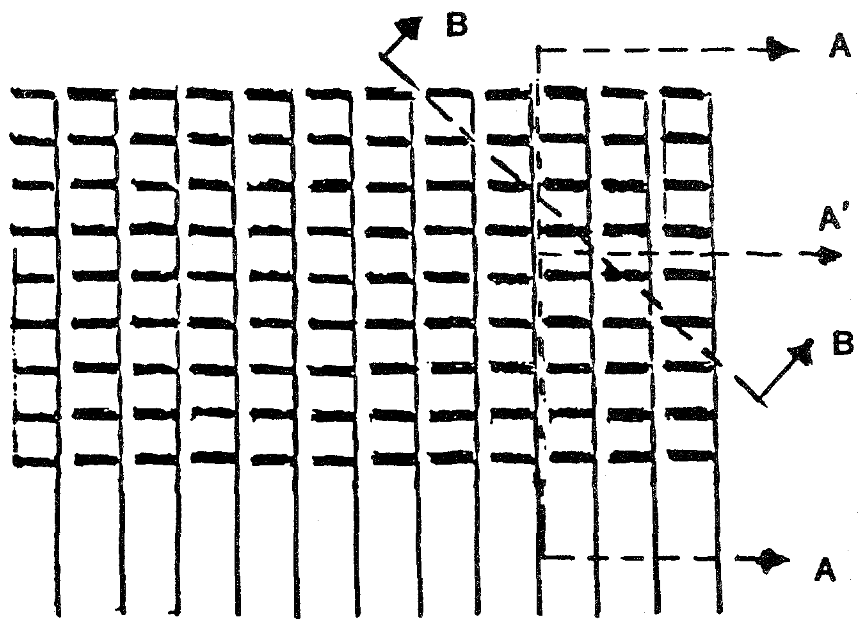


b. LONGITUDINAL PERMANENT MAGNETIZATION

FIG. 12 MAGNETIC DOMAIN MOVEMENT



a. INPUTS



b. OUTPUTS

FIG. 13 TRIMMING COLUMNS

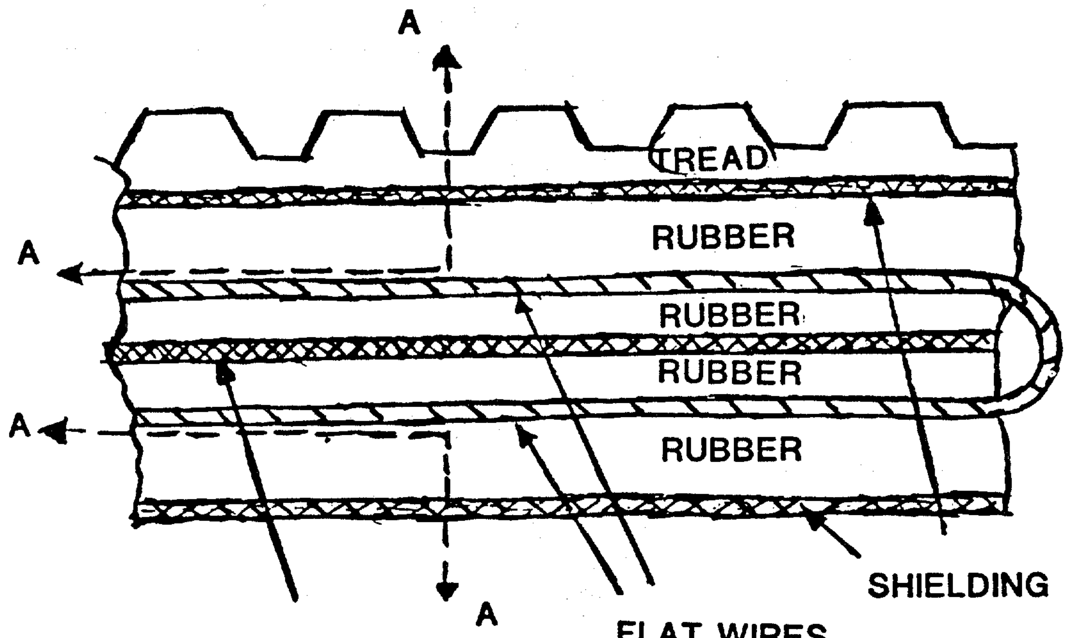
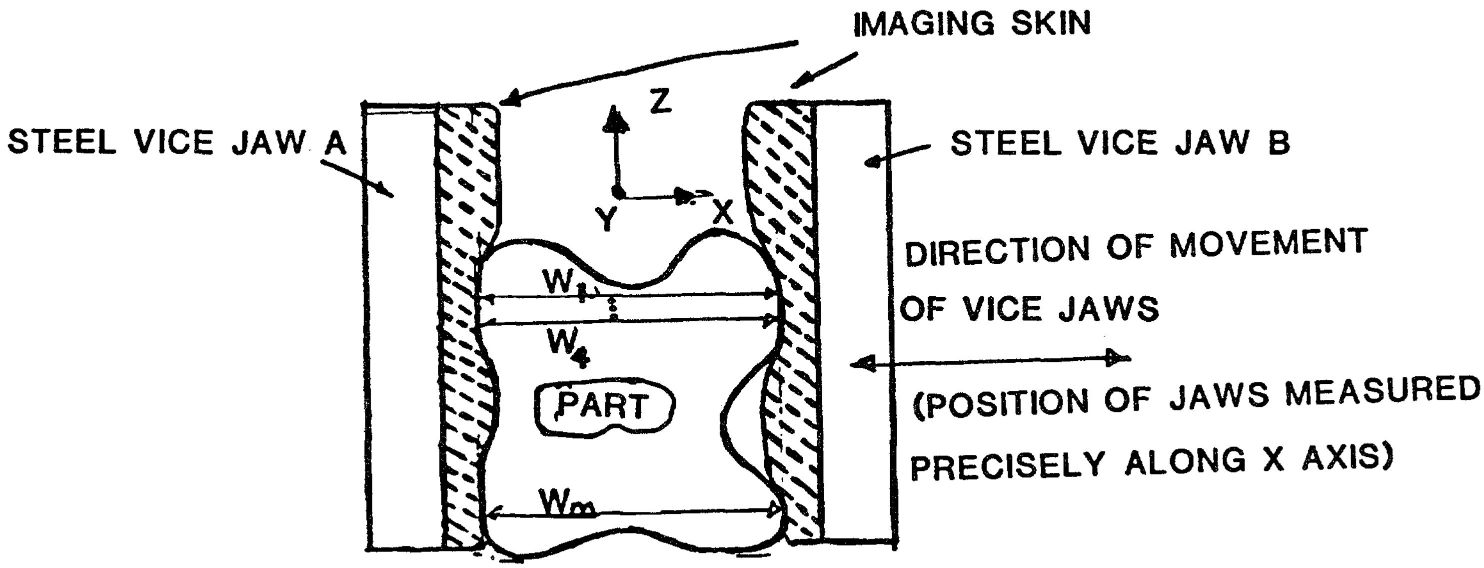
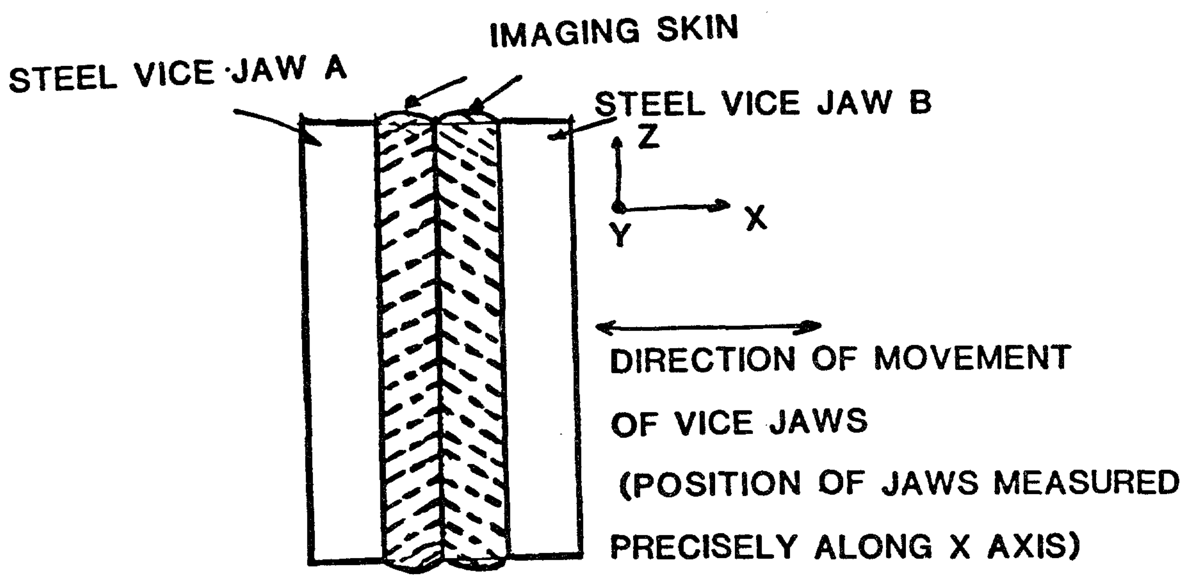


FIG. 14 TRIMMING ROWS



a. PARTS INSPECTION



b. INSPECTION DEVICE CALIBRATION

FIG.15 QUALITY CONTROL INSPECTIO DEVICE USING IMAGING SKIN