ENGINEERING CHARACTERISTICS OF CYLINDRICAL THIN-FILM PARAMETRONS FOR USE IN DIGITAL SYSTEMS

The National Cash Register Company
Electronics Division
Hawthorne, California

I. INTRODUCTION

The parametron, a phase-locked subharmonic oscillator, is one of the newer devices available to the system designer for use as a logical element in digital systems. The basic concept of phase-locked oscillators for logical operations has been discussed in the literature.\(^{(1)}\)\(^{(2)}\) Parametrons are inherently reliable, being composed of passive elements only, are potentially inexpensive, and possess a unique universality since one basic type of parametron may be interconnected to perform all logical functions (gates, flip-flops, comparators, etc.).

Compared to more conventional ferrite parametron devices, thin-film parametrons\(^{(3)}\) have several advantages. From a systems viewpoint, the most promising one is increased operating speed. The rotational properties of thin magnetic films permit an increase in speed over conventional ferrite units by an order of magnitude or better.

A parametron utilizing an electrodeposited thin-film on a small cylindrical wire substrate offers many attractive features. The continuous plating technique used for preparation of the thin magnetic film results in improved uniformity at reduced costs.

Use of the substrate wire to carry the pump current provides a low inductance pump circuit, allowing a large number of parametrons to be driven from a single pump source, as well as providing close coupling between pump field and magnetic film.

II. BASIC PARAMETRON CONCEPTS

For a detailed review of parametron logical circuit operations, the reader is referred to Goto.\(^{(1)}\) However, a brief review of the basic functions performed by a parametron will be helpful.

The parametron is capable of implementing a complete logic system. As such, it has inherent bistability which exists in the phase domain, since the subharmonic oscillation can exist only in two distinct phase states which are 180° apart.

Directionality, the ability to propagate signals in one direction only, is complicated by the fact that the input and output for a parametron exists at the same two terminals. However, by means of a “three-beat” excitation system, this problem can be overcome.

The device possesses circuit gain, typically in the order of 60 db, and “live” storage may be provided by a closed loop of three parametrons circulating information in a ring. A unique feature of the parametron is its ability to provide logical inversion without delay. This may be obtained by reversing the winding sense of the input term to the input transformer.
Parametrons are basically threshold elements; as such, they are more efficiently used with logic written in majority notation. This operation involves the algebraic summation of all input signals to the parametron. The net signal provides the “seed” signal to establish the phase state of the parametron as the pump is turned on.

Since phase is a relative concept, a standard for comparison must be established in a system. This is normally done by connecting three parametrons in a ring and defining the state of the ring as a “one” for the entire system. All references to “one” or “zero” are made with respect to this ring. Aside from this restriction, normal concepts of majority logic will apply.

It may be seen that it is possible to mechanize, in a primitive fashion, “and”, “or”, “not” functions—the normal Boolean set. However, with a threshold device, the fan-in capability is rapidly dissipated in this inefficient mechanization. For example, the parametron to be described here has a fan-in capability of 7. This allows only four-input Boolean gates. However, it is known that, in many cases, a given problem can be implemented more efficiently using majority logic. This is especially true of comparators and carry circuits for adders. A unified analytic theory of majority logic design is slowly evolving but has not yet reached the refinement of present conventional Boolean logic synthesis.

III. DEVICE CONFIGURATION

Figure 1 is a circuit of a single cylindrical thin-film parametron element. A 20-mc pump current, approximately one ampere peak to peak, superimposed on 500 ma dc-bias, is passed down the substrate wire to provide pumping action. Inputs are transformer-coupled by one-turn loops through the ferrite toroid. Thus, a completely floating system with good common mode noise rejection is obtained. The use of a lossy core provides proper phase shift (theoretically 90°) of the seed current to achieve phase matching between seed current and circulating (tank) current of the parametron to be controlled.

For ease of application in experimental systems, parametrons are assembled in modules of 12 units as shown in Figure 2, each with appropriate input and output connectors. The plated wire is positioned in a slot milled in the board. An etched circuit strip on the back forms a return path reducing the inductance of the pump line. The 40-turn tank solenoids are preformed on an automatic winder, slipped over the plated wire, and assembled on the board, one piece of plated wire serving twelve parametrons. Resistors and capacitors are connected in normal fashion. The outputs are brought through sets of pins at the top for connection to the logical circuitry. The aperture through the input core is used for the logical input.

IV. WIRE PLATING PROCESS

The electroplated wire is prepared in a continuous plating process as shown in Figure 3.
Prestraightened 10 mil diameter beryllium-copper wire is first given a thorough cathodic cleaning, then electrochemically polished and chemically etched, and finally plated with 81Ni-19Fe alloy (permalloy) using a variation of Wolf's plating bath. A uniform magnetic field of 120 oersteds is applied parallel to the axis of the wire during plating to produce the uniaxial magnetic anisotropy. It should be mentioned that a plated wire with circumferential rather than axial anisotropy would perform in a similar manner. However, production of plated wire with axial anisotropy is a less complex process and is none-the-less suitable for this application.

The magnetostrictive characteristics of the permalloy are critical with regard to producing material of good uniformity. Insensitivity to stresses introduced during assembly also necessitates low magnetostriction. The magnetostriction is a function of the nickel-iron ratio and can be minimized by proper adjustment of the plating temperature.

Typical low-frequency B-H characteristics are shown in Figures 4(a) and 4(b). For a 1.2 micron-thick plate, the coercive force, \( H_c \), is normally 1.5 oersteds and the anisotropy field, \( H_A \), is 2.5 oersteds, when measured from the B-H loop. The threshold in the easy direction is above 90% of \( H_c \), and the hard direction loop remains closed up to saturation.

V. THEORY OF OPERATION

A phenomenological theory of operation for a cylindrical, thin-film parametron may be based on the concept of the permeability tensor of the plated film. If the film possesses axial anisotropy, a pumping current applied down the substrate generates a circular H field which causes \( \vec{M} \) to rotate in an effort to align itself with the applied field. As this field is varied sinusoidally, \( \vec{M} \) executes appropriate oscillatory motion. Thus, the film permeability, which is the slope of the B-H loop presented to the subharmonic tank coil, is made to vary, and a time-variable inductance due to pumping results. The variation is made symmetrical by superimposing the pump current on a dc-bias current. Using films with relatively high anistropy and low \( H_A \), it is possible to meet the criteria of parametric oscillation. The non-linearity may be enhanced by use of a film with \( H_A \approx H_c \).

Because the steady state subharmonic tank current is considerable (100 ma pp), the effect of the axial field produced by this current must be considered. The combined axial and transverse fields produce a three-dimensional B-H
trajectory (Figure 5) whose shape may be deduced from Figure 6.

The area traced out by points ①-②-③-④-⑤ over a subharmonic cycle may be considered as representing a power loss. Since the pump excitation field and the axial fields are sufficient to drive the film to the near-saturation region (saturation pumping), any increase in applied field (axial or transverse) will result in only a slight increase in area. Losses are therefore relatively constant if sufficient pump field is applied for “saturation” in the transverse direction, and the subharmonic tank current provides the axial field to “saturate” in the axial direction. The shape of this area is determined by $B_{max}$, $H_a$, and $H_e$ of the film, which are carefully controlled and highly reproducible.

The perimeter of area ①-②-③-④-⑤ also represents the locus of varying permeability presented to the tank coil over a pump cycle. This varying film permeability determines the subharmonic oscillation buildup which is of the form (1)

$$i = KeA (\gamma - \delta)t$$

where

$$\gamma = \frac{2\Delta L}{L_a}$$

$$\delta = \frac{1}{Q}$$

The constant area caused by pumping to “saturation” results in a fixed $\gamma$ which, with the equally fixed $\delta$, tends to stabilize the oscillation amplitude and buildup rate.

VI. DEVICE PERFORMANCE

Previous mathematical treatments of parametron operation yielded only general, approximate solutions, and little information of operation in the time domain was available. To gain additional insight, a low-speed parametron was simulated on an analog computer. The data thus obtained was of considerable value for determining an advantageous operating point, judging the influence of phase shifts in signal and pump lines, and verifying results obtained with the actual high-speed parametron.

A. Choice of Pump Frequency

With the circuit $Q$'s possible, approximately 5 to 10 cycles are required for the parametron to reach steady state after the pump is switched on. Thus, the clock or gating rate is directly dependent upon the pump frequency $2f$. A high value of $2f$ is desirable from the viewpoint of high-speed operation. However, distribution of the pump current becomes more difficult...
with increasing frequency. The chosen frequency of \( 2f = 20 \text{ mc} \) is an engineering compromise which allows relatively high operating speeds (up to 300 kc), yet requires relatively simple equipment for pump generation and distribution.

B. Choice of Operating Point

The operating point of a parametron is determined by the excitation (pump) current \( I_p \), and the bias current \( I_b \). Figure 7 is a diagram of the region of operation of a typical parametron where the limit of operation was defined as an output current variation of \( \pm 4.2\% \), about a chosen nominal value of 4.8 ma. As will be shown later (Table II), a current variation of up to \( \pm 14\% \) can be tolerated for a fan-in of 7. Obviously, the highest safety margin is obtained by choosing an operating point in the center of the “operational area”. Additional factors influencing the choice are power consumption and limiting.

The power consumption, both rf and dc, should be kept to a minimum. Exploitation of the limiting mechanism, however, requires “saturation pumping”, i.e., a power level higher than the desired minimum power consumption. Thus, the choice of the proper operating point is a compromise between three partly conflicting conditions—optimum safety margin, minimum power drain, and optimum limiting.

Recognizing this, an operating point of \( I_p = 1,000 \text{ ma pp} \) and \( I_b = 500 \text{ ma} \) was chosen. This results in pump power of approximately 80 mw (gated operation) which includes some 35 mw of copper loss in the substrate alone. These values were determined calorimetrically. This pump power results in practical requirements for system pump generators. Figure 8 shows the waveforms of a typical parametron gated at 200 kc.

C. Fan-In Considerations

Parametron majority logic is based upon the phase differences of an odd number of ideally equal input currents. The input currents derived from practical parametrons, however, spread over a certain amplitude range. The possible number of inputs is primarily determined by this range of tolerances. Table I shows the input current tolerance restrictions for majority gates of three to eleven inputs.

<table>
<thead>
<tr>
<th>Number of Inputs</th>
<th>( I_{\text{min}} )</th>
<th>( I_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>( 2 I_{\text{min}} )</td>
<td>( I_{\text{max}} )</td>
</tr>
<tr>
<td>5</td>
<td>( 3 I_{\text{min}} )</td>
<td>( 2 I_{\text{max}} )</td>
</tr>
<tr>
<td>7</td>
<td>( 4 I_{\text{min}} )</td>
<td>( 3 I_{\text{max}} )</td>
</tr>
<tr>
<td>9</td>
<td>( 5 I_{\text{min}} )</td>
<td>( 4 I_{\text{max}} )</td>
</tr>
<tr>
<td>11</td>
<td>( 6 I_{\text{min}} )</td>
<td>( 5 I_{\text{max}} )</td>
</tr>
</tbody>
</table>

Due to the high tangential sensitivity of the plated wire parametron, only a small excess current is required to assure reliable phase locking. Analog computer simulation and experimental verification have shown that an excess current of less than 50 \( \mu \text{a} \) is sufficient to satisfy the requirements of Table I. For example, 7 inputs are feasible if \( 4 I_{\text{min}} \) exceeds \( 3 I_{\text{max}} \) by 50\( \mu \text{a} \). Table II shows the allowable

---

**Figure 7.** Region of Operation.

**Figure 8.** Switching Waveforms of a Typical Parametron.
percentage deviations of the nominal input current \( I \) for majority gates with 3 to 11 inputs. Here again, the required excess current determines by how much the listed ideal tolerance limits have to be reduced.

**TABLE II**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>( I ) ±</th>
<th>±</th>
<th>±</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1/3</td>
<td>±</td>
<td>33%</td>
</tr>
<tr>
<td>5</td>
<td>1/5</td>
<td>±</td>
<td>20%</td>
</tr>
<tr>
<td>7</td>
<td>1/7</td>
<td>±</td>
<td>14%</td>
</tr>
<tr>
<td>9</td>
<td>1/9</td>
<td>±</td>
<td>11%</td>
</tr>
<tr>
<td>11</td>
<td>1/11</td>
<td>±</td>
<td>9%</td>
</tr>
</tbody>
</table>

In addition to input current variations, at least three more factors limit the number of inputs, and warranted investigation. First, phase shift along the signal line reduces the effective component of the input current. Second, coupling between signal lines can alter amplitude and waveform. Third, jump coupling (to be discussed below) requires an increased excess seed current to overcome the influence of the backward leakage signal.

The analog computer simulation\(^8\) determined that the extent of allowable phase shift is \( \approx 20^\circ \). In a large system, some signal lines might exceed the maximum allowable length and excessive phase shift could result. In these cases, a buffer parametron, located next to the parametron to be controlled, can re-establish phase synchronism.

The buffer parametron, receiving only one input, is far more tolerant of phase shift of the input signal. However, in order to re-establish the correct propagation sequence, one additional clock cycle and two additional parametrions are sometimes required.

Coupling between signal lines and the resulting problem of amplitude and phase alteration can be kept within limits by judicious layout. To get a general feeling for the magnitude of this effect, the mutual inductance between two circular loops of six-inch diameter and three-inch spacing in the same plane was computed.

At 10 mc and a current flow of 4 ma pp in one loop, the induced voltage in the second loop will be 0.014 volt or 0.35% of the nominal output voltage of 4 volts pp.

In consideration of the above factors, the parametron was specified as capable of accepting 7 majority inputs.

**D. Fan-Out Limitations**

1. Jump Coupling. Figure 9 is the circuit diagram of three parametrions connected in series. Under normal operating conditions, parametron A will receive its input information from a parametron excited by Beat III. However, an undesired input may find its way from parametron C (which is also excited by Beat III) through the inactive parametron B into parametron A. An analysis of this network shows that a current, \( i_{\text{2n}} \), is generated in the inactive parametron B by the active parametron C and is given by:

\[
i_{\text{2n}} = \frac{e_c}{R_1^2 + 2R_1R_2 + \omega^2 (L^2 + C^2 R_1^2 R_2^2)}
\]

Substituting the values of the actual parametron

\[
R_1 = 10 \Omega \quad (Q = 3.14) \\
R_2 = 1k \Omega \\
L = 0.78 \mu h \\
C = 330 pf \\
\omega = 2\pi \times 10^7 \quad (f = 10 \text{ mc/s}) \\
e_c = 100 \text{ mv pp (measured)}
\]

one obtains

\[
i_{\text{2n}} = (0.015 - j 0.4) \times 10^{-3} \text{ a pp}
\]

The voltage \( e_c = 100 \text{ mv pp} \) is generated by a circulating current of \( i_{\text{c}} = 100 \text{ ma pp} \) in the active parametron C. The induced current \( i_{\text{2n}} \), circulating in the inactive parametron B, is
approximately 0.4 ma pp.* Assuming identical transformers, voltage $e_B$ across the input transformer of parametron B will be smaller than $e_C$ by the ratio $i_B / i_C$

$$e_B = 0.1 \times \frac{0.4 \times 10^{-3}}{0.1} = 0.4 \text{ mv pp}$$

Assuming, for purposes of this analysis, that the active parametron A presents an impedance network similar to its inactive one, the voltage $e_B$ will then induce a current $i_{2A}$ in parametron A of magnitude

$$i_{2A} = (0.015 - j 0.4) \times 10^{-3} \times \frac{0.4 \times 10^{-3}}{100 \times 10^{-3}} = (0.06 - j 1.6) \times 10^{-6} \text{ a pp}$$

The effective value of this current is approximately

$$i_{2A} = 1.6 \times 10^{-6} \text{ a pp}$$

The magnitude of the desired seed signal flowing in the $i_{2A}$ loop is $I_n = 10^{-3} \text{ amp}$ (as transformed to the secondary of the input transformer from $i$, flowing in the primary). Therefore, the ratio of desired to undesired locking signals equals

$$\frac{I_n}{i_{2A}} = 10^{-3} \times \frac{1.6 \times 10^{-6}}{625} = 625$$

This means that up to 625 third-generation parametrons ("grandsons") could be connected. With the chosen fan-out of ten (which results in a maximum of 100 grandsons) jump-coupling is of second order importance only for low fan-in circuits. It should be noted that the above ratio is computed for unity fan-in. The worst-case available seed signal for a maximum fan-in of 7 is considerably less, restricting the logical designer from complete freedom to use maximum fan-in and maximum fan-out simultaneously for several levels of logic.

2. Phase Shift. Figure 10 shows the equivalent output circuit of a parametron. The phase of the output current, $I_n$, is determined by

$$\tan \alpha = \frac{n \sum \omega L_n}{\frac{R_2}{1}}$$

* For a conservative analysis only the amplitudes have been considered, since any phase shift will weaken the influence of the jump coupling signal.

According to Reference (8), the required locking signal is essentially constant for phase angles between 0 and 20°

Thus, for $\alpha = 20^\circ$ and $R_2 = 1000 \Omega$,

$$\sum \omega L_n = 364 \Omega$$

should not be exceeded

With $L = 0.03 \mu \text{h}$ for a single input transformer, this allows a fan-out of

$$\frac{364}{2 \pi \times 10^7 \times 3 \times 10^{-8}} = 19$$

In addition, series resistance of the actual circuit such as core and wire losses will reduce the phase shift so that even a fan-out of 19 would be conservative.

The chosen fan-out of 10 is clearly within the limits imposed by jump-coupling and phase shift.

VII. ASSOCIATED EQUIPMENT

Since the parametron approaches a true "universal" building block, all operations in a given system will most likely be performed in phase script. However, it is obviously necessary to provide interface to the "outside world". The necessity of a simple and inexpensive technique for converting to and from dc to phase script thus exists.

Parametrons, whose inputs are derived from saturable reactors operating at the subharmonic frequency, have been used as simple dc-
phase converters. The following is a description of such a device suitable for operation at a subharmonic frequency of 10 mc.

A. DC-to-Phase Converter

The schematic of a dc-to-phase converter is shown in Figure 11. Cores A, B, and C are mounted on a small, clip-on device which can be attached to a single parametron in the 12-parametron module, converting it to a dc-to-phase input stage. Core D is the input core of the controlled parametron. The number of turns on each core and their winding sense are shown in the schematic. Cores B and C are mounted together and have a common dc (control) winding. The relative sense of the control and signal windings is such that no rf voltage is induced in the control winding.

Core A injects three "unit weights" of input to the output line, while cores B and C provide four units in the opposite phase, resulting in a net output of —1 unit. As cores B and C are driven toward saturation by the dc control field, their contribution to the induced signal in the output line decreases. If, for example, it is reduced to more than 50% of its normal value, the phase reverses.

Tolerance calculations for the circuits have shown an extremely wide operating range with regard to the applied dc control current, largely due to the high tangential sensitivity of the parametron. The chosen dc control current of 300 ma assures reliable phase reversal. A photograph of the device is shown in Figure 12.

B. Phase-to-DC Converters

The basic phase-to-dc converter requires a phase sensitive comparator. This is not as complex a circuit as one might expect. Since the phase and the amplitude are both quantized, the use of simple algebraic summing is possible.

With reference to Figure 13, basic operation is as follows: the outputs of two parametrons, one delivering a "constant" signal (for example, always "one"), the other, whose output is to be sampled, are fed to the input transformer of the comparator. Transformer coupling is preferred over direct coupling to eliminate any ground connections, to minimize ground loop noise, and to keep the entire parametron system floating and symmetrical to ground. This type of coupling is consistent with logical connections on the parametron modules proper. Input turns are kept to a minimum to allow the use of a standard logic output line for providing input signals to the phase-to-dc converter.

From the collection of the Computer History Museum (www.computerhistory.org)
If the input transformer is constructed with the same type core as used in the parametron modules, the inductive loading of the two input turns is equivalent to a fan-out of two. Since the input signal available from two turns is small, the secondary must be tuned to the subharmonic frequency (10 megacycles). Tuning rejects spurious noise and increases the output voltage. If the constant parametron provides input signals in the same phase as the unknown parametron, the two signals add and overcome the diode threshold, allowing rectification. However, if the constant signal is in opposite phase to the unknown parametron, the two signals cancel. The worst-case residual signal due to imperfect cancellation is insufficient to overcome the diode threshold.

Normal half-wave rectification is used with single stage RC filtering. Since the ratio of carrier frequency to modulator frequency is relatively low (~30:1), a pulse output up to 300 kc without “diagonal clipping” is difficult to achieve. Either more sophisticated carrier filters are necessary or the system design must be arranged to require no high duty-cycle outputs.

The dc voltage is now fed to a dc amplifier. Silicon diodes and a silicon input transistor are used to avoid L, problems. The output of the amplifier is sufficient to drive further amplifying circuits.

D. Pump Supply and Distribution System

The pump supply for operating parametrons corresponds to the power supplies for conventional logic. In this case, approximately 80 mw (at 20 mcs) per parametron is required in addition to dc-bias current.

A 20-mc supply, consisting of three identical channels capable of being gated at a 300-kc rate with appropriately overlapped pulses, was developed for use in a number of system experiments. The capacity of each channel is 25 watts cw. Each channel consists of three amplifier stages. The first stage, a 20-mc ECO, is common to all three channels. The output is distributed to each of three 7AK7 pentodes operating as gated amplifiers. The carrier is gated by 40-volt pulse signals applied to the suppressor grid. The third and final stage is a conventional, single-ended Class C amplifier employing a 6146 beam-power tube and driving a 17"-matching network to match to a 93-ohm output line. It should be noted that the use of a master oscillator-power amplifier combination is necessary since the preservation of phase coherence between all three channels is a requirement for parametron phase script logic.

A 17" output matching network is used because considerable sophistication is required in the pump distribution network for these frequencies. Distribution lines between the pump source and the parametron modules must be kept short. A special distribution transformer with a 93-ohm resistive input impedance was developed to allow driving from moderately long lengths of matched cable. For long runs, the cable lengths for each output (Beats I, II, and III) must be identical to insure matched phase shift due to cable delay in each line. This means that the pump supply can be located anywhere in the computer frame. Figure 14 is a

![Figure 14. Block Diagram of RF-Section of Parametron Pump Supply.](https://www.computerhistory.org)
Figure 15. Parametron Pump Supply Schematic of Cne Channel.

Figure 16. Block Diagram of Three Phase Gating System.

Figure 17. Diagram of Excitation Scheme.

block diagram of the entire rf section of the pump supply. Figure 15 is a schematic of a single channel.

Three different gating modes were incorporated into this pump supply: 1) 200-kc gating with nominal 33% overlap between adjacent beats, 2) manual gating with fixed overlap where alternately beats I, II, and III are energized, and 3) continuous mode where all channels run cw simultaneously. Operation in one of the three modes is controllable by a front panel selector switch. For the normal operation of parametron systems, 200-kc gating is used.

The 200-kc gating circuit block diagram is shown in Figure 16. It consists of a 200-kc Colpitts oscillator feeding sine wave signals to one-shot multivibrators through three phase shift networks so that each of the three one-shots is triggered with 120° phase shift. The output pulse width of each one-shot is adjustable so that the overlap between the turn-off of one channel and the turn-on of the adjacent channel is adjustable. This is ideally 33%. To compensate for the finite turn-on time of the parametron, a pump duty cycle greater than 33% can be utilized to make the overlap of the subharmonic signals equal 33%. The output of each multivibrator drives a voltage amplifier providing a 40-volt gate for the 7AK7 stages.

Manual gating is provided by a scale-of-three counter, with manual advance by a front panel push-button switch. This is useful in troubleshooting since the machine may be stepped through any cycle manually and any one state held continuously until manually advanced.

For the final mode, continuous gating, the 7AK7 gating tubes are switched to a dc level, allowing all channels to operate cw. This is useful for checking the phase of the 20 megacycle pump current in any parametron module.

In large systems with hundreds or thousands of parametrons, simple series connection of modules is unsuitable. Experiments have shown that the electrical length of the pump path in a single module of 12 parametrons is long enough compared to a wavelength, to cause severe standing waves if a number of these are connected in series. A distribution transformer scheme, shown schematically in Figure 17, was evolved, whereby a small group of modules, two in this case, are connected in series and driven from an isolated secondary winding. These are series-tuned to cancel module reactance; two such secondaries are coupled to a
given primary. All primaries are connected in series and driven from the power output stage through matching cable. All parametrons are connected in series for dc-bias. The various secondary circuits are isolated by rf chokes. The dc-bias is blocked from the transformer secondary by the tuning capacitors. The effect of this arrangement is that groups of parametron modules form a balanced network that is symmetrical to ground, minimizing the loading effects due to complex logic wiring. Ground loops are, of course, minimized by completely floating circuitry. Figure 18 is a photograph of one such distribution transformer.

VIII. SYSTEM EXPERIMENTS

A number of small systems, utilizing the 12-parametron modules, have been constructed and operated. One, a 6-bit shift register capable of automatic or manual circulation, is typical. The actual register is shown in Figure 19. Note the simplicity of the logic wiring which is basically point-to-point.

Also included in the register are a number of constant parametrons and input-output parametrons to allow simplified observation of the state of the register for laboratory studies. Waveforms of a 110000 pattern circulated at a 200-kc rate are shown in Figure 20. The blanking technique described earlier has been used for the display, making determination of the one and zero states quite simple.

A much larger network has been tested to allow demonstration of the worst-case fan-out capability. As discussed previously, the logical specifications for this parametron are a fan-in of 7 (majority gate of 7 inputs) and a fan-out of 10. The logical diagram of a worst-case network is shown in Figure 21. Basically, it consists of complementing flip-flop, parametrons P1, P2, P3, which form an alternating 1010 pattern. This output is used to lock parametron P4 which, in turn, drives the logical fan, P5 through P16. Each one of these latter parametrons in turn drives 12 more parametrons. It may be seen that 144 parametrons are operating in Beat I in the phase state opposite that of parametron P4. This delivers jump-coupling signals to P4 in phase opposition to the input signal from the complementing flip-flop.

Figure 22 is a photograph of a large array of parametrons, some of which are connected in the worst-case logic arrangement.
IX. CONCLUSIONS

The preceding discussions and data have presented characteristics of a highly practical, cylindrical thin-film parametron. In great measure, the practicability of this device is due to the construction, where thin magnetic film has been electroplated on a wire substrate. This technique allows continuous high-yield processing from a simple manufacturing facility, reducing tooling costs for production of the device. The use of the substrate wire itself as the pump conductor allows maximum coupling between the pump field and the film, providing a highly efficient pumping mechanism and reducing the pump power required for parametric oscillation. The assembly of parametrons into a basic module of 12 units allows one length of plated wire to serve a number of parametrons. This reduces the assembly cost of parametron modules.

The module design has been established; component tolerances are understood and have been shown to be practical. The module design is highly amenable to automated production techniques. Since the parametron is suitable for all logical as well as storage functions within the parametron computer system, it is a true universal logic element.

Since the plated film characteristics are highly uniform and since saturation pumping is used as well, a high fan-in capability is achieved because of the highly uniform subharmonic output. The logical fan-in of 7 is obtained for standard pilot line units. This results in an extremely powerful parametron from the logical designer's standpoint.

The ability to construct and operate large systems has been achieved with simple and practical pump distributing systems. Power requirements of the parametron are such that simple vacuum tube circuits of moderate cost are suitable for pump distribution. In the very near future, high power, high frequency transistor circuits will be competitive in price with existing vacuum tube circuitry at these frequencies.

XI. DEFINITIONS (10)

A phase-locked subharmonic oscillator is a parametrically excited resonant system with n stable states of phase where n is the ratio of pump frequency to subharmonic frequency. The subharmonic frequency of the described PLSO's
(parametrons) is \( \frac{1}{2} \) of the pump frequency. Thus, two stable states of phase are obtained, corresponding to "1" and "0" in a logic system. The subharmonic oscillation can be phase-locked by injecting a seed current of the desired phase into the tank circuit of the PLSO.

The seed current (input current) is a control current (small compared to the circulating tank current it controls) at the subharmonic frequency and is derived from the output of a controlling parametron and injected into the tank circuit of a controlled parametron which is excited by the following beat of the three beat excitation system.

The three beat excitation system or pump supply provides three channels of square wave modulated rf pump currents of sufficient amplitude to excite (pump) a given number of parametrons. If \( T \) is the period of the square wave modulation the turn-on times of succeeding beats are staggered by \( \frac{T}{3} \) so that only two of the three channels are operating simultaneously. This excitation scheme assures unidirectional information flow in the parametron majority logic system.

Majority logic is based upon the comparison of an odd number of input propositions. In parametron systems the phases of the seed currents are compared. The vector sum of the phase-states of the seed currents determines the phase of the output current of the controlled parametron.

X. ACKNOWLEDGEMENTS

A project of this scope is obviously the work of a number of people. In particular, we would like to acknowledge the efforts of Mr. R. Sloppy in many of the experimental aspects of the work; of Mr. L. Douglas for preparing the large amounts of plated wire to our specifications; of Mrs. J. Greenwell and Miss M. Roberts for their skillful assembly of modules and system wiring.

Discussions with Japanese scientists and engineers engaged in parametron research, in particular Dr. E. Goto of the University of Tokyo, Mr. Y. Hata of TDK, and Mr. K. Mori of Kanematsu, greatly added to our understanding of this new art.

XII. REFERENCES


8. V. K. Randery, "Parametron Simulation on an Analog Computer", to be published.

9. H. Takahasi and Kiyasu-Zen'iti, Editors, "Parametron", Parametron Institute, Tokyo, Japan (1960), pp. 139-144.