GRAPHICAL EXPLORATION IN ELECTRICAL CIRCUIT AND MODEL DESIGN

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Introduction

The value of interactive computer graphics to the process of design has recently been the subject of a number of investigations spanning a wide range of research objectives. One such investigation has been in progress at Imperial College, London, for the past three years; and had as its objective an exploration of the potential of interactive graphics for the design of electrical circuits. As engineers concerned with the actual application of a design tool, we set the investigation firmly within the context of an operational facility available for serious use by designers. Nevertheless, in view of the little that was - and still is - known about interactive graphic design, as well as the limited manpower available (approx. 4 man-years), the facility we chose to implement was a relatively modest one in terms of available analysis options. In the circumstances it was judged unwise to plan and initiate an extensive facility; what was essential was a flexibility to experiment with techniques within the gradual evolution of an acceptable design tool from which useful conclusions could be drawn.

The major characteristics of the facility are described below, and used as the context for comments concerning profitable areas for future research.

Circuit Design

The facility permits the frequency domain analysis of linear nonreciprocal 3-terminal electrical two-ports (e.g. a transistor amplifier) containing a maximum of 16 nodes, 50 two-terminal elements (±R, ±C, ±L) and 7 four-terminal voltage-controlled current sources. Input of the circuit diagram (Fig.1), as well as the numerical values of elements, parameters and frequencies, can be achieved very simply by means of the light-pen. The network function computed is the voltage loss between input and output ports, at 220 frequencies[1] between limits specified by the user. The result of the analysis is displayed, on the same screen, as graphs of magnitude and phase to a base of frequency.(Fig.2).

The computer system used is a PDP-9 with 16K of core store, a 250K disc and a DEC-340 interactive CRT display with light-pen. For the analysis of the larger networks a tied-line to a commercial Univac 1108 has been employed to reduce the time required for analysis.

Either for the convenience of the user, or to enable the characteristics of the facility to be studied, a number of additional options have been provided. They include

(a) A desk-calculator option, based on the teletypewriter, to permit the minor calculations often encountered in design,
(b) The provision of easily scanned operating instructions on demand, without loss of circuit,
(c) The computation and display of reverse transmission, and of the change in (forward) loss from a previously designated nominal case,
(d) The input and/or output of data via the teletypewriter, to permit comparison with purely graphic methods[2], as well as the accurate interrogation of circuit response at selected frequencies,
(e) The paper-tape storage of a circuit description, and
(f) A means of recording on magnetic tape, for later study, the manner in which the facility is used.

Most of these options illustrate our concern to provide a realistic working tool for the designer. This concern has, in fact, led to our concentration upon the problem of graphic man-machine communication, which we feel to be crucial to the general acceptance of any interactive graphic design facility. It has been our aim to render the computer as 'transparent' as possible to the designer, who should be able to concentrate on his problem and not be distracted by the computer. Thus, the underlying theme of this paper is the importance of man-machine communication and, more broadly, of system ergonomics.

Ergonomics

The ergonomic aspects of the facility, and the techniques employed to facilitate man-machine communication, are best illustrated by movie film. The film shows, for example, the use of a search pattern which permits the simple initiation of circuit drawing at any point on the display; the tracking cross need not be laboriously established in position. Reaction of the display is essentially immediate, and the drawing action resembles very closely the use of pencil on paper; there are no periods of blank screen to distract the user. Both the connection of an element symbol and its orientation are achieved by a single light-pen hit on the menu symbol; for each one-third of a second the pen is active the connected symbol rotates through 90°. Right-angle joining of wires follows de-activation of the pen, during line drawing, within tracking-cross range of a previously drawn line. Pen resolution in the selection of one of a number of closely spaced connection points is achieved by successive pen activation until a marker is sequentially moved to the desired point

The input of element and parameter values is straightforward. Numeric and multiplier light buttons (Fig.3) hit by the pen appear superimposed on the selected element, whose symbol now flashes (as a reminder of its type) at much reduced intensity. For later element value interrogation, a continuous pen hit on the VAL OUT button causes the circuit diagram to alternate between its normal state and one in which element symbols are replaced by values (Fig.4); either state can be 'frozen' by pen deactivation. This technique is capable of considerable exploitation where there is a need to display one or more circuit properties (such as sensitivity or dissipated power) that can individually be associated with the elements. During circuit analysis the traversal of an otherwise blank screen by a cross in the time required for analysis both reassures and informs the designer[3].

Application

The design facility has been employed as a tool in a variety of investigations, one of which concerned device modelling. In the choice of a model for each device in a network intended for analysis, many advantages accrue from a selection of the simplest model that is adequate for the given circuit application and a given allowed tolerance upon circuit performance. The proposal had been made that such a model could be derived automatically from a complex equivalent circuit model by the successive annihilation of model elements according to their effect upon circuit performance, a process termed 'model pessimization'[4]. While testing this idea, it was found helpful to perform an experiment in which the elements of a transistor equivalent circuit model(Fig.5) were annihilated in the order of their suspected effect upon the voltage gain of an amplifier. The facility allowed examination of the change in voltage gain (Fig.6) from the situation (Fig.7) in which all model elements were present.

This example illustrates, in passing, the educational value of the facility, as well as the important need to consider modelling as an integral part of the design process. A device model is just as much a candidate for design as the circuit of which it will be a part, and the concepts and design procedures common to the activities of modelling and circuit design strongly suggest their inclusion - and interaction - within the same facility.

Perhaps more importantly, however, the example illustrates one aspect of circuit design - that of exploration - to which we feel insufficient attention has been paid, and which is worthy of further comment.

Dynamic Exploration

It could be said that the principal aim of most presently available interactive graphic facilities for circuit design is to provide a convenient interface with 'batch' type circuit analysis programs. In so doing, they thereby perform the valuable service of reducing the tedium and time delay elapsing between the conception of an idea and its verification. Such a service is, indeed, entirely consistent with an assumption (shared with non-interactive design) that the principal aim of the designer is to verify an idea, or obtain confirmation that the performance of a circuit lies within specification. We feel, however, that only part of the process of circuit design can be characterized in this manner, and that there is a need to recognize the fact that design, especially in its early stages, is largely exploratory in nature[5]. To permit the formulation of ideas worth testing, the designer must at first seek insight and understanding rather than confirmation or assurance, and to do this must be able rapidly to explore a wide range of circuit and model properties.

The need to explore as well as verify has at least two important consequences. First, we observe that exploration will often be incremental, in that only a small part of the circuit - typically a single component - will undergo change at any one time. With the assumption that the effect of an incremental change involves little computation, it follows that the predicted effect could be displayed concurrently with the cause, e.g., a continuous change in element value effected by the designer via the light pen. In other words, we can contemplate the dynamic exploration of circuit and model properties, an activity that could greatly facilitate the human designer's insight and understanding.

As an example, recent research in network sensitivity[6] has shown that it is realistic to propose, within an interactive graphic facility for linear frequency domain design, an option whereby the designer can control, by light pen, the extent of a circular tolerance region in the plane of a response voltage, and simultaneously view the movement of the corresponding tolerance region in the plane of a selected network admittance (Fig.8). Such an option could, for example, be of considerable assistance in the choice of nominal element values and tolerances[7], in addition to its value in the exploration of circuit behaviour. To obtain the few constants involved in this calculation it is necessary, first, to invert the admittance matrix of the circuit[8]. Though this inversion may involve a wait on the part of the designer, it is likely to be tolerated gladly in view of the potential value of later dynamic exploration. Other circuit properties may well be amenable to computation in this manner, and thereby lend themselves to dynamic exploration; small-change sensitivity of first[9] and higher[9,10] orders is already known to be calculable very simply once the circuit's admittance matrix has been inverted.

Dynamic exploration need not be associated exclusively with manually simulated changes in circuit components and tolerances. In the context of interactive graphics it is possible for the designer to define, monitor and if necessary intervene in some useful automatic operation upon a circuit or model, such as its optimization to minimize a performance-based cost function. A visual indication of the progress of such an operation would be useful not only to allow its observation, but also to enable the designer to gain a 'feel' for the error surface involved[11].

A second aspect of circuit exploration that is worthy of comment is the fact that an 'order of magnitude' or 'ballpark' assessment of a wide range of circuit properties will often be preferable to the precise understanding of relatively few. This is, again, especially true of the early stages of design, which tend to be 'fuzzy', with loosely formulated ideas. The visual images associated with the circuit properties, as well as the manner of their presentation, must therefore be chosen accordingly. As Negroponte[12] has remarked in the context of architecture, "One does not sketch with a 6H pencil, or make working drawings with a felt pen". Thus, a display (Fig.9) in which each element symbol is replaced by a circle whose size is indicative[13] of the sensitivity of circuit performance to that element, and which can be stepped at, say, one-third second intervals through a frequency range of interest, could quickly give the designer an extremely valuable 'feel' for the overall sensitivity properties of a circuit. From such a global view he could turn, later, to a local and more precise study appropriate to a refined design. This example serves to emphasize one of the more important aspects of research in graphic man-machine interaction - that of identifying properties and concepts whose display is potentially valuable, and then designing their embodiment in visual images suited to human interpretation.

Conclusions

The conventional interactive graphic circuit design facility undoubtedly serves a useful role within the overall task of circuit design, particularly if proper attention is paid to ergonomic factors. What we urge in this paper is a deeper investigation of one aspect of the design process - that of exploration in general and dynamic exploration in particular - whose potential for enhancing the designer's insight, and with it his creative ability, appears to be promising, and which poses interesting problems in the area of man-machine communication.

Acknowledgments

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References

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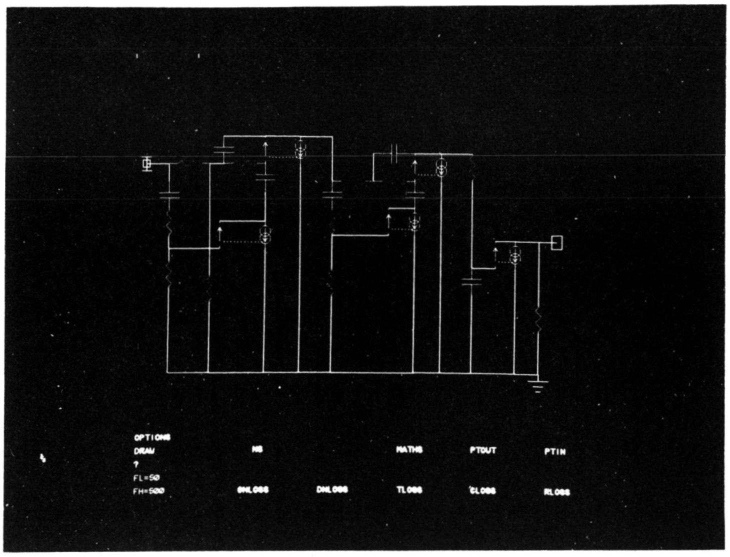

OPTIONS
DRAW NS MATHS PTOUT PTIN
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FL=50
FH=500 GNLOSS DNLOSS TLOSS CLOSS RLOSS

FIG. 1 The circuit diagram drawn by the designer

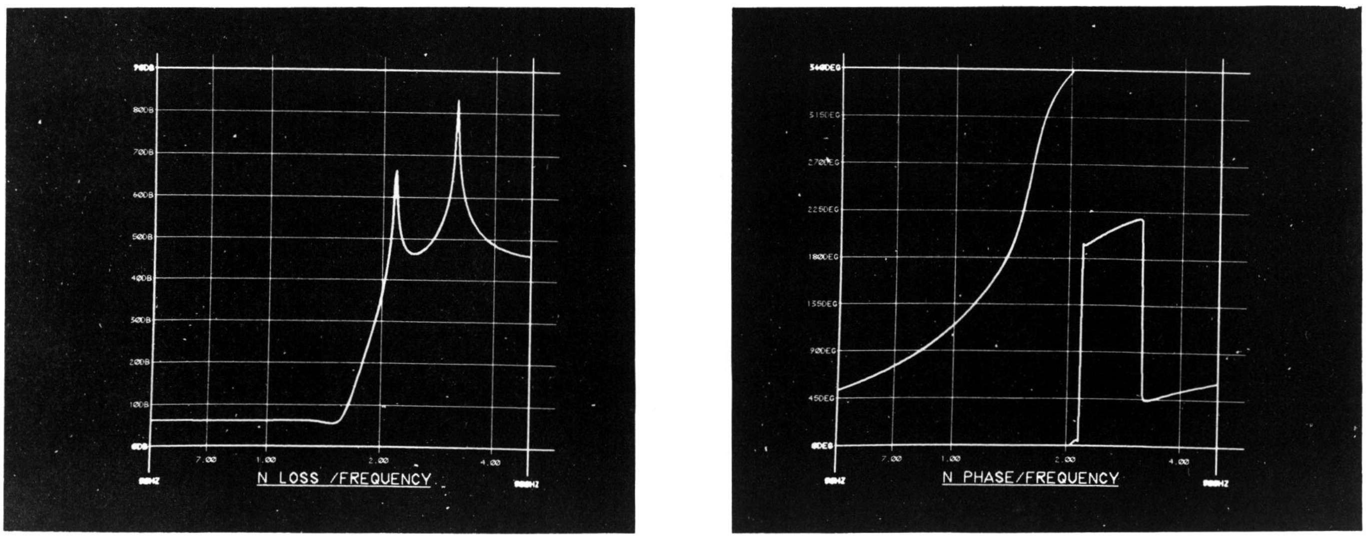
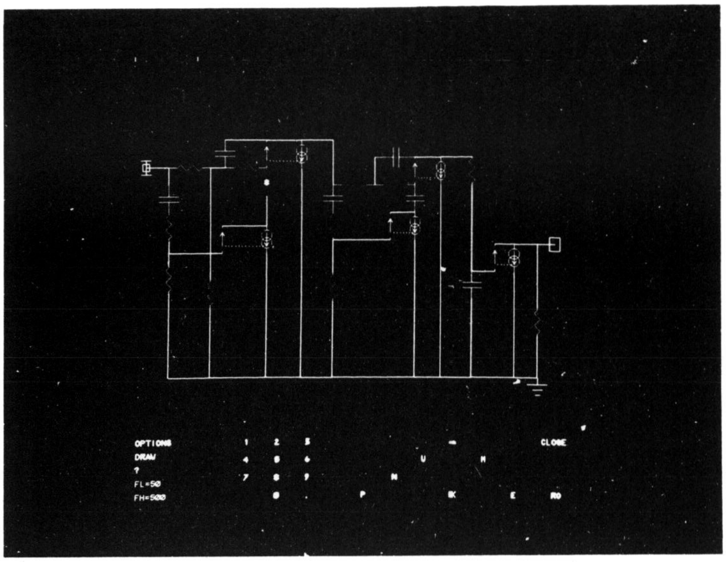


FIG. 2 The magnitude and phase of the voltage loss between input and output ports



OPTIONS	1	2	3				m			CLOSE
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FIG. 3 Numeric and multiplier light buttons used for the definition of element, parameter and frequency values

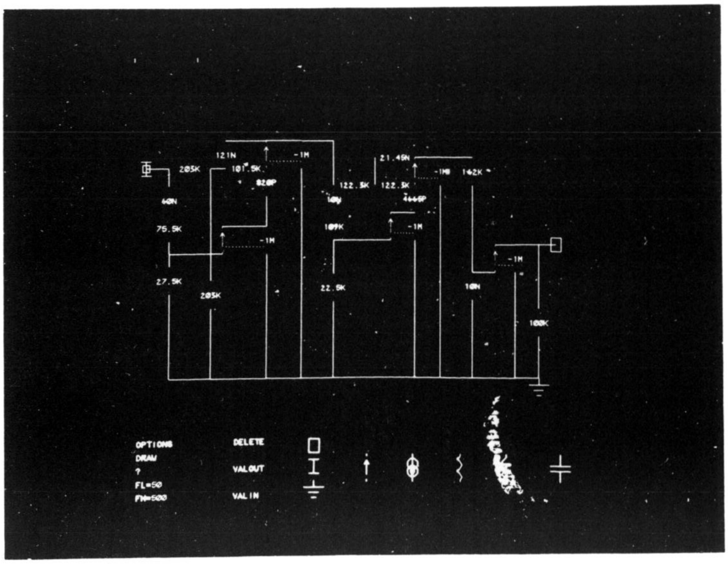


FIG. 4 The interrogation of circuit element and parameters

FIG. 5

Small-signal model of a transistor amplifier in which the transistor is modelled by its hybrid-pi equivalent circuit

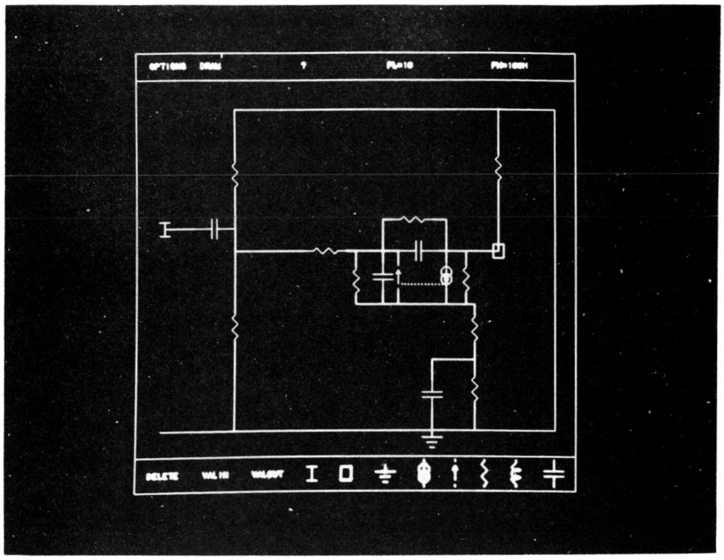


FIG. 6

Change in voltage loss from that shown in Fig. 7, due to removal of the output resistance of the transistor model

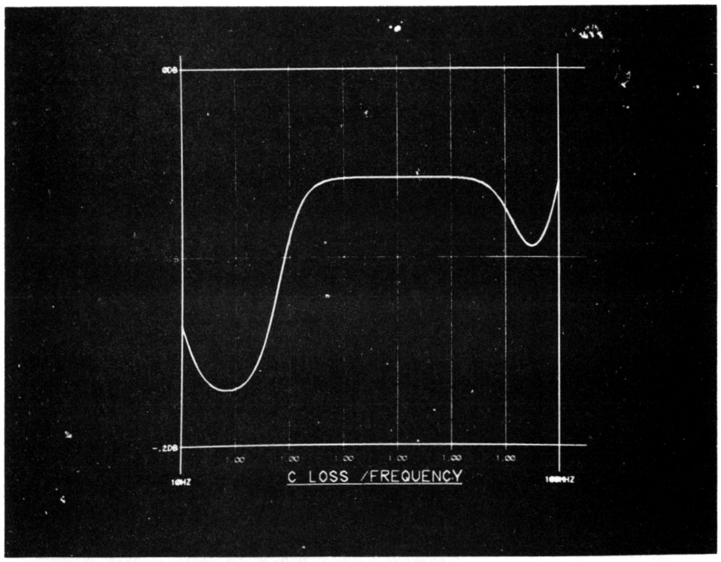
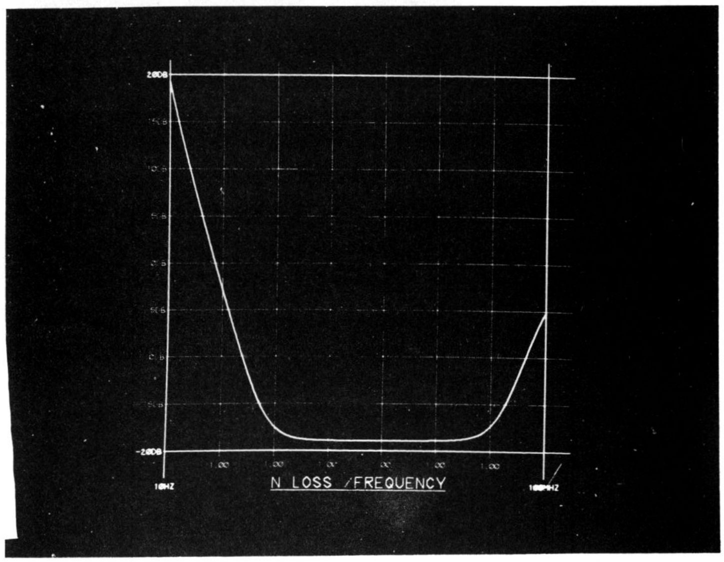


FIG. 7

Voltage loss of the circuit shown in Fig. 5



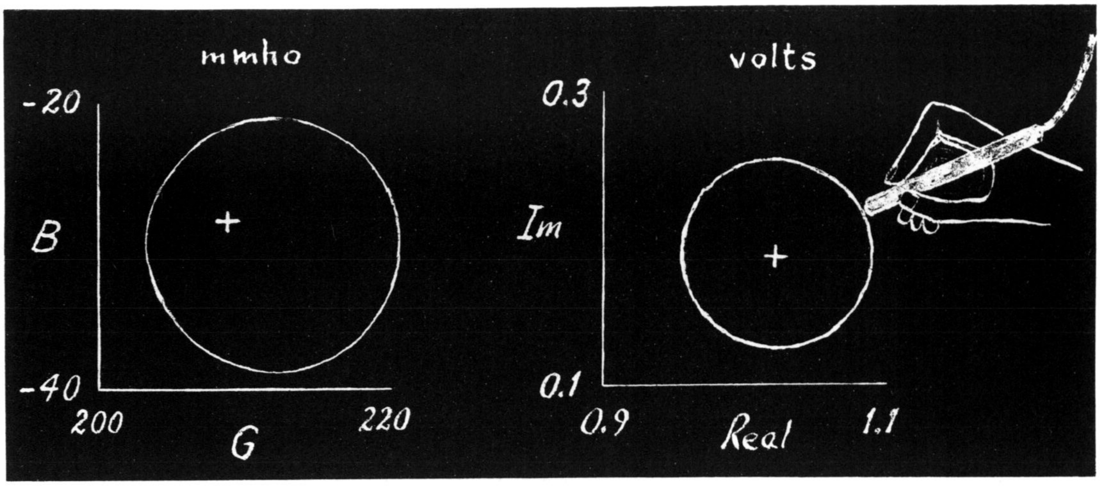


FIG. 8 Sketch of a possible display allowing study of the relation between response tolerance and admittance tolerance

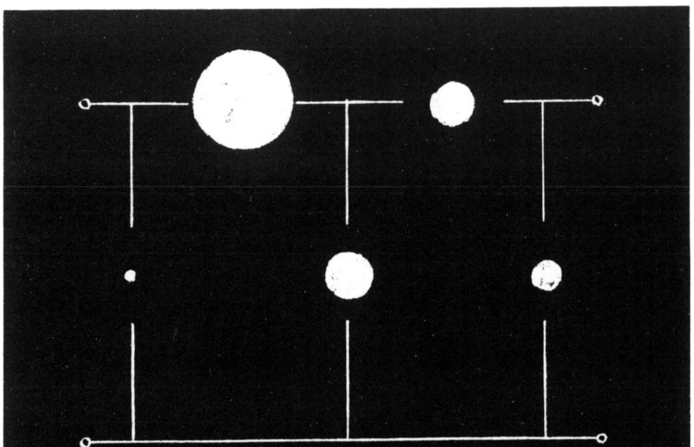


FIG. 9 Sketch of a possible display for indicating the sensitivity of response to individual circuit elements