A NETWORK-FUNCTION SIMULATOR

A Thesis
Presented to
the Faculty of Graduate Studies
and Research
The University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Electrical Engineering

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by
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October 1958

PREFACE

The study presented in this thesis on the application of the potential analog to circuit theory was initiated by the Department of Electrical Engineering at the University of Manitoba in 1956. The first use of the analog was in network analysis for the presentation of a physical picture of the logarithmic modulus and phase characteristics of an immittance function. The next step of study led to the application of the analog to network synthesis problems and in order to facilitate this study it was decided to construct an automatic scanning and display system. The unit produced is similar to one developed at Stanford University and described in a research memorandum (SF).

The material is divided into the following five chapters. Chapter 1 presents the fundamental theory of the potential analog. Chapter 2 describes the Network-Function Simulator and gives its construction and performance details. Chapter 3 outlines the calibration and operating procedures. Chapter 4 presents a series of tests which serve to determine the operating characteristics of the analog. Chapter 5 contains a discussion of the results and the conclusions.

The appendix of this thesis contains much important material which could have been included in the main body of the thesis; however, it was felt that to maintain continuity an arrangement of this type would be preferable.

The studies conducted in this thesis were made possible by a research grant (NRC G584-1956) from the National Research Council of Canada. Appreciation for this support is extended to the Council. Thanks are also extended to Siemens Brothers for their kind donation of equipment.

Finally, the author wishes to express his gratitude to Professor R. A. Johnson for his able supervision of this project, his invaluable suggestions and technical assistance, without which the completion of this thesis would have been difficult.

ABSTRACT

This thesis is an investigation into the application of the potential analog to circuit theory. A dry type of electrolytic tank with a carbon-impregnated paper was used. The fundamental theory and the description of a device for automatically scanning the analog is presented. Tests were performed to determine the characteristics of the conducting sheet and the analog.

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CHAPTER 1

FUNDAMENTAL THEORY

1.1 INTRODUCTION

The two dimensional potential field may be represented by the theory of functions of a complex variable and is indeed one of the earliest applications of this theory (CH)#. Network immittance functions are all functions of a complex variable (DA) which suggests their representation by a potential field model. The characteristic behaviour of any immittance function is specified by it s pole-zero distribution just as the characteristic of the potential field is determined by its charge distribution. Thus, if the complex planes of the potential field and the immittance function are identified and the charge distributions and pole-zero locations equated, an analog relationship is created.

This analog relationship serves two fundamental purposes with respect to circuit theory : a) it gives a physical picture of the response of networks, and b) it provides a powerful tool in determining the immittance function characteristics for a given type of response. The latter application is the first stage of a network synthesis procedure and is accomplished by manipulating the charge distributions until the desired response characteristic is obtained.

Various conformal transformations may also be applied to the two dimensional potential field in order to expand the required response region.

1.2 THE IMMITTANCE FUNCTION

All immittance functions (let us define them as F(s)) have the form of a quotient of polynomials such as

$$F(s)= \frac{a_o s^n + a_1 s^{n-1} + \ldots\ldots + a_{n-1} s + a_n}{b_o s^m + b_1 s^{m-1} + \ldots\ldots + b_{m-1} s + b_m} \qquad 1.1$$

The letters in parentheses refer to the Bibliography

They are all rational functions of the complex variable $s=\alpha+j\omega$ which is defined as the complex frequency (VA).

Factoring each polynomial yields the following equation:

$$F(s)=\frac{H\,(s-s_1)(s-s_3)\ldots\ldots(s-s_n)}{(s-s_2)(s-s_4)\ldots\ldots(s-s_m)} = \frac{H\prod(s-s_x)}{\prod(s-s_y)} \qquad 1.2$$

The roots of the numerator are called the zeros of the immittance function, the roots of the denominator the poles and H is a scale factor. Let us now express the immittance as a phasor quantity:

$$F(s)=|F(s)|\;e^{j\ \mathrm{Argument}\ F(s)} \qquad 1.3$$

or $$F(s)=H\frac{\prod|s-s_x|\;e^{j\theta_x}}{\prod|s-s_y|\;e^{j\theta_y}} \qquad 1.4$$

if $$s-s_i=|s-s_i|\;e^{j\theta_i} \qquad 1.5$$

Consider now the logarithmic transform of this immittance function:

$$\ln F(s)=\ln\left(|F(s)|\;e^{j\ \mathrm{Argument}\ F(s)}\right) = W(s)\ \text{say,} \qquad 1.6$$

thus $$W(s) = \ln|F(s)| + j\ \mathrm{Argument}\ F(s) \qquad 1.7$$

In terms of the poles and zeros, where it is understood that in the algebraic summations the zeros contribute positive valued terms and the poles negative valued terms, we may write:

$$W(s) = \ln H + \Sigma\ln|s-s_i| + j\Sigma\,\theta_i \qquad 1.8$$

In general we have:

$$W(s) = M(s) + j\Theta(s) \qquad 1.9$$

a function of the complex variable s with $M(s)$ giving the logarithm of the immittance magnitude and $\Theta(s)$, the immittance phase.

1.3 THE TWO DIMENSIONAL POTENTIAL FIELD

Let us consider a sheet of homogeneous isotropic conducting paper as a two dimensional plane of the complex variable $z=x+jy$. Unit currents are injected at the points $z_o, z_1, z_2 \ldots\ldots z_n$. The electric field produced in the sheet is given by:

$$\underline{E}(z) = -\nabla \phi(z) \qquad 1.10$$

where it is understood that:

$$\nabla \phi(z) = i\frac{\partial \phi(z)}{\partial x} + j\frac{\partial \phi(z)}{\partial y}$$

The current flow in the sheet is given by:

$$\underline{I}(z) = \sigma\ \underline{E}(z) \qquad 1.11$$

where σ is the surface conductivity of the conducting sheet.

The divergence of the current must be zero everywhere in the sheet except at the points of current injection and if the divergence at these points of discontinuity is represented by a Dirac delta function (ST) we have:

$$\nabla \cdot \underline{I}(z) = K\ \Sigma\ \delta\ (z-z_i) \qquad 1.12$$

Using equation 1.11 we may write:

$$\nabla \cdot \underline{E}(z) = \frac{K}{\sigma}\ \Sigma\ \delta\ (z-z_i) \qquad 1.13$$

and substituting from equation 1.10, there results:

$$-\nabla \cdot \nabla\ \phi(z) = -\nabla^2 \phi(z) = \frac{K}{\sigma}\ \Sigma\ \delta\ (z-z_i) \qquad 1.14$$

This is Poisson's equation for the two dimensional field having a driving function

$$\rho(z) = \frac{K}{\sigma}\ \Sigma\ \delta\ (z-z_i).$$

The solution of this well known equation (WE) is:

$$\phi(z) = C_1\ \Sigma\ \ln\ (z-z_i) + C_o \qquad 1.15$$

where C_o is some arbitrary constant. If polar co-ordinates are introduced such that:

$$z-z_i = |z-z_i|\ e^{j\psi_i} \qquad 1.16$$

then $$\emptyset(z) = C_0 + C_1 \Sigma \ln |z-z_i| + jC_1 \Sigma \psi_i \qquad 1.17$$

where it is understood that at points of current source negative terms are contributed to the summations and at points of current sink positive terms (or vice versa if it is so defined).

If we identify:

$$V(z) = C_0 + C_1 \Sigma \ln |z-z_i| \qquad 1.18$$

and $$\psi(z) = C_1 \Sigma \psi_i \qquad 1.19$$

we may write $$\emptyset(z) = V(z) + j\psi(z) \qquad 1.20$$

a function of the complex variable, z, where V(z) is the potential function and $\psi(z)$ the stream function.

1.4 THE POTENTIAL ANALOG

We have shown that the potential field of a two dimensional conducting sheet is a function of a complex variable, z , and has the form:

$$\emptyset(z) = C_0 + C_1 \Sigma \ln |z-z_i| + j C_1 \Sigma \psi_i \qquad 1.17$$

where the z_i are the points of current source and sink.

Also it has been shown that any immittance function as a rational function of a complex variable s has the general logarithmic form:

$$W(s) = \ln H + \Sigma \ln |s-s_i| + j \Sigma \theta_i \qquad 1.8$$

where the s_i are the pole and zero locations.

With the identification of the plane of the potential field with the complex frequency plane, s=z, and the location of the current sinks at the zero positions and current sources at the pole positions, the potential field becomes the analog of the immittance function.

Thus $$\emptyset(s) = K_0 + K_1 W(s) \qquad 1.21$$

where K_0 is a reference constant and K_1 a scale factor.

Rewriting equation 1.21 we have:

$$V(s) + j\psi(s) = K_0 + K_1 \ln F(s)$$
$$= K_0 + K_1 \ln |F(s)| + j K_1 \text{ Argument } F(s) \qquad 1.22$$

Identifying real and imaginary parts yields:

$$V(s) = K_o + K_1 \ln |F(s)| \qquad 1.23$$

and $$\psi(s) = K_1 \text{ Argument } F(s) \qquad 1.24$$

Any point s_o on the plane may be used as a reference potential and at this point:

$$V_o = K_o + K_1 \ln |F(s_o)| \qquad 1.25$$

also at any other point, say s_1

$$V_1 = K_o + K_1 \ln |F(s_1)|$$

The potential difference between the reference point and the arbitrarily selected point yields the logarithm of the ratio of the ~~impedance~~ immittance magnitudes at the two points.

Thus $$V_1 - V_o = K_1 \ln \frac{|F(s_1)|}{|F(s_o)|} \qquad 1.26$$

or $$\ln \left|\frac{F(s)}{F(s_o)}\right| = \frac{V}{K_1} \qquad 1.27$$

where V is the potential measured at s with respect to the potential at s_o.

Consider now the stream function

$$\psi(s) = K_1 \text{ Argument } F(s) \qquad 1.24$$

Rewriting $\text{Argument } F(s) = \frac{\psi(s)}{K_1}$

The stream function at any point may be determined by a line integration.

Thus $$\psi(s) = \int \frac{d\psi(s)}{ds} ds \qquad 1.28$$

or $$\psi(s) = \int \left[\frac{\partial\psi(s)}{\partial\alpha} d\alpha + \frac{\partial\psi(s)}{\partial\omega} d\omega \right] \qquad 1.29$$

From the Cauchy-Riemann conditions the following relations must hold for any analytic function (DA):

$$\frac{\partial\psi(s)}{\partial\alpha} = -\frac{\partial V(s)}{\partial\omega} \qquad 1.30$$

and $$\frac{\partial\psi(s)}{\partial\omega} = \frac{\partial V(s)}{\partial\alpha} \qquad 1.31$$

Substituting into equation 1.29 we now have:

$$\psi(s) = \int \left[-\frac{\partial V(s)}{\partial \omega} d\alpha + \frac{\partial V(s)}{\partial \alpha} d\omega \right] \qquad 1.32$$

In particular, if the line integration is performed up the real frequency axis and started at the origin, since $d\alpha = 0$, we have the following:

$$\psi(0,\omega) = \int_0^\omega \frac{\partial V(0,\omega)}{\partial \alpha} d\omega \qquad 1.33$$

That is $\psi(0) \equiv 0$ for any immittance function. Now substituting equation 1.33 into equation 1.24 gives:

$$\text{Argument } F(\omega) = \frac{1}{K_1} \int_0^\omega \frac{\partial V(0,\omega)}{\partial \alpha} d\omega \qquad 1.34$$

which may be written in summation form as:

$$\text{Argument } F(\omega) = \frac{1}{K_1} \sum_0^\omega \frac{\Delta V(0,\omega)}{\Delta \alpha} \Delta\omega \qquad 1.35$$

We may also use an alternate symbol to represent immittance phase, that is Argument $F(\omega) = \Theta(\omega)$. The immittance time delay or phase slope is defined as $\frac{d\,\Theta(\omega)}{d\omega}$. Differentiating equation 1.34 yields the immittance time delay as:

$$\frac{d\,\Theta(\omega)}{d\omega} = \frac{1}{K_1} \frac{\partial V(0,\omega)}{\partial \alpha} = \frac{1}{K_1} \frac{\Delta V(0,\omega)}{\Delta \alpha} \qquad 1.37$$

Let us again consider equation 1.32 which may be recognized as:

$$\psi(s) = \int [\, \underline{E}(s) \cdot \underline{n} \,] \, ds \qquad 1.38$$

where $\underline{n}$ is a unit vector normal to the path of integration. Substituting from equation 1.11 we have:

$$\psi(s) = \frac{1}{\sigma} \int [\, \underline{I}(s) \cdot \underline{n} \,] \, ds \qquad 1.39$$

That is, the phase is proportional to the total current crossing the path of integration.

1.5 SYMMETRICAL PROPERTIES OF THE ANALOG

The coefficients of the polynomials describing any immittance function must be real, which results in all the roots being real or occurring in complex conjugate pairs (ST). Because of this property the immittance function is symmetrical about the α or attenuation axis.

Thus $$F(s) = F(\alpha,\omega) = F(\alpha,-\omega) \qquad 1.40$$

which implies that $$\left.\frac{\partial F(s)}{\partial \omega}\right|_{\omega=0} = 0 \qquad 1.41$$

In the potential analog this corresponds to the fact that the α axis is a current flow line. The implication is that only that half of the plane with the positive frequency axis need be simulated, the other being represented as a reflection product.

Let us now consider a quarter plane which has its real and imaginary axis open -circuited. The poles and zeros of this quarter plane are reflected into the other three quadrants of the plane so as to set up a function having quadrantal symmetry.

That is $$F(s) = F(\alpha,\omega) = F(-\alpha,\omega) = F(\alpha,-\omega) = F(-\alpha,-\omega) \qquad 1.42$$

Now if $F(s)$ is representative of an immittance function then $F(s)F^*(s)$ will possess quadrantally symmetrical properties, where $F^*(s)$ is the complex conjugate function, and it may be shown (ST,GU) that along the real frequency axis:

$$F(\omega)F^*(\omega) = |F(\omega)|^2 \qquad 1.43$$

that is $$\ln F(\omega)F^*(\omega) = 2 \ln |F(\omega)| \qquad 1.44$$

Again consider a quarter plane but in this case having the imaginary axis short-circuited and the real axis open. The poles and zeros of this plane are reflected into the other three quadrants so as to create a function having dissymmetric properties.

That is $$F(\alpha,\omega) = - F(-\alpha,\omega) \qquad 1.45$$

If $F(s)$ is an immittance function then $\frac{F(s)}{F^*(s)}$ is a function which is dissymmetric and it may be shown (ST,GU) that along the real frequency axis:

$$\frac{F(\omega)}{F^*(\omega)} = e^{j\,2\text{ Argument }F(\omega)} \qquad 1.46$$

that is $$\ln \frac{F(\omega)}{F^*(\omega)} = j\,2\text{ Argument }F(\omega) \qquad 1.47$$

It is also of interest to note that if the immittance function is an impedance then the interchange of poles for zeros and zeros for poles yields the admittance response (or vice versa).

1.6 CONFORMAL TRANSFORMATIONS

Once the immittance function is shown to be an analytic function of a complex variable the applicability of the potential analog to a conformal transformation is apparent. Many transformations are possible (CH), namely, exponential, logarithmic, orthogonal circle (Smith diagram), the Schwartz-Christoffel transformations etc. The logarithmic transformation was selected as being of particular interest since it has the property of presenting the immittance attenuation in a logarthmic scale versus the frequency, also in a logarithmic scale.

The complex frequency plane s is now identified with a new plane, say $w=u+jv$, by the transformation

$$w = \ln s \qquad 1.47$$

If the polar co-ordinate system is used to define the s plane, namely:

$$s = |s|\, e^{j\emptyset} \qquad 1.48$$

then a mapping of significant axes may be performed as follows:

a) for the positive attenuation axis

$$w = \ln(\,|s|\, e^{j0}) = \ln|s| + j0$$

b) for the positive frequency axis

$$w = \ln(\,|s|\, e^{j\pi/2}) = \ln|s| + j\,\pi/2$$

c) for the negative attenuation axis

$$w = \ln(\,|s|\, e^{j\pi}) = \ln|s| + j\,\pi$$

This mapping is illustrated in figure 1.1 .

The properties of the quarter plane may be applied as well to this transformed plane when the proper boundaries are left open or short-circuited. This transformed plane does not lend itself to phase measurement techniques utilizing the voltage gradient method since the incremental sampling distance $\Delta\alpha$ changes along the real frequency axis.

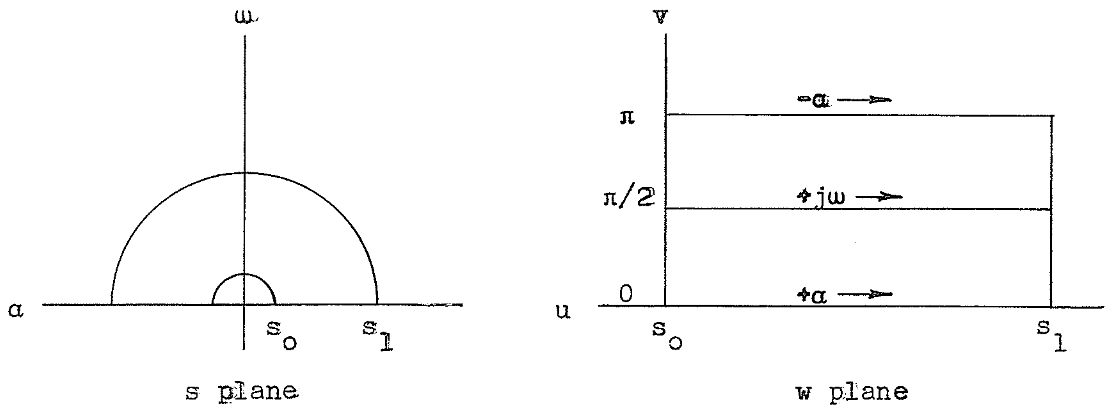

FIGURE 1.1

THE LOGARITHMIC TRANSFORMATION

CHAPTER 2

THE POLE-ZERO NETWORK FUNCTION SIMULATOR

2.1 GENERAL DESCRIPTION

The pole-zero network function sumulator is basically a device for simulating and scanning the complex frequency plane. A dry type of electrolytic tank using a carbon-impregnated paper and excited from several movable probes serves as the potential analog. The automatic or manual scanning is accomplished by a series of mounted probes which feed a motor driven rotary switch.

The equipment layout is illustrated in figure 2.1 and consists of a) a portable rack mounting the electronic units and b) a work table carrying the conducting sheet, probe chassis, transposition frame, movable probes, a distribution unit and a plane reference bias circuit. The portable rack holds, from top to bottom, a monitor oscilloscope, an operational unit consisting of d.c. amplifiers, a constant current pole-zero supply, a set of manual selector switches, a regulated power supply for the d.c. amplifiers and the panel for the motor-driven rotary switch.

Figure 2.2 is a block diagram which illustrates the functional operation of the unit. A set of movable probes supply d.c. current to the conducting sheet and create a two-dimensional potential field. The d.c. supply is a constant current device having six current outputs and six current inputs. Thus, by using a half plane an immittance function having up to 12 poles and 12 zeros may be simulated. Each probe is plugged into the distribution unit which in turn is connected to the pole-zero supply.

A probe chassis consisting of 208 probes is located on the real frequency axis of the analog plane. The potential created by the electric field is sampled by the probes and passed through the transposition frame to either the manual selector switch or the rotary switch. The manual selector switch permits an individual selection of any one probe, the signal of which may be fed directly or through the d.c. amplifier to a metering system. A rotary switch scans the probes in sequence and supplies a