TRANSMISSION LINE EXPERIMENTS AT LOW COST

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ABSTRACT
The GHz-range equipment and components normally required for the basic experiments in transmission line and microwave topics are expensive and often beyond the budgets of small programs. The LC lumped-element transmission line model provides an economical alternative for such experiments. Appropriate choice of inductance and capacitance values for the LC sections makes it possible to establish standing waves several half-wavelengths long on physically small models at operating frequencies well below 1 MHz. At the low operating frequencies, measurement and data collection can be accomplished using general-purpose lab instruments that are readily available in most basic laboratories. The prototype “lines” built by the author and used in a transmission line course are described and the lab exercises and procedures for determining the propagation properties such as standing wave pattern, phase constant, and wavelength are outlined. Typical experimental results are also provided.

INTRODUCTION

The experiments for the study of the basic characteristics of the propagation along transmission lines are performed at frequencies above 1 Ghz. These experiments usually require the measurement of voltage or the electric field along a test section of the transmission line. From such data, the standing wave pattern, the phase constant, wavelength, and the VSWR of the line can be obtained. To yield these results, the data must cover a span of the line that includes at least one, and preferably several, $\lambda/2$ of the standing wave. This requirement can be met for a physically short line if the operational frequency is high. However, since the components and particularly the instrumentation at these frequencies are costly, a lab setup for transmission line experiments can be prohibitively expensive for a small program. For example, a minimum setup, consisting of a signal source, one or more detectors, a detection instrument, a frequency counter, a slotted line section, and a few other components such as attenuators, terminations, and loads can run from $15,000 to over $50,000 per station, depending on the frequency range.

Since the basic characteristics of the propagation phenomena are the same for lines operating at different frequencies, an obvious low cost approach would be to utilize lines that operate at a low enough frequency where general-purpose instrumentation could be used for the measurements. Although theoretically possible, this is physically impractical, since the line sections that would be required to obtain the needed data would be very long. For example, the length of the line section required to span even a single $\lambda/2$ of the standing waves at an operating frequency of 10kHz (with a propagation velocity equal to the velocity of light in vacuum) is 15 kilometers!

A practical way of getting around the need for high frequency instrumentation is to use a physical model of the transmission line rather than an actual line. The LC-section lumped-element model is such an example, in which with appropriate choice of LC values, it is possible to achieve multiples of $\lambda/2$ of the standing wave within a practical length at low frequencies.

THE LC LUMPED-ELEMENT MODEL

The idea of using a lumped-element circuit that experimentally behaves like a transmission line is based on the classical approach to analyzing the wave propagation on transmission lines. In this approach, the line is considered to be composed of an infinite number of sections, each made of discrete lumped elements R, L, C, G (see Fig 1.)

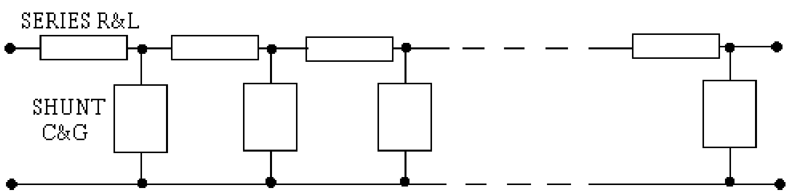

Figure 1. Lumped-element equivalent model of a transmission line.

By applying the circuit laws to a section and solving the resulting differential equations, one is able to find the voltage and current of the line as functions of time and distance.[1,2] These solutions and some of the other results for time-harmonic operation may be written as

$$v(x,t) = [Ae^{-\gamma x} + Be^{+\gamma x}]e^{j\omega t} \qquad i(x,t) = (1/Zo)[Ae^{-\gamma x} - Be^{+\gamma x}]e^{j\omega t}$$

$$Zo = [(R + j\omega L)/(G + j\omega C)]^{1/2} \qquad \gamma = \alpha + j\beta = [(R + j\omega L)(G + j\omega C)]^{1/2}$$

in which A and B are arbitrary constants, to be determined from the input voltage and the load (i.e. the boundary conditions), and Zo and γ are the characteristic impedance and propagation constant of the line. The latter two, for low-loss or loss-less lines (R=G=0) simplify to,

$$Zo = [L/C]^{1/2} \qquad \gamma = 0 + j\beta = j\omega[LC]^{1/2}\ .$$

The line constants R, L, C, and G, are distributed properties, uniformly spread along the length of the line. They are, in effect, microscopic properties even though they are given in macroscopic units of per meter, per kilometer, etc. Therefore, the lumped-element model as a circuit description of the line is accurate if the section length for which the lumped components are defined is made infinitesimal. It would be expected, then, that a model (proposed here) that has a finite number of sections made from discrete components should behave, at least in an approximate manner, like a transmission line.

DESIGN CONSIDERATIONS

Two important factors that will enable the transmission line models to have acceptable characteristics are an adequate number of sections and a close matching of section components. For the loss-less line model, the relationship between the section components, frequency, and wavelength is given by: $\lambda f = [LC]^{-1/2}$.

Since the main reason for use of these models is to be able to do the transmission experiments at low frequencies, it would seem reasonable to first choose an appropriate frequency value as in the design process. For practical reasons, however, it is advisable to specify λ first. This should be based on the desired voltage distribution and the total number of sections in the model. For example if the line has n sections and it is desired to have m full wavelengths distributed over the entire line, the size of the wavelength should be specified as n/m sections. Once λ is specified, various standard values of L and C should be tried in the above relation to obtain a frequency in the audio range. If the frequency is specified first, only one of the remaining quantities, L or C, can be chosen at will, hence the other may not compute out to a standard value.

Each of the models constructed for our transmission line experiments has 18 LC sections. We chose λ to be equal to 14 sections to assure an adequate number of data points within one wavelength. Following the above procedure we then computed the recommended operational frequency for each line by choosing different standard values for L and C. The following table shows the specifications for four of the lines.

TABLE 1. TRANSMISSION LINE SPECIFICATIONS

T-Line ID	Series L (mH)	Shunt C (μf)	Frequency (kHz)
A	1.2	.050	9.22
B	3.9	.022	7.71
E	2.7	.050	6.15
F	6.8	.010	8.66

The physical construction of a model is simple. In our case, the components were assembled on a perf-board approximately 15cm by 70cm long, with the inductors soldered between adjacent banana jack posts and the capacitors soldered from each post to a ground wire that runs the length of the line. The banana jacks provide the test points for measuring the voltage. Thus, the model represents a transmission line, 18 sections long, on which voltage can be measured at the input, at the load, and at 17 other equally spaced points on the line. Two important features of the model that the students should be reminded of are: (a) whereas on a real line it is theoretically possible to access the line at any point along its length for measuring the voltage or E-field, in the case of these models, such measurements can only be taken at finite number of points on the “line”; (b) that for this “line” the units of the distributed elements (L, C,...) are in “per section” rather than per unit length, hence all other transmission line quantities that have per-unit-length in their units must be given in “per section”.

TYPICAL EXPERIMENTS

The main data collection in each experiment is the measurement of voltage at the 19 test points of the line with an oscilloscope. A DMM can be used for the measurements if the operational frequency of the line is within the DMM's frequency response; however, when data is used for phase constant determination, the oscilloscope will be required.

The procedure of a typical experiment involves connecting a line to a generator, with its frequency set to the recommended value for the line, and taking the voltage data for specified loads. The voltage data enables the student to draw the standing wave patterns for different loading conditions, and to find the wavelength, VSWR, and the propagation constant (both

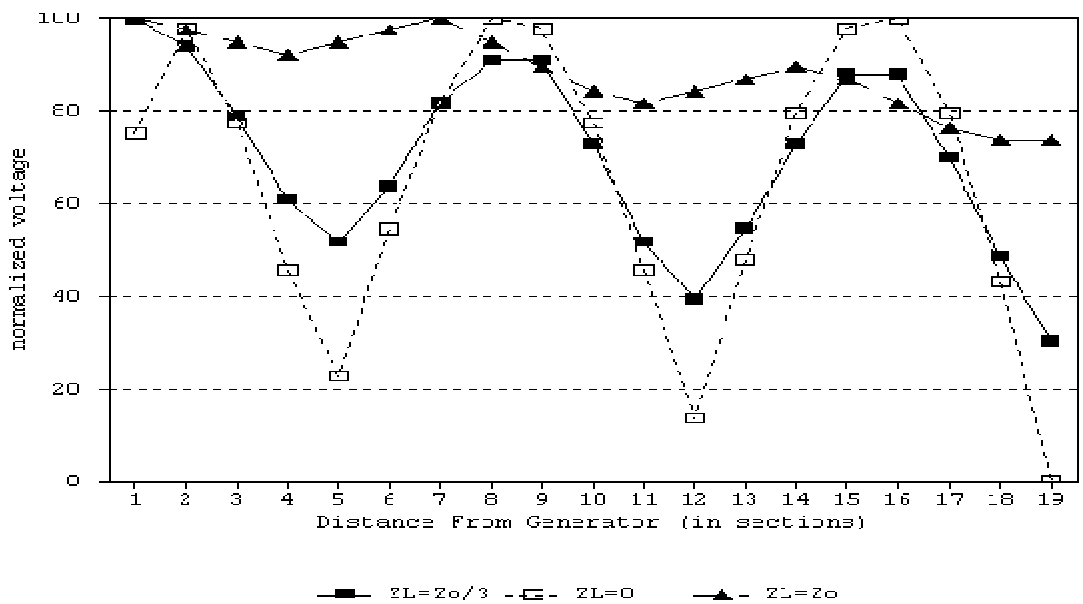

Fig. 2. Voltage Standing Wave Pattern for Transmission line E.

phase and attenuation) of the line. The experimental results for line "E" are given in Figure 2.

As can be seen from the graphs, the wavelength of this line is 14 sections (twice the number of sections between two adjacent nulls). The averaged phase and attenuation constants, obtained from the matched load voltage data were: α=0.015 nepers/sc ; β=26.5 degrees/sc. These are in good agreement with the theoretical values of α=.012 and β=25.7 that are computed using the transmission line relations, the nominal LC values of the components, and the coil resistance of the inductors for R. The results for the VSWR have a lower agreement with the theoretical expectations. However, they do illustrate adequately the concept that as the load impedance approaches Zo, the VSWR approaches unity.

SUMMARY
The LC lumped-element model of a transmission line may be used in a number of experiments in a transmission line course as a substitute for a real lines which necessitate expensive measurement setups. The model can be designed and built easily and inexpensively using off-the-shelf components. By proper choice of components, the operational frequency for the model can be located in the audio range, allowing use of general-purpose instrumentation for data collection.

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