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CABLE PARAMETERS AND ACOUSTIC PROBE PERFORMANCE

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Abstract – Acoustic (ultrasound and SONAR) probe designers shorten development times and gain physical insights from mathematical models and numerical simulations of acoustic load, transducer, cable and transmit/receive electronics. Figures of merit including frequency-dependent electrical admittance and transmitting voltage response (TVR) may be "accurately" calculated from "correct" component models. However, in our experience, designers under-appreciate how strongly cable properties affect device behavior in both experiment and simulation. This paper extends a known method for determining cable (transmission line) parameters from measurable quantities; frequency-dependent parameters are closely approximated with frequency-independent parameters for use in time-domain simulation codes. A naval-SONAR probe case study shows that "more careful" determination of cable parameters significantly improved the match between predicted and measured admittance and TVR.

I. INTRODUCTION

Numerical models of acoustic probes (transducer + cable) are commonly assembled from models of the various components and used to predict design-option impacts on performance. Currently available modeling methods (e.g. PZFlex™) provide useful predictions in the sense of shortening product development times and lowering costs. Of course, this statement assumes that "accurate" component descriptions are used in the modeling. However, in our experience designers often under-appreciate the impact of cable properties upon device performance. This is particularly true in probes with long cables (long in terms of wavelength, λ) and large impedance mismatches between the cable and the termination impedances (transducer and system input/output). Common cable-modeling errors include incorrectly determined electrical-parameter values, using lumped-element representations where distributed-element representations are needed and even neglecting the cable entirely. This paper reviews aspects of cable-parameter determination for 2-port transmission lines (TL). The paper offers certain new detail for approximating frequency dependent parameters with frequency independent parameters; this greatly facilitates probe response calculations in the time domain. Comparing predictions and measurements for a naval-SONAR probe illustrates how attention to cable parameterization improved prediction accuracy in a real-life example.

II. METHODS

Cable/transmission-line parameters

Transmission lines may be characterized by R(f) ohms/m, L(f) henries/m, C farads/m and G(f) siemens/m where f denotes frequency or Hz. R and L vary with f because the skin effect [1-4] causes a redistribution of current density within conductors as f changes. Dielectric losses, accounted for by G, often have a negligible effect upon signal transmission; unless otherwise stated, G = 0.0 herein. Figure 1 shows the general R and L dependence upon frequency. At low frequencies the current distributes

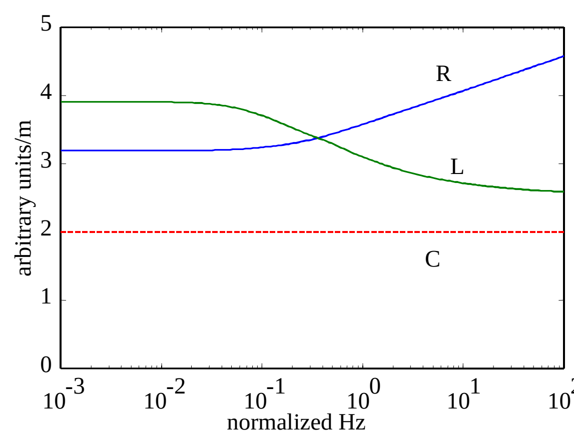

Fig. 1. Typical TL parameters computed by FEM [5].

uniformly over conductor cross sections. As frequency increases the current tends to stop flowing in the central portions of the conductors; R begins to increase with sqrt(f) and L asymptotically decreases to a high-frequency limit, L_{hf}.

In general, there are no obviously correct R & L values to use in time-domain simulations. However, for frequencies above the point where R & L begin to change, Yen et. al. [6] found that the frequency dependency can often be represented by the simple circuit of Fig. 2. This is exactly the usual representation for a short section of line except that R

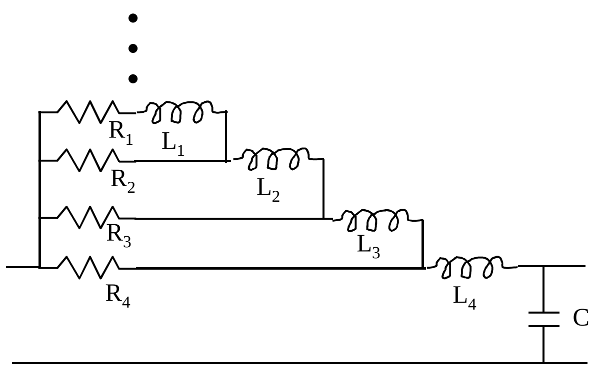

Fig. 2. Equivalent circuit for a "short" section of transmission line. More or fewer R_i-L_i sections can be employed to get a better fit to cable parameters or reduce complexity. $N \equiv \max(i)$.

is shunted with a ladder network. Yen provides an algorithm for choosing the elements of Fig. 2; the algorithm is intended for frequencies where R & L are changing. We find empirically that by choosing the R_i and L_i values appropriately the Fig. 2 circuit can also be made to mimic line R & L at frequencies where R & L change insignificantly.

A new and simple least-squares (LS) procedure for setting R_i and L_i follows. Use the constraints that $R_{i+1} = k_1 R_i$, $L_{i+1} = L_i/k_2$ (for i+1<N), $k_1 > 1$, $k_2 > 1$ and $L_N = L_{hf}$. Subject to said constraints, find R_i, k_1, L_i and k_2 such that the impedance of the series portion of the Fig. 2 circuit approximates the impedance of R(f) and L(f) for the cable being modeled. An example illustrates the results.

Transmission line R & L were computed for an illustrative cable. Figure 3 shows the true R as a solid trace and two Fig. 2-style approximations to R with the broken traces. Both approximations let N = 4 and span three decades of frequency. Figure 4 depicts the true and approximated L values obtained concomitantly with the Fig. 3 traces.

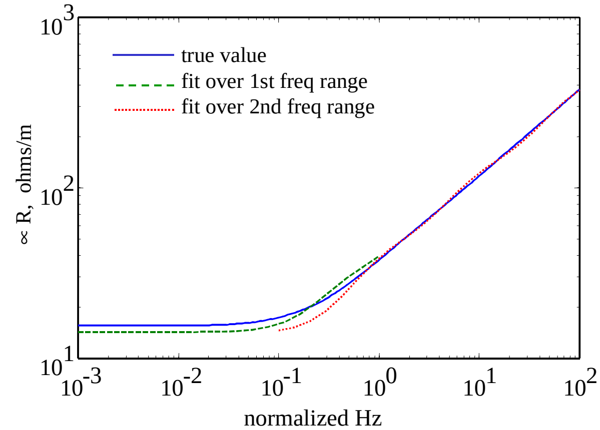

Fig. 3. Actual and approximated transmission line resistance values.

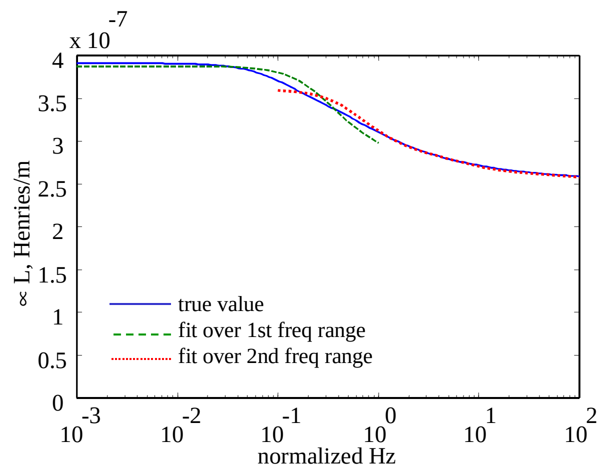

Fig. 4. Actual and approximated transmission line inductance values.

The equivalent circuit provides an imperfect but usually very good match to the transmission line R & L. The match is within manufacturing variations for many lines and using the approximation provides frequency independent parameters which are easily used in time-domain simulation. For best results, perform the LS fit over just the frequency band of interest.

The preceding verbiage employs "true" TL parameter values from calculations. However, "measuring" the parameters is sometimes preferred. Quotation marks are used because one generally cannot directly measure TL parameters. Instead, a quantity, which varies with the parameters in a known way, is measured so that parameters can be back calculated or "estimated." One commonly used estimation procedure follows. Let Zs and Zo denote cable input impedance with the distal end of the cable shorted and open respectively. From the definitions of characteristic impedance (Zc) and propagation constant (γ) it can readily be shown that

$$Zc = \sqrt{Zs\ Zo}$$

$$\gamma = \frac{1}{length}\tanh^{-1}\left(\sqrt{\frac{Zs}{Zo}}\right)$$

$$Zc = R + j\omega\, L \quad and$$

$$\frac{\gamma}{Zc} = G + j\omega\, C$$

where ω = radians/s and length refers to the length of tested cable. High quality instruments are available for measuring Zo and Zs. Processing those measurements via the above equations yields estimates of R, L, C and G. At certain frequencies the length of test cable resonates and parameter estimates become very inaccurate. Carefully choosing the length of test cable and the frequencies, at which measurements are taken, largely mitigates the accuracy difficulty. NB: Letting the test-cable length equal the use-length of cable for an application is often inadvisable; consider choosing the test-cable length to minimize estimation errors.

Probe modeling

For this study the commercially available FEM code PZFlex™ [7] evaluates models of the connected acoustic probe components. Results are obtained in the time domain and then converted to the desired frequency domain by Fourier transform. Since the studied transducer (similar to the one in [8]) is somewhat nonlinear, comparing measured and calculated results requires driving physical and model probes with the same excitation signals.

Probe measurements

Two measurements characterize an experimental SONAR probe. First, input admittance or impedance is measured at the input to 152 m of cable terminated with a flextensional transducer. Second, transmitting voltage response (TVR) is measured to define the mechanical output of the device as a function of frequency. We measure TVR by placing the test device in water and applying a sinusoidal voltage drive. A hydrophone in the far field of the device measures sound-pressure level; this is automatically repeated across the frequency range of interest. Measurements are taken in the far field where pressure amplitude decays with 1/range so that said measurements may be easily "backed up" to the standard 1-m range. TVR is pressure, at a 1-m range, re 1 µPascal per volt of excitation, in dB. Measured values were compared with calculated admittance and TVR from PZFlex.

III. RESULTS

The experimental cable consisted of four separate insulated conductors fastened together at intervals much shorter than the electrical λ. Two lines are made common at the ends to serve as a signal lead; the other two lines are made common at the ends to serve as the return-current path. Fresh water surrounds the cable during use so the water forms part of the cable dielectric. A first set of TL parameters was found (not by the approach described in the methods section of this paper) as R_a = 0.3333 Ω/m, L_a = 0.466e-6 H/m, C_a = 133e-12 F/m and G_a = 0.0 independent of frequency. Simulated and measured probe parameters matched disappointingly when simulations employed this first cable description.

A second set of TL parameters was found by the methods described herein. We find $R_b \cong$ 0.0192 Ω/m, $L_b \cong$ 0.533e-6 H/m and $C_b \cong$ 269e-12 F/m over the frequency range of interest. G_b ranges from ≅ 0.0 to 2.5e-7 S/m in the frequency range which causes negligible effect on probe performance so we can let G_b = 0.0 S/m. Figure 5 shows R_b and L_b as

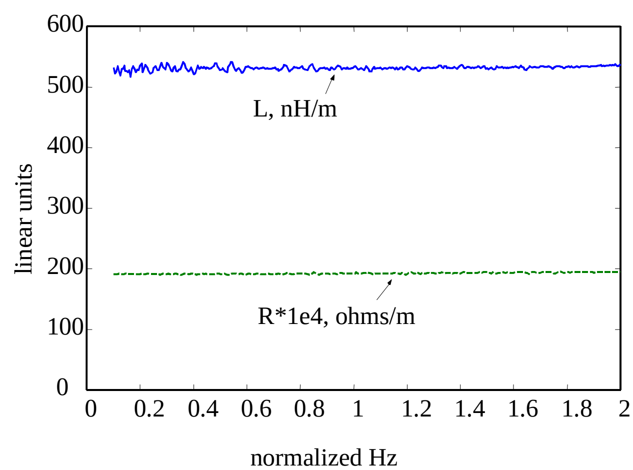

Fig. 5. TL parameters from measured Zo & Zs.

estimated from the Zo and Zs measurements. For this application, the experimental cable clearly operates at frequencies below which the skin effect becomes significant. This is not always true for acoustic probes, for example see [3].

Figures 6-7 show input admittance, Yin, seen looking into the probe (transducer-terminated cable).

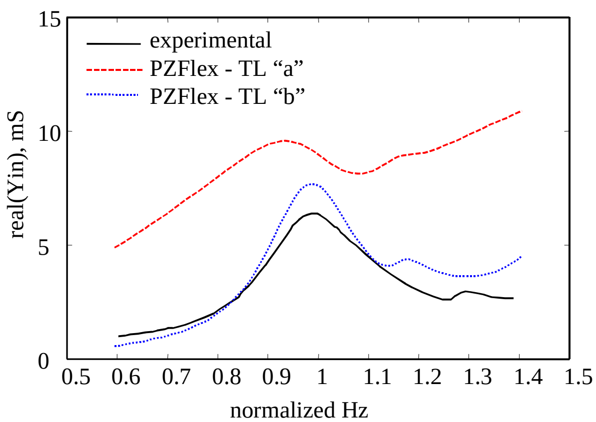

Fig. 6. Real portion of measured and calculated Yin.

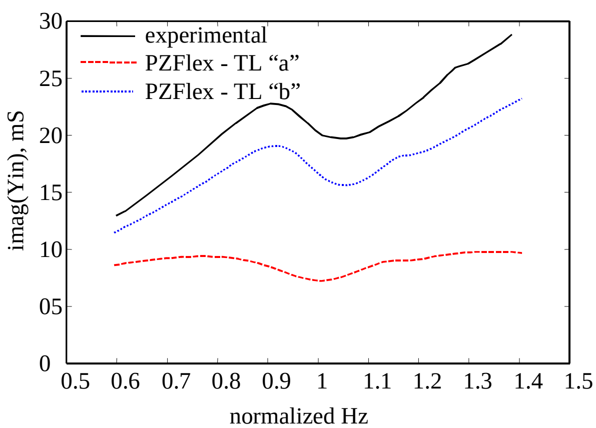

Fig. 7. Imaginary portion of measured and calculated Yin. PZFlex calculations use at least 20 TL sections per λ.

Using the more carefully determined cable parameters appears to reduce the measured-predicted mismatch by about a factor of three. Correctly predicting Yin would be important, for example, in designing a power-efficient electronic driver.

Figure 8 illustrates that “improved” cable parameters allow PZFlex to better predict the mechanical output of our experimental device.

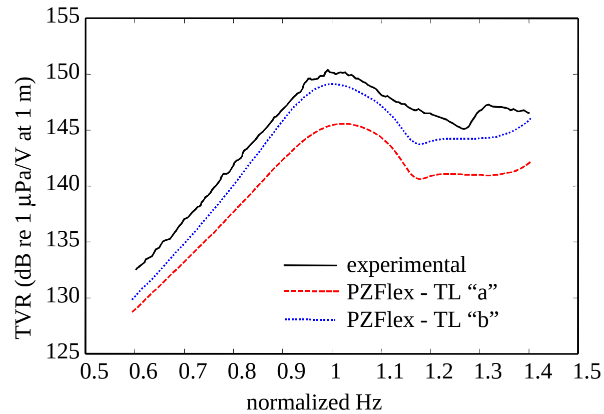

Fig. 8. Measured and calculated TVR for experimental naval probe.

Judging from Fig. 8, changing from “a” to “b” TL parameters takes the measured-predicted TVR mismatch from ≈5 dB to ≈2 dB.

IIII. DISCUSSION / CONCLUSIONS

A widely applicable new method has been presented for deducing frequency-independent parameter values from frequency-dependent parameters computed (e.g. SI 2D™) from TL cross sectional geometry and material properties of 2-port cables. Alternately, the f-dependent parameters may be estimated from Zo & Zs measurements. These parameters allow accurate representation of frequency-dependent cable resistance and inductance – operating frequency may be low or into the skin-effect region. Because the deduced parameter values, Fig. 2, do not depend on frequency, they are easily employed in time-domain simulators, such as PZFlex. An advantage of time-domain simulation is that a single simulation, combined with FFTs, determines admittance and TVR at all frequencies.

Various LS procedures could be used to find the ladder circuit R_i and L_i values. For example, one can obtain very close agreement between the true and fit R(f) & L(f) curves by optimizing on each of the R_i and L_i parameters. However, in our experience the suggested method results in well-conditioned problems that quickly converge to unique answers. Also, using said method has yielded true-fit mismatches within usual cable-fabrication tolerances.

For the example naval probe, the Fig.-2 circuit is more general than needed. However, carefully gathering and processing Zo & Zs measurements substantially "narrowed" the gap between measured and PZFlex-calculated probe behavior; narrowed means relative to calculations based on first-cut cable parameters.

IV. Acknowledgement

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V. References

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