The angle property of positive real functions simply derived

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The sensitivity of $T(j\omega)$ to circuit elements may be computed as

$$S_T(j\omega) = \begin{cases} 1 \\ \frac{n}{K'} \end{cases} D(j\omega)$$

The sensitivity of $T(j\omega)$ to circuit elements may be computed as

$$S_T(j\omega) = \begin{cases} 1 \\ \frac{n}{K'} \end{cases} D(j\omega)$$

and

$$\sum_{i=1}^{n} S_{T_i}(j\omega) = \sqrt{n^2 + (n/K')^2 \cos \phi} - (n/K') \sin \phi$$

where $\phi$ is a passive circuit element (a resistor or a capacitor) of the three-terminal RC network, $\phi$ is the phase function of $T(j\omega)$, and $n$ is the total number of like elements (resistors or capacitors) of the three-terminal network.

The sensitivity of $T(j\omega)$ to the gain of the amplifier has been utilized here in controlling the gain constant of the all-pass function realized. It is seen from (15d) and (15c) that for the network sensitivities to $n$ and the passive elements $x_i$ to be low, the ratio $n/K'$ must be small. For the all-pass realization, the minimum value of the ratio $n/K'$ may be seen to be unity for which

$$\sum_{i=1}^{n} S_{T_i}(j\omega) = 2 \cos \phi / 2$$

In thin-film networks, the resistances fabricated on the same substrate track closely with temperature, and consequently the variation in the value of $n$ is very small; hence, the gain and phase sensitivities of $r(j\omega)$ to $n$ given in (15b) and having a maximum value of $-n/K'$ each do not pose any problem. It may be noted from (15d) that the sum of the magnitudes of the sensitivities of $T(j\omega)$ with respect to each passive circuit element of the three-terminal network may be minimized by minimizing the sum of the magnitudes of the corresponding sensitivities of $T(j\omega)$. As has been indicated in the literature [8], the sum of the sensitivities of the transfer function of a passive three-terminal RC network with respect to each passive element can be made negligible if (1) all the like elements (resistors or capacitors) of the circuit track with temperature, and 2) the fractional variation of a resistor is equal and opposite to that of a capacitor. Thus for low sensitivity figures to passive circuit elements, these conditions must be satisfied, which are not difficult in the thin-film network.

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References


The Precise Theoretical Limits of Causal
Darlington Synthesis

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In this short paper we announce a mathematical theorem concerning Darlington (or Belevitch) synthesis for lumped-distributed circuits. The detailed paper giving proofs will appear in a mathematical journal. A bounded (real) matrix $S(z)$ is said to be (real) losslessly embeddable if there exists a lossless bounded (real) matrix

$$U(z) = S(z) A(z)$$

The theorem we wish to announce is the following.

Theorem: The bounded (real) matrix $S(z)$ is (real) losslessly embeddable if and only if each entry of $S(z)$ is the boundary value of a meromorphic function defined on the left half-plane.

In particular, $S(z)$ is (real) losslessly embeddable if each entry of $S(z)$ is a rational function, while it is not if one of the entries has an isolated branch point. It is not difficult to see that every lossless bounded matrix $U(z)$ has a meromorphic extension into the left half-plane. The extension can simply be written down: it is $E(p) = (U(-\bar{p})^*)^{-1}$ for each $p$ in the left half-plane. This implies that each entry of $U(p)$ has such a meromorphic extension and, consequently, yields one side of the theorem. The other side of the theorem is much more difficult. A point worth noting is that there are embeddable matrices $S(z)$ (and in fact lossless matrices) which are not actually meromorphic on the entire complex plane. The hypothesis of the theorem does not force $S(z)$ to be meromorphic on the imaginary axis.

Our theorem extends Theorem 4 in Section 6 of DeWilde [1]. He deals with a class of matrix functions which he calls "roomy scattering matrices." Our work shows that these precisely the matrices, each entry of which is a rational analytic function in the right half-plane and possessing a meromorphic extension to the left half-plane. We conclude by mentioning that a rather thorough study of functions of this type can be found in [3]. (Although the results there are stated for the unit disk, they hold via conformal mapping for the right half-plane.) One characterization of these functions in terms of rational approximation in [3, theorem 4.1.1.] might be of particular interest.
quadrant, arg $s = \arg Z(s)$ can rather easily be shown to be nonnegative. The extremum theorem of analytic functions then assures that arg $s + \arg Z(s)$ cannot be negative inside the first quadrant; thus the angle property is demonstrated in the first quadrant. The same result is obtained immediately in the fourth quadrant.

It is an obvious fact that if a function $Z(s)$ is analytic in the right half of the $s$-plane and if, furthermore,

$$|\arg s| \geq |\arg Z(s)|$$

in this region, then $Z(s)$ is a positive real function. On the other hand, if a function $Z(s)$ is known to be positive real, then the angle property just stated always holds: this fact, though well known, is far from obvious. In the standard literature two proofs are cited [1], [2], both of which, however, are complex and long winded to the extent that even modern and thorough texts often refrain from presenting a proof; see, e.g., [3], [4]. It is the purpose of this short paper to offer a simple and perspicuous proof of this angle property of positive real functions.

Consider then a positive real (rational) function $Z(s)$, temporarily only in the first quadrant of the $s$-plane, with a view to proving that in this quadrant $|\arg s| = \arg Z(s)$ or, equivalently, that both

$$\arg s - \arg Z(s)$$

and

$$\arg s + \arg Z(s)$$

are nonnegative anywhere in this quadrant. The proof will consist of an application of the well-known theorem that, over a region, either component of an analytic function will assume its extremum values on the boundary of that region. The analytic function in question will be $u + jv$, where

$$u + jv = \ln \frac{s}{Z(s)} = \ln \frac{s}{Z(s)} + j(\arg s - \arg Z(s))$$

or

$$u + jv = \ln \frac{Z(s)}{s} = \ln \frac{s}{Z(s)} + j(\arg s + \arg Z(s))$$

and it is the imaginary part of each of these functions that will be examined for its minimum.

In essence, the proof now proceeds as follows. First, an investigation of $v$ is made along a contour enclosing the entire first quadrant. It turns out that $v$ will be nonnegative anywhere on this contour. Next, the theorem just mentioned is applied to the first quadrant including the contour enclosing it. It then becomes evident that

$$v = \arg s + \arg Z(s)$$

cannot be negative at any point in this region. So, the angle property has been demonstrated in the first quadrant. Finally, in the fourth quadrant the same result is easily obtained.

Readers interested in an account of the—rather simple—details of the proof are referred to the Appendix.

### Appendix

To carry out the proof in precise details, one considers Fig. 1, which shows the first quadrant of the $s$-plane along the $j\omega$-axis, $\arg s = \arg Z(s)$ will now be studied. Along the $\sigma$-axis, $v$ is evidently zero. At infinity $Z(s)$ must possess either a simple pole with a positive "residue" or a simple zero with a positive "derivative," or it must be equal to a positive constant; to put this more plainly, near infinity $Z(s)$ must behave asymptotically like $s$, $Ls$, or $1/\cos$, where $\sigma$, $L$, and $C$ are positive constants. Along the large quarter circle at the origin, a discussion, in fact highly similar to the one given for the large quarter circle, will show that $v$ will be nonnegative on the quarter circle with infinitely small radius $r = 0$.

Along the parts of the contour that are shared with the $j\omega$-axis, $v$ clearly is nonnegative since $\arg s = \arg ju = 90^\circ$ and since $|\arg Z(s)| = |\arg Z(j\omega)| = 90^\circ$.

In summary, then, along the entire contour one can make $v > -\varepsilon$, where $\varepsilon > 0$ is arbitrarily small, by sufficiently increasing $R$ and sufficiently decreasing $r$.

Now suppose that at a finite point $s_0$ in the first quadrant, either $v = \arg s - \arg Z(s)$ or $v = \arg s + \arg Z(s)$ assumes a negative value. Then, by increasing $R$ and decreasing $r$ sufficiently, one can always make $v$ less negative than this value at all points of the contour. However, according to the theorem mentioned, the lowest value of $v$ must be assumed on the contour. Therefore, the assumption of a negative value of $v$ at some such point $s_0$ is not possible. So in the first quadrant one has that $v \geq 0$ or that $|\arg s| \geq |\arg Z(s)|$.

In the fourth quadrant the same result can be obtained from entirely analogous reasoning or, even simpler, immediately from the identities $|\arg s*| = |\arg s|$ and $|\arg Z(s*)| = |\arg Z(s)|$, where $s* = -\sigma - j\omega$ when $s = \sigma + j\omega$. Thus it has been proved that the angle property is a characteristic of all positive real (rational) functions.

### References


### The Maximum Power Transfer Theorem for n-Ports

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Abstract—The maximum power transfer theorem is proved by an elementary and simple method. The class of all impedance matrices which achieve maximum power transfer is completely described. Cases where $Z_+ + Z_*$ is not positive definite are completely discussed.