VII. Application to Devices & Computer Simulation

Rigorous network analogs have been obtained for configurations of stacked crystal plates excited piezoelectrically. At various places in the text, a number of applications of these configurations has been indicated. Realization and optimization of practical devices based upon these ideas, however, can best proceed by introducing a step intermediate between a circuit and the physical device it represents. This step consists in utilizing the network to simulate the ideal behavior of the device using CAD programs. In this way changes can be made easily without having to resort to a breadboard model each time it is desired to know the effect of some alteration in structure or composition. Since the networks are exact, they will faithfully reflect the behavior of the devices, subject only to the mild restrictions under which they were derived.

It is to a brief demonstration of these ideas that the present chapter is devoted. Here we will consider two of the simpest structures whose operation is based upon the ideas we have presented. Our object is to indicate how the structures can be expected to operate, and what avenues of future work are likely to be most fruitful in the reduction of our general results to practice.

Devices such as delay lines and pulse and code generators are best characterized in the time domain, while resonators and filters are best treated in the frequency domain. Our networks are valid and apt for both descriptions, but here we shall focus our attention upon filters to illustrate the ideas of this dissertation. Applications to the other areas indicated, as well as to related topics, such as frequency discriminators, is relatively straightforward.

A. Double-Resonance Filter Crystals.

The first structure we will discuss is perhaps the simplest of its kind. This is the LETM-driven, traction-free resonator possessing two excitable modes having frequencies close to one another. The configuration consists of a single plate and it is used as a one-port device. A filter would be constructed from two of these elements, arranged, for example, as a half-lattice (23,25,26). In this arrangement the passband consists of those regions where the reactances of the two arms are opposite in sign. Mason & Sykes (150) describe lattice filters composed of more than one crystal in each arm; in our case each single plate is equivalent to two conventional filter crystals because of the use here of two of the three thickness modes in the plate. One can make use of this effect to reduce the number of crystals required, or to increase the filter performance by improving the shape factor or in-band ripple. Alternatively, it can be used to increase the bandwidth beyond what could be accomplished with a resonator having a single resonance of the same strength. This last application is promising with the use of crystals having high piezoelectric coupling factors, such as the refractory oxides now being investigated (181,186).

Although quartz does not possess high piezoelectric coupling, so that wide band quartz filters are not achievable without additional circuit elements, its physical properties are well known. For this reason we will use it to illustrate the double-resonance filter application; the discussion is readily applied to any other suitable substance. In quartz, the shear and quasi-shear frequencies approach one another for rotated

Y-cuts $(YX\ell)\theta$, where θ is approximately -24°. Plates of substantially this orientation may be driven in LETM in such a way that the two modes of interest are of equal strength (214). The quasi-longitudinal mode is also driven, but is about 18% higher in frequency and can be neglected for our purposes.

A plate with electrodes attached for applying the lateral field is shown in Fig. 40. The angle ψ measures the field direction with respect to the z' axis. By changing ψ, the effective coupling factors of the two modes may be altered according to the graph of Fig. 41, which shows the two coefficients to be equal when $\psi = 34^\circ$ for a plate cut to $\theta = -23^\circ 50'$.

Given on the right of Fig. 40 is the bisected form of the equivalent network of the plate, which follows from our general results, almost by inspection. The complete, bisected network of Fig. 19 has been here reduced by making one of the turns ratios equal to zero. In order to take into account the neglected third mode, the value of $\underline{C_o}$ may be augmented by the capacitance value presented to the input by the third transmission line at the frequencies of interest, which are near the nominal filter center frequency. This capacitive effect is negligible for the present case, but might not be for a substance with a high coupling coefficient for the third mode. In designing the filter, it is usually easiest to think in terms of the equivalent network parameters, and then to interpret these further in terms of the underlying physics.

For example, the lattice filter mentioned above might be designed as follows. Since the passband consists of the region where the reactances or susceptances of the two arms differ in sign, the crystal elements can be made so that they each possess equally spaced poles and zeros, the first zero of one crystal plate coinciding with the first

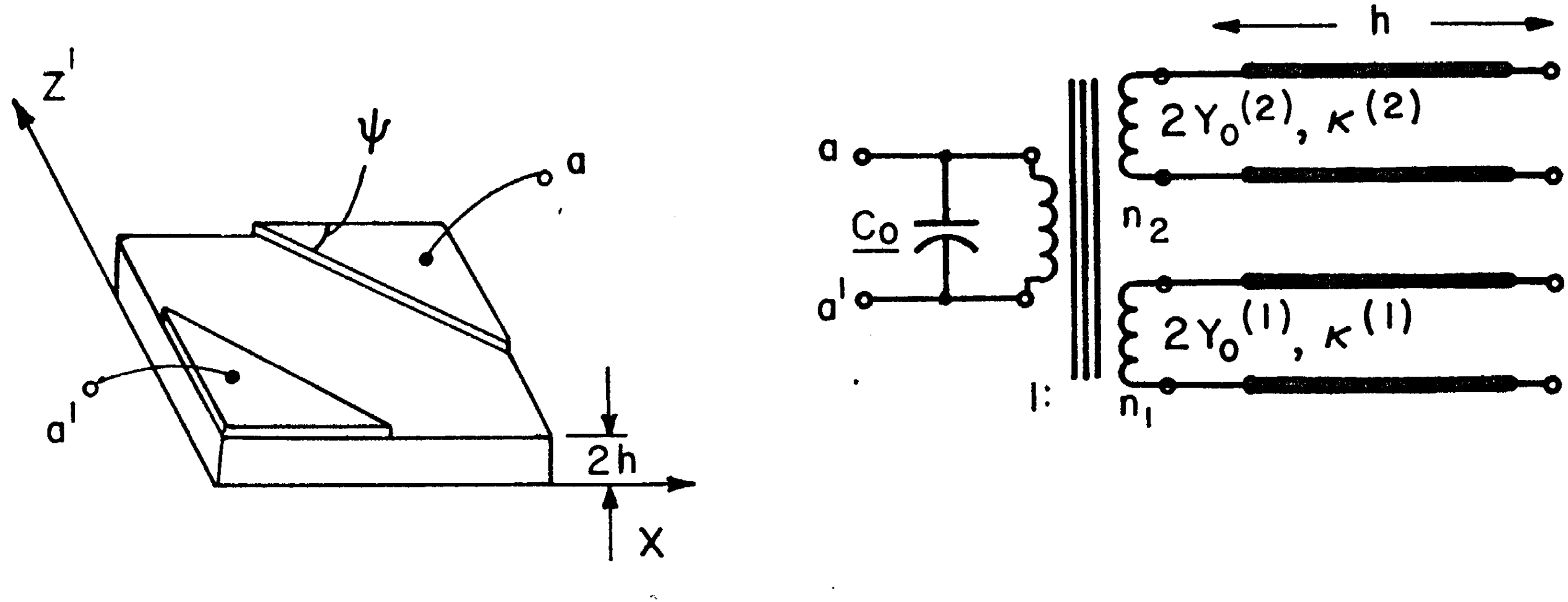

FIG. 40. LETM - DRIVEN QUARTZ PLATE, (YXℓ) θ, AND NETWORK REPRESENTATION.

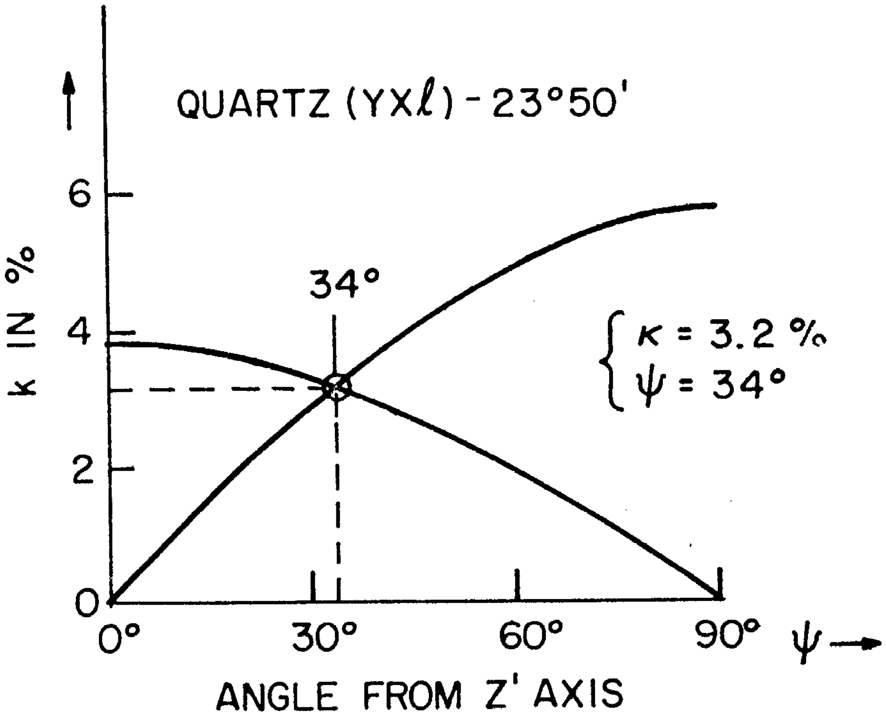

FIG. 41. EFFECTIVE LETM COUPLING COEFFICIENTS IN ROTATED Y-CUT PLATE, AS FUNCTION OF LATERAL AZIMUTH.

pole of the other. To arrange the equal spacing of the poles and zeros of each plate requires, for a given total fractional bandwidth, that the input reactance or susceptance function determined from the network of Fig. 40 be solved for the three values $k^{(1)}$, $k^{(2)}$ and $(v^{(1)}/v^{(2)})$ that simultaneously accomplish this. It is almost mandatory that this be done by computer. The resulting values may or may not be achievable with the substance chosen; this is determined by reference to curves such as those in Fig. 41 and the corresponding set for the velocities. Once the velocity ratio is known, the angle θ can be chosen, and when this has been picked, a value of ψ can also be chosen. A limitation of the technique is that $k^{(1)}$ and $k^{(2)}$ cannot be chosen independently.

After a normalized design has been arrived at, the absolute frequency is fixed by the choice of the plate thickness 2h. Figure 42 shows a graph of the computer-generated reactance function for rotated Y-cut quartz, $(YX\ell)$ $-23^{\circ}50'$, using $\psi = 34^{\circ}$. The reactance has been normalized to the reactance of <u>Co</u> at the frequency of the lower shear mode; this frequency is used to normalize the abscissa scale also. In this case the pole-zero spacings are nearly equal when the two coupling factors are equal. The total fractional bandwidth is only about 0.2% here, which is a factor of four smaller than can be attained by the use of AT-cuts of quartz alone, but is serves as an illustration of the principles involved for more practical designs based upon strongly piezoelectric materials. The requirements imposed by the filter network are readily interpreted by reference to the crystal equivalent circuit parameters, which are then determined from material constants and dimensions.

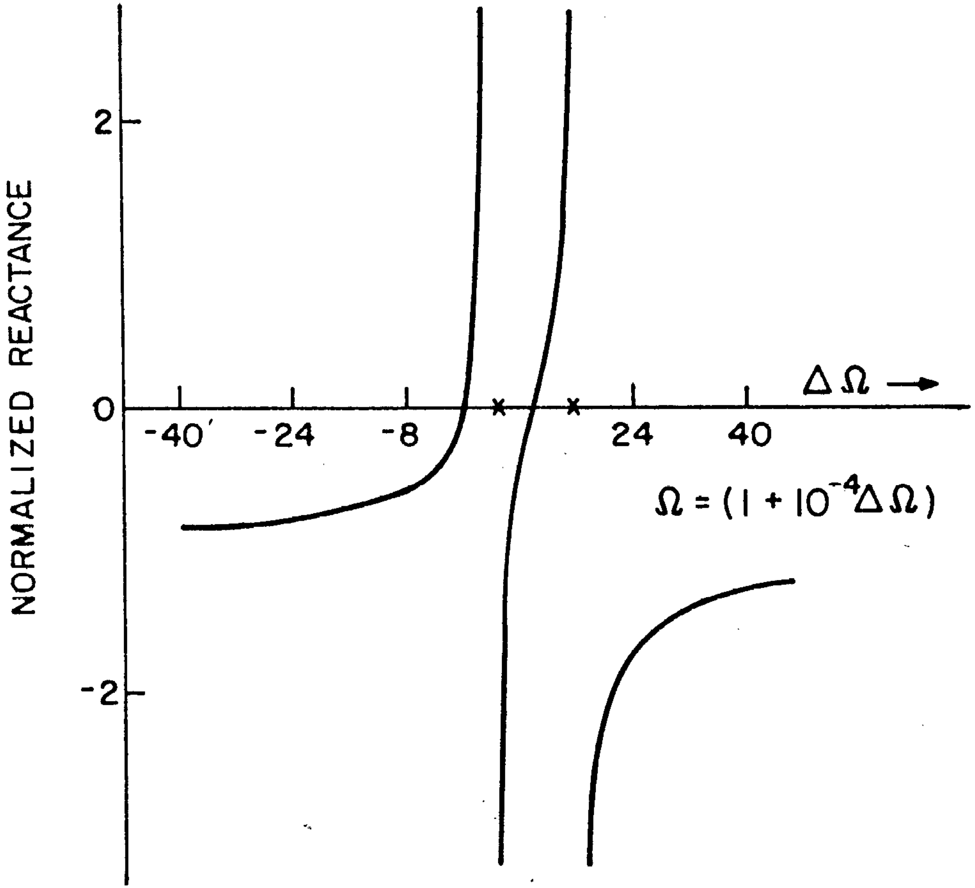

FIG. 42. NORMALIZED INPUT REACTANCE OF ROTATED Y-CUT QUARTZ PLATE (YXℓ) - 23°50', IN THE VICINITY OF RESONANCES OF THE SHEAR & QUASI-SHEAR MODES. LETM-DRIVEN BY A FIELD 34° FROM THE Z' AXIS.

B. Two-Layer Integral Crystal Filters

This section is devoted to a structure that is somewhat more complicated than the double-resonance crystal just considered. It has, however, possibly much greater potential for practical device realization. This structure consists of a two-layer stack of plates in welded contact, driven in TETM. We have mentioned this configuration in Section VI B in connection with the interface networks shown in Fig. 25 ff, and will make use of some of that discussion in the example we shall give below. In contrast to Section A, we now have two plates, instead of one, and will consider six modes instead of two; the device will be operated as a two-port, and will be TETM- driven. With these increased complexities it would be hard to derive much benefit from any but a most extended discussion, so we shall introduce a few compensating simplifications to enable us to see the outlines, at least, of the workings of this class of devices.

Before any simplifications are made, we will discuss the problem briefly in general. A sketch of the plate arrangement is given in Fig. 43. Where the field orientation provided a degree of freedom in the example of the first section, the relative rotation of the plates about the common x_3 axis similarly provides a means of investigating the effects of changes in the mechanical interface transformer turns ratios in the present case. The angle ψ is now taken to measure the relative rotation of the two plates from some fixed origin. The TETM driving arrangement consists of three electrodes, one at each of the traction-free surfaces, and one at the welded interface. The input and output can be taken in a number of ways; we shall consider the central electrode as common to both input and output.

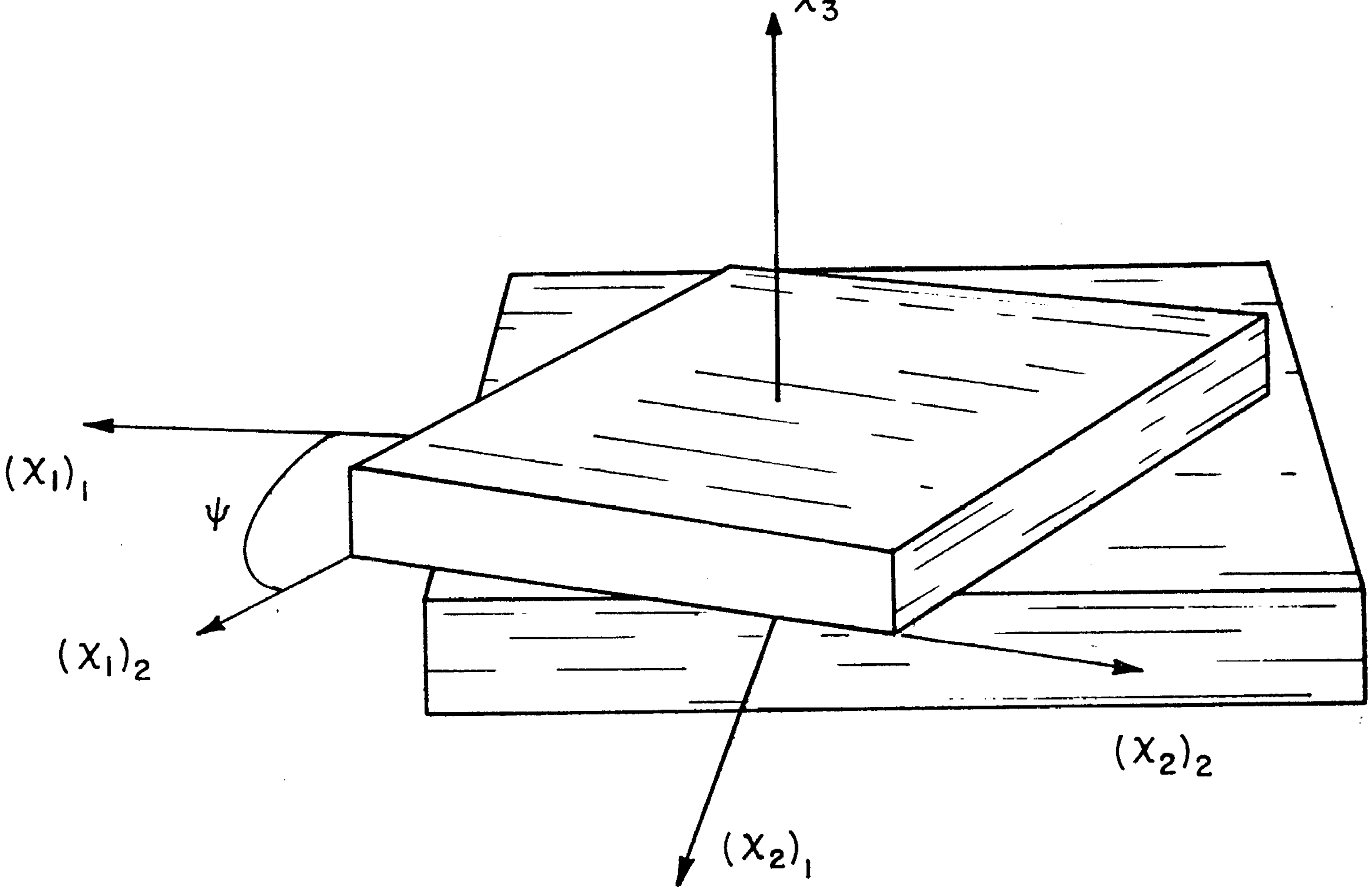

FIG. 43. TWO-LAYER STACK OF CRYSTAL PLATES SHOWING RELATIVE ROTATION ABOUT COMMON X_3 AXIS.

In this configuration we have a frequency selective device composed of two strata wherein the three modes of each layer are permitted to interact with each other via the mechanical boundary conditions. Mutual shielding or packaging is not required. The device is inherently robust because of its integral construction, and also lends itself readily to miniaturization. In fact there is no reason why integral crystal filters of this type, with two or more layers, could not be made completely compatible with integrated circuit technology.

Our illustrative example consists of computer simulated attenuation response curves of a two-layer integrated filter device. Having the overall impedance matrices for each layer, as given in Chapter V, it is not difficult to obtain the two-port impedance matrix between the electrical ports of the two-layer stack. The top and bottom faces of the plates are traction-free, so that the transmission lines representing the plates are shorted here, while the three internal mechanical ports of each plate are connected together, leaving only the electrical ports unconnected. Matrix methods pertinent to the interconnection of networks may be found in (18 & 21); we do not consider these details here but pass on to the attenuation function, A(dB).

Once the interconnected networks have been characterized by a two-port impedance matrix Z_{ij}, the attenuation may be determined provided the source and load impedance are known. Our first simplifying assumption is that these are of equal value, and are purely real:

$$Z_{source} = Z_{load} = R.$$

Then, using the equations found, e.g., in Zverev (25), the attenuation, in decibels, is

$$A(dB) = 10 \log_{10} \left\{ [Z_{11} + Z_{22}]^2 + [(\det Z)/R + R]^2 \right\} - 20 \log_{10} |2 Z_{12}| .$$

Because our circuit impedances are all purely reactive, A(dB) is given by the same expression with reactance written for impedance, and the sign of det Z changed.

We are now ready to choose the materials to be used for the layers. Again, because of the completeness with which its material constants are known, and because it preserves so many connections with currently used devices, we pick quartz. Specifically, both plates are chosen to have precisely the same orientation, that of the AT-cut: $(YX\ell)\theta$, $\theta = +35^{\circ}15'$. This has four major consequences. First, the behavior of single plates of this cut is universally known, so that our filters can be contrasted with known results for quartz filters of standard construction. Second, the selection of the same cut makes the eigenvalues of both plates equal, so that the critical frequencies of each plate, taken separately, are in the same ratios. Third, the lower shear mode is a pure mode, so that the interface network is simplified. Finally, only the pure shear mode in each plate is TETM- drivable, so the piezoelectric interconnections are simplified.

We mentioned in Section VI B when describing Fig. 34, that it could be used to represent the mechanical interface transformer network between two rotated Y-cut plates of quartz. The entire discussion given there is pertinent to our application now, since the AT-cut is a member of this family. Figure 34 describes the mechanical network we consider here, with the piezoelectric connections made only at ports (1) and (4) of the interface and at the traction-free plate surfaces. Because both plates have the same orientation angle θ , the corresponding transmission lines on each side of the figure are identical. When the relative rotation angle ψ is zero, the device becomes identical with a single plate of quartz, except for the central electrode. The mechanical network then degenerates into a set of three direct feed-throughs. When $\psi \neq 0^\circ$, the network of Fig. 34 is appropriate and the modal matrix components governing the transformer ratios on the right hand side are then functions of ψ if the x_i axes of the crystal on the left hand side is chosen as the reference set.

The final simplifications are that the plates are of equal thickness,

$$\omega_1 / 2\pi = 100 \text{ MHz},$$

and

$$R = 1/(\omega_1 C_o) = 50 \text{ ohms},$$

where ω_1 is the angular frequency at which the reference plate, taken alone, has its first admittance zero. The capacitance Co refers to the shunt capacitance of a single plate.

The effect of making the plates to be of equal thickness is to force the frequencies of both plates to be the same, so that only three, and not six modes have to be considered. This restriction is the first which should be lifted in a continuation of the work described here; two plates whose thickness differ by a few percent can be expected to exhibit a narrow-band filter characteristic.

Using all of the above-mentioned simplifying assumptions we are left with results that are easily described and analyzed. The computer-generated output is plotted in Fig. 44. Frequency normalized to ω_1 is used as the abscissa. Curves are presented for the three angles $\psi = 0^\circ$, 4° and 8°. When $\psi = 0^\circ$, the stack appears as an asymmetrically driven single plate of thickness 4h, and because of the lack of symmetry, the stack possesses resonances at integer values of Ω. The only driven mode is the lower shear mode which is a pure mode. Hence this mode is

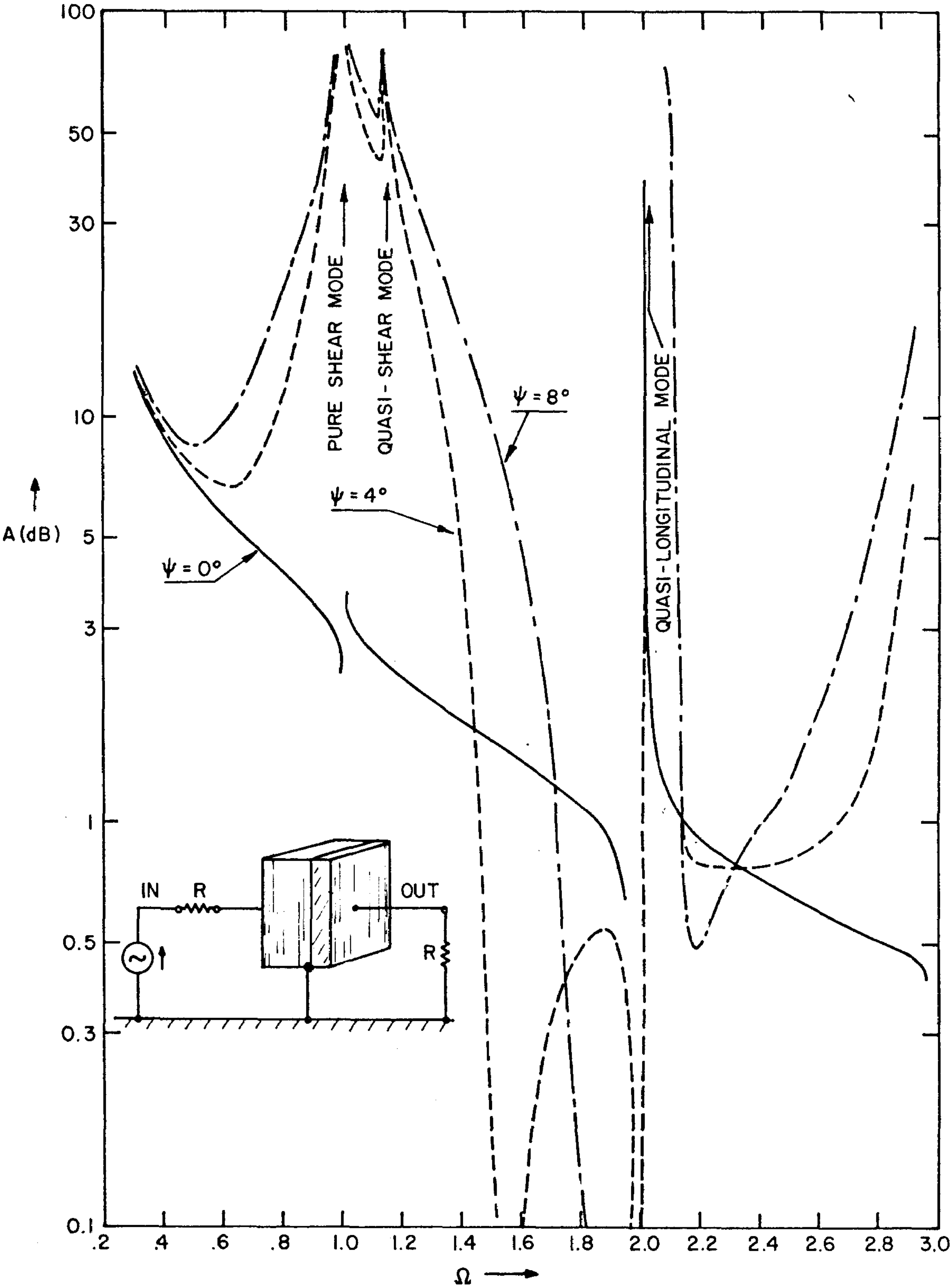

FIG. 44. ATTENUATION VERSUS FREQUENCY FOR A TWO-LAYER STACK OF 100 MHz AT-CUT RESONATORS AS FUNCTION OF RELATIVE ROTATION ψ ABOUT COMMON THICKNESS AXIS

completely uncoupled from the others, so that any resonances due to them do not appear in the attenuation function. In both cases where $\psi \neq 0^{\circ}$, the attenuation has poles at $\Omega = 1.000$, 1.142 and 2.105, corresponding to modal velocities $v^{(i)}$, of 3.328, 3.800 and 7.007 $\times 10^{3}$ meters/second. If the plate thicknesses had not been made equal this correspondence would have been destroyed, and an important check could not be made. An easy way to explain the presence of the poles is to recognize that every time a transmission line becomes one half wavelength long, the short circuit at the traction-free boundary appears across the other end of the line and uncouples the two plates.

Notice that although the poles are fixed, the shape of the curves may be changed by varying ψ, so that one has a simple means of obtaining different filter responses. Although the purposes of our illustration are to indicate how devices based on these principles might operate and to provide an example that is still quite simple, and readily interpreted, the resulting curves for $\psi = 4^{\circ}$ and 8° are already reasonable wide band filter responses in the region just below $\Omega = 2$. Removing the restriction to equal plate thicknesses will also permit narrow band filters to be designed as integral filters.

The possible filter responses available for even the simplest two-layer structure are very large. Even if the plates are restricted to a single material, each plate cut is specified by two angles and the mutual rotation angle between the plates makes five disposable parameters to which must be added the ratio of the plate thicknesses. A large area for investigation is present here. Extensions to structures composed of more than two plates, and the use of different materials for each of the plates further widens the possibilities of these devices for frequency selection and control.