time sampling interval is $T = 2\tau' = l/c$. Sketch the discrete-time frequency response from the source to the lips. Deduce the discrete-time transfer function. How many resonances are now represented over the frequency interval $[0, \pi]$?

(d) Find a continuous-time impulse response with bandwidth π/T, that, when sampled with sampling interval T of part (c), gives the discrete-time frequency response [of part (c)] over the discrete-frequency interval $[-\pi, \pi]$. How does this continuous-time impulse response differ from the true continuous-time impulse response of the tube? How does it differ from the true impulse response at the time samples $nT = n2\tau'$? How many equal-length tubes (same cross-section) of a concatenated tube model do you need as a basis for the resulting discrete-time model to represent the true impulse response for all time?

(e) Suppose now that energy loss takes place in a spatially-varying tube, and its frequency response, given in Figure 4.36, is bandlimited to 24000 Hz. Suppose all energy loss occurs at the output radiation load, and suppose that the spatially-varying tract is approximated by a concatenated-tube model. How many equal-length tubes are required in a discrete-time model to represent the frequency response over only the first 12000 Hz?

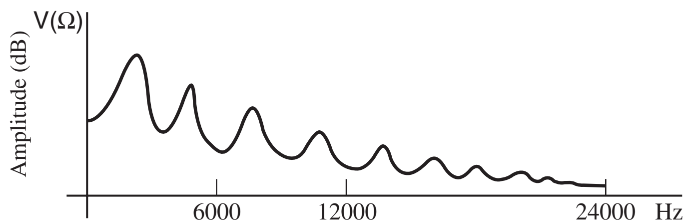

Figure 4.36 Lossy tube frequency response.

4.19 In this problem you will fill in some of the missing steps in Section 4.5 on vocal fold/vocal tract interaction and the "truncation" effect. We saw in Figure 4.22 an electrical analog of a simple model for airflow through the glottis. P_{sg} at the left is the subglottal pressure in the lungs that is the power source for speech, $p(t)$ is the sound pressure corresponding to a single first formant, and $Z_g(t)$ is the time-varying impedance of the glottis, defined as the ratio of *transglottal pressure* across the glottis, $p_{tg}(t)$, to the *glottal volume velocity* through the glottis, $u_g(t)$.

(a) Writing the current nodal equation of the circuit in Figure 4.22, and using Equation (4.43), show that

$$C\frac{dp(t)}{dt} + \frac{p(t)}{R} + \frac{1}{L}\int_0^t p(\tau)d\tau = A(t)\sqrt{\frac{2p_{tg}(t)}{k\rho}}. \tag{4.50}$$

(b) Differentiate Equation (4.45) with respect to time and show that

$$C\frac{d^2p(t)}{dt} + \left[\frac{1}{R} + \frac{1}{2}g_o(t)\right]\frac{dp(t)}{dt} + \left[\frac{1}{L} + \frac{1}{2}\dot{g}_o(t)\right]p(t) = \dot{u}_{sc}(t). \tag{4.51}$$

Then argue from Equation (4.51) that Figure 4.24 gives the Norton equivalent circuit to the original circuit of Figure 4.22, where the equivalent time-varying resistance and inductance