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DUCT LINER OPTIMIZATION FOR TURBOMACHINERY NOISE SOURCES

By

Harold C. Lester and Joe W. Posey

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INTRODUCTION

In recent years much research effort has been directed towards developing mathematical models for understanding the propagation and attenuation of sound in acoustically lined, axisymmetric, aircraft engine ducts. This paper discusses the related problem of predicting optimal multisectioned acoustical liners for circular ducts by the application of numerical optimization alogrithms to analytical duct models.

An optimal liner is achieved by judiciously selecting the impedance characteristics of the liner so that maximum sound attenuation is produced for a given design condition. The often cited work of Cremer (ref. 1) is, perhaps, the earliest attempt to define an optimal liner criterion. Cremer's approach is based on maximizing the attenuation rate of the lowest-order (least attenuated) acoustical mode propagating in an infinitely long, two-dimensional duct. Tester (ref. 2) recently generalized and extended Cremer's results for application to rectangular and circular cross-sections and to arbitrary (higher-order) modes. This extension was obviously motivated by the consideration that the bulk of the acoustical power is not always carried in the lowest-order mode. Optimal liner impedance values have also been determined by Rice (ref. 3) for a plane-wave source in an infinitely long, uniformly lined, circular duct without flow. Rice's model is based on the superposition of a finite number of soft-wall radial duct modes. Contour maps were employed to determine optimal liner impedance values.

Apparently Wilkinson (ref. 4) was the first to calculate optimal liner impedance values by using a numerical optimization procedure. He utilized an integral-equation duct propagation model coupled with the method of steepest descent (gradient method). His results for uniform cylindrical liners with a plane-wave source compare favorably with Rice (ref. 3). Limited success, due to numerical difficulties, was obtained for a uniform annular duct liner with flow and a bellmouth termination. Quinn, in a recent paper (ref. 5), used a finite difference solution of the convective wave equation although details of his minimization method are not mentioned. Results are presented for a variety of axisymmetric multisectioned liner configurations with and without uniform flow. In another recent paper (ref. 6), Beckemeyer and Sawdy investigated the properties of optimal multisectioned, two-dimensional duct liners. Their theoretical model is based on modal superposition (mode matching method). A conjugate gradient algorithm was utilized in the optimization process. Simple acoustic sources, expressed in terms of mode amplitude and phase angles, were investigated.

In this paper optimal circular duct liners are calculated by using Zorumski's (ref. 7) multisectioned theory and the optimization algorithm of Davidon, Fletcher, and Powell (ref. 8). Uniform liners and liners with two and three sections are investigated. Whereas previously published results have emphasized optimization for plane-wave sources, here the source models include a point source located axisymmetrically on the duct centerline and a source model representing rotor/outlet-stator viscous wake interaction effects for a typical research compressor configuration operating at an axial flow Mach number of 0.4. For this latter source, the classic Kemp-Sears theory is used to describe the unsteady blade loadings (ref. 9). Optimal liner properties predicted for the exact set of source amplitudes and phase angles are compared with those for equipartition-of-energy, zero-phase and least-attenuated-mode source approximations. A uniform flow velocity profile is assumed.

SYMBOLS

b	duct liner radius
E(z)	axial acoustical energy flux at z
f	frequency, $\omega = 2\pi f$
I{ }	denotes imaginary part of { }
j	$\sqrt{-1}$
k	wave number
m	circumferential wave number
R{ }	denotes real part of { }
β	nondimensional admittance, $\beta = \beta_R + j\beta_I$
θ	angle of incidence
ϕ	transmission loss in decibels

DISCUSSION

For the present study, the mode summation propagation theory developed by Zorumski (ref. 7) for multisectioned, axisymmetric ducts is employed. This approach allows for the straight forward modeling of any of the liner configurations shown in figure 1, which are made up of a sequence of circular sections each having uniform admittance properties. A finite section of an infinite duct or a truly finite duct can be easily handled. Arbitrary source spatial distributions are defined by giving the amplitudes and phase angles of the various modes. Also, source impedance and termination impedance conditions can be imposed. All calculations presented here are based upon a wave source, such that the right-moving wave at the source plane is specified. Configurations a and b (fig. 1) are used for the point source calculations, while configurations c, d, and e are used with turbomachinery sources.

A comparison of this theory with an independent modal theory (ref. 3) applied to the configuration shown in part (a) of figure 1, with a uniform pressure profile at $z = 0$, shows excellent agreement (not shown here for the sake of brevity). Good agreement also exists with a finite difference solution (ref. 5) which employed a uniform pressure source at $z = 0$ and a uniform axial impedance at $z = L$ equal to the characteristic impedance of the medium.

The optimization process is indicated in figure 2. For any given duct geometry, flow field, and spatial distribution of a pure-tone noise source of frequency f (with a time dependence $\exp(-j2\pi ft)$), the Davidon-Fletcher-Powell minimization algorithm is used to predict the liner admittance giving the largest possible transmission loss ϕ between the axial stations $z = 0$ and $z = L$. The liner is taken to be locally reacting, so that its properties are completely specified by giving the normal acoustic admittance, β = (complex acoustic normal velocity)/(complex acoustic pressure), for each of its segments. The transmission loss is the reduction in axial acoustic energy flux expressed in dB. All results which follow are for transmission losses across a length of the duct equal to its diameter (L = 2b).

Figure 3 is a plot of the maximum transmission loss as a function of normalized frequency kb for a uniform liner (fig. 1a) with a point source located on the duct axis at z = 0. Since the situation is axisymmetric only circumferential wave number m = 0 modes are excited. Along with the numerical optimization results, a curve determined from Cremer's least-attenuated-mode criterion (ref. 2) is shown. At very low frequencies, when only the lowest-order mode is cut on, Cremer's criterion works well. However, significant differences in the two predictions occur as soon as the first higher-order radial mode begins to propagate. Cremer's criterion predicts a maximum ϕ at kb = 20 of less than 4 dB, while about 10 dB is actually possible. This is simply because higher-order modes are much more strongly excited by the point source at high frequencies.

Since one generally has difficulty in forming a clear mental picture of acoustical propagation expressed as the sum of many modes, it is of value to compare the high frequency behavior of the numerically optimized liner of figure 3 with the predictions of geometrical acoustics. When kb >> 1, geometrical acoustics is applicable to the point source in a short duct and a ray-tracing solution is a valid approximation. Therefore, the acoustic pressure and particle velocity at any point on the duct cross section at z = L may be found by summing the contributions from the direct ray and all the reflected rays passing through that point (see fig. 4). From this viewpoint, the best that any liner could do would be to completely absorb all incident rays, thereby reducing the acoustic wave at z = L to only the direct radiation. For $L = 2b$ only 12 percent of the rays emitted from the right side of the source are radiated directly through the $z = L$ cross section, implying an upper limit for the transmission loss of 9.6 dB ($kb >> 1$). Figure 3 shows the optimal ϕ predicted from the modal theory settling down to about this value as kb approaches 20.

Naturally, no uniform, point reacting liner could provide complete absorption of all incident rays, since the angle of incidence θ and the distance from the source, $b/\cos\theta$, are not constant. Complete absorption occurs only when the surface admittance in the direction of the incident ray is equal to the specific acoustic admittance of a spherical wave at the appropriate distance from the source. Normalized with respect to the characteristic admittance of the medium, this specific admittance is $(1.0 + j\,\frac{\cos\theta}{kb})$. Because the rays are not normal to the locally reacting liner, the requried normal admittance is not this spherical wave admittance but is this quantity multiplied by $\cos\theta$ (ref. 10).

In estimating the optimal uniform liner admittance from geometrical acoustics considerations, it is reasonable to assume that any ray at $z = L$ which has been reflected off the liner more than once makes a negligible contribution to the acoustic disturbance. Figure 4 shows a ray which is reflected only once and then just clears the end of the duct. Such a ray strikes the liner at $z = L/3$ and any ray which hits the duct wall closer to the source will suffer multiple reflections. Therefore, using a single reflection criterion requires maximizing absorption for rays which first contact the liner between $z = L/3$ and $z = L$. For such rays, the average value of cos θ is approximately 0.7, implying an optimal normal admittance of about $(0.7 + j\frac{0.5}{kb})$.

The real and imaginary parts of the optimal admittance which correspond to the maximum transmission loss of figure 3 are shown in figures 5a and 5b, respectively, as functions of normalized frequency kb. These values determined from the modal theory are in good agreement with geometrical predictions for large kb.

Optimal liners with two sections of equal length (fig. 1b) were also calcualted for a point source. The optimization procedure was initialized at the optimal uniform admittance solutions. The resulting maximum ϕ (fig. 6) is little better than that for the uniform liner either at very low kb values (where only the lowest-order mode is cut on) or at large kb (where geometrical acoustics applies). However, at some intermediate frequencies more than 20 dB improvement is possible. The largest segmentation advantage for this source in this duct is in the kb range between 4 and 6, where only the lowest two radial modes are cut on in a hard walled duct. The results at large kb values are again consitent with geometrical acoustics, with the optimal admittances (not shown) approaching the single reflection criterion values of approximately $(0.8 + j\frac{0.6}{kb})$ and $(0.6 + j\frac{0.4}{kb})$, respectively.

When a flow is introduced in the minus z direction, sound propagation in the positve z direction is retarded, giving a liner of fixed length more time to attenuate a disturbance. Figure 7 shows the effect of flow on transmission loss ϕ and admittance β for upstream propagation, kb = 6, and a point source. It can be seen that about twice as much loss is possible at Mach 0.5 as with no flow.

While the optimal admittance is seen to change considerably with flow, the performance of the zero flow optimal liner in the presence of flow is near optimal up to a Mach number of about 0.3. Thus, for this specific case, the sensitivity of liner performance to normal admittance is not excessive.

A 12-inch research compressor currently installed in an anechoic chamber at Langley Research Center is selected as a realistic turbomachinery noise source. The design parameters appropriate to this axial compressor, configured with a single stage having a rotor with 19 blades and 26 outlet guide vanes, are supplied to a computer program (ref. 9) which employs the Kemp-Sears viscous wake interaction model to determine appropriate amplitudes of the acoustic modes for a rotor/stator interaction noise source. A uniform axial flow of 0.4 Mach number, corresponding to a normalized blade passage frequency of $kb = 16.53$, is assumed. According to the usual Tyler-Sofrin analysis, three $m = -7$ radial modes are cut-on.

Results are summarized in figure 8. The bar labeled "exact" shows the maximum transmission loss determined for the calculated source structure in the duct configurations shown in parts c, d, and e of figure 1. While for the point source (as well as for the plane-wave source, though it is not discussed here) very little is gained from segmentation at a kb as large as 16, this turbomachinery noise can be reduced an additional 3 dB by using two segments and 5 dB by using three segments.

The other bars in figure 8 correspond to variations from the exact calcualted source. Optimal attenuations are shown for one-, two-, and three-segment liners for each source variant: (1) putting equal energy in each of the three propagating radial modes with the calculated relative phasing retained, (2) setting the amplitudes of the two higher-order radial modes to zero, and (3) replacing the three complex modal coefficients with their absolute values. It is clear that while segmentation results in a significant improvement regardless of the source type, the liner cannot be optimally designed unless both the modal distribution of source energy and the relative phasing among these modes is known.

CONCLUDING REMAPKS

The results of the present optimization procedure compare well with least-attenuated mode theory at low frequencies and with geometrical acoustics at high frequencies. This favorable agreement lends credibility to the results at intermediate frequencies, where there is no simple theory with which to compare.

It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial source distributions.

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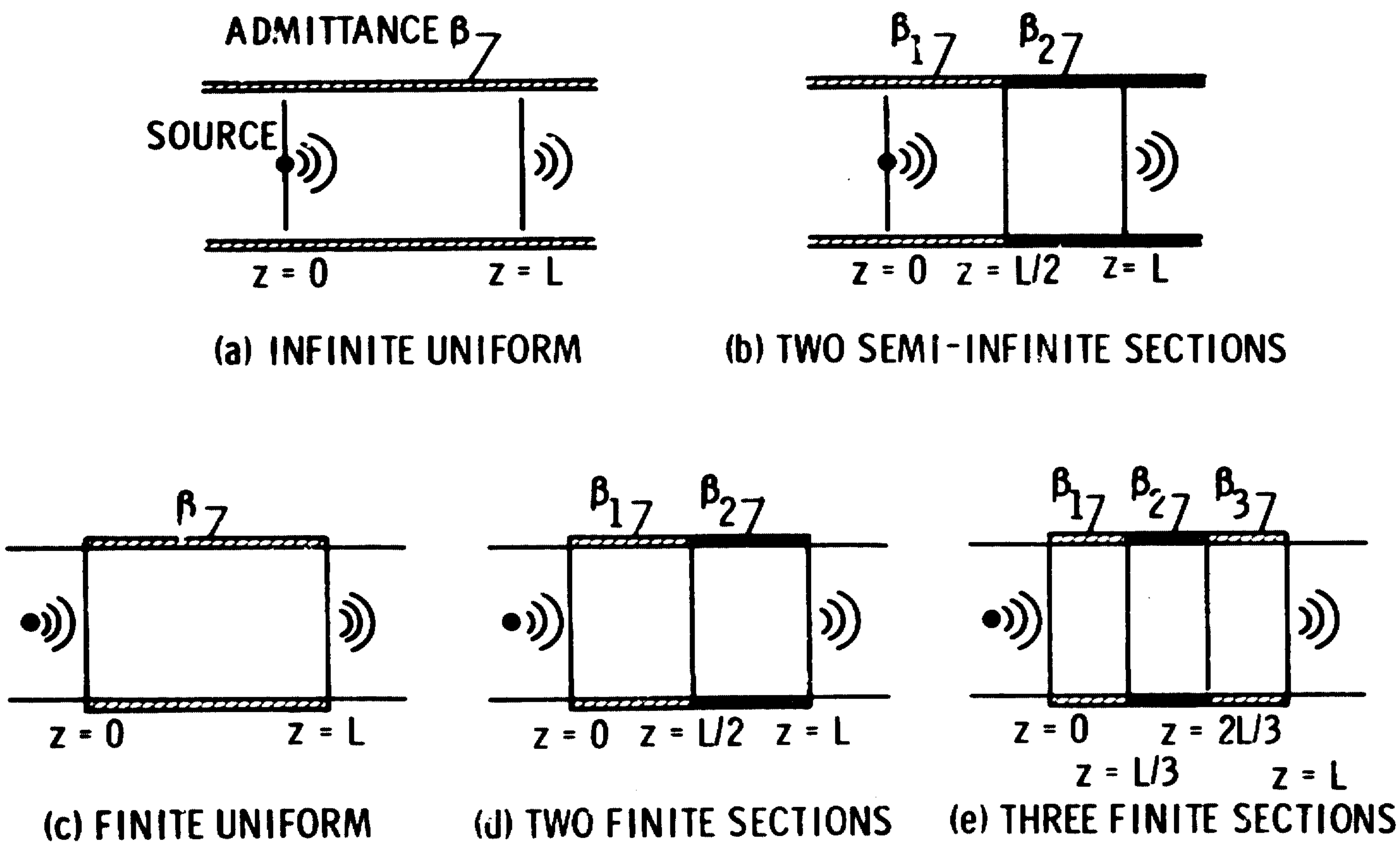


Figure 1.- Duct liner configurations.

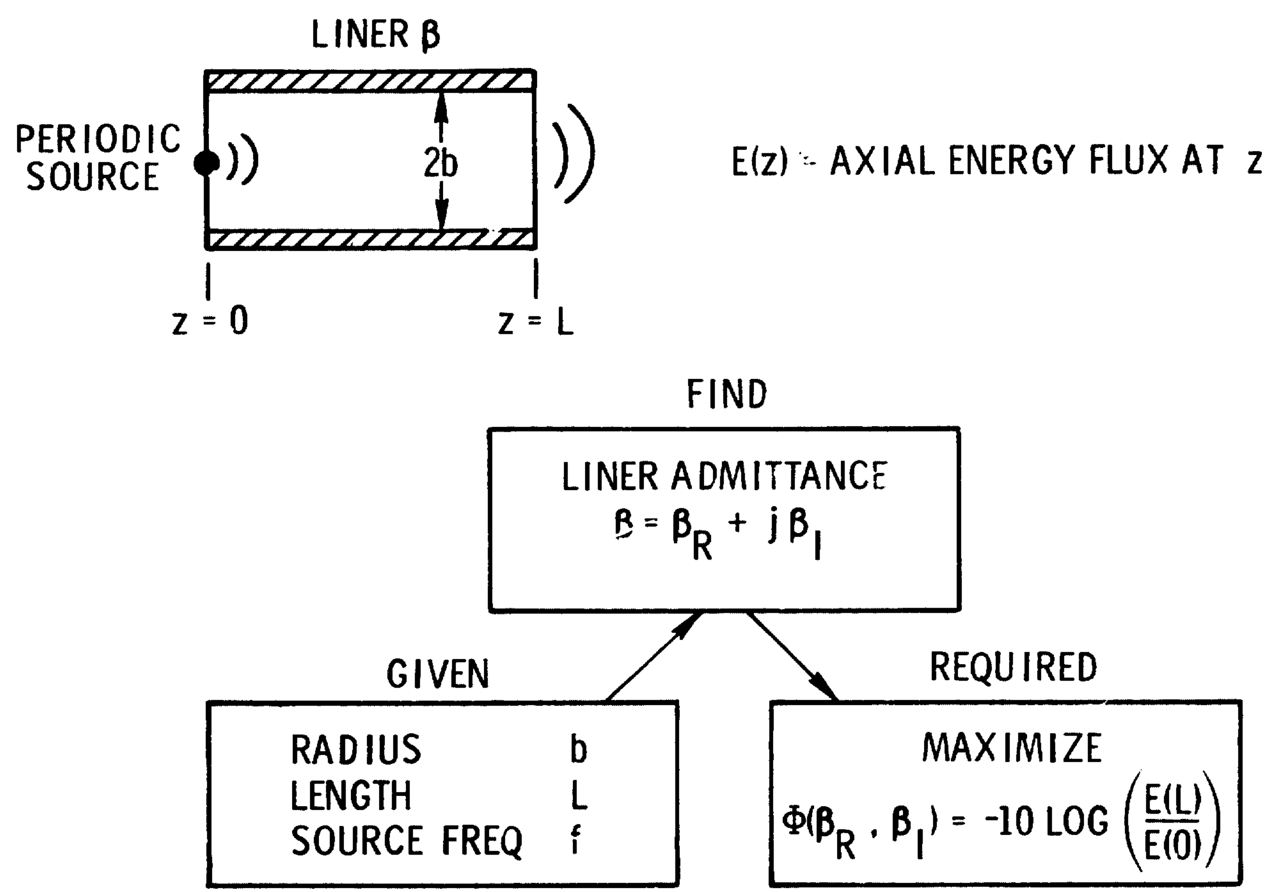


Figure 2.- Liner optimization design concept.

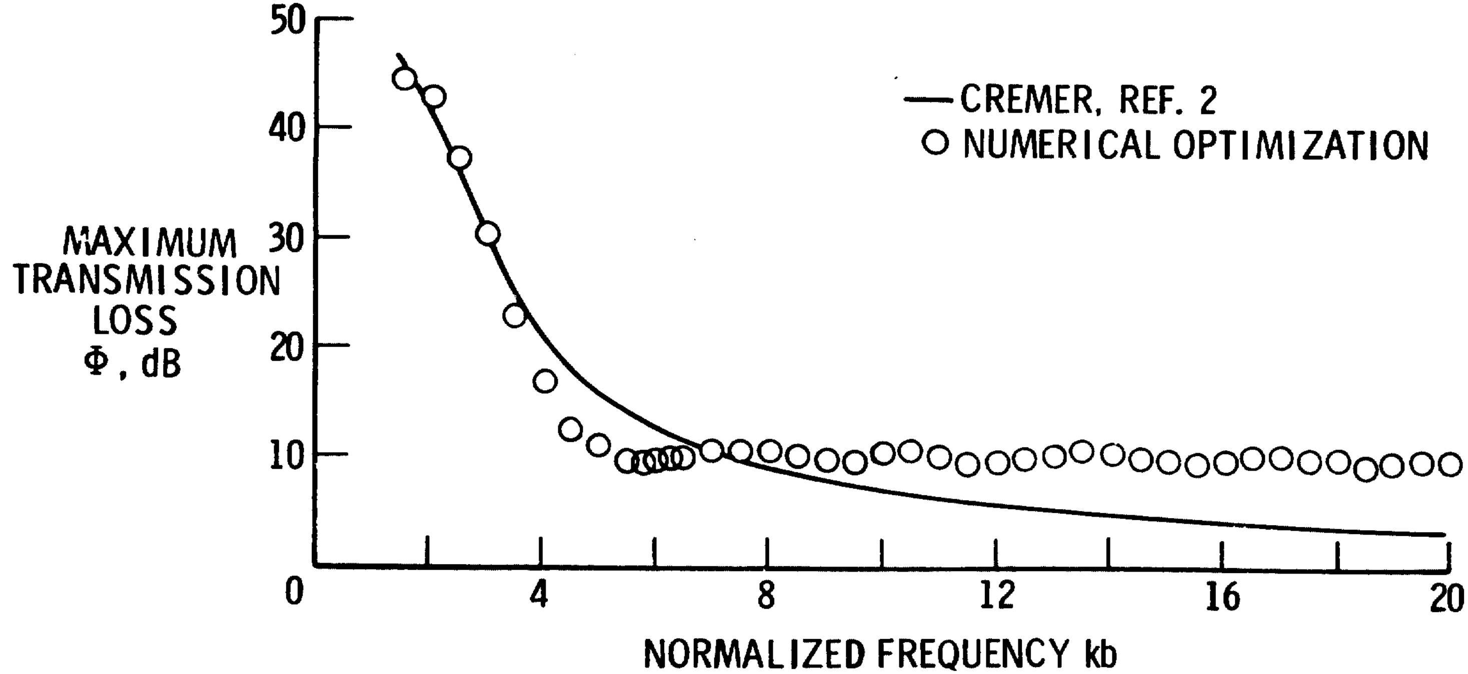
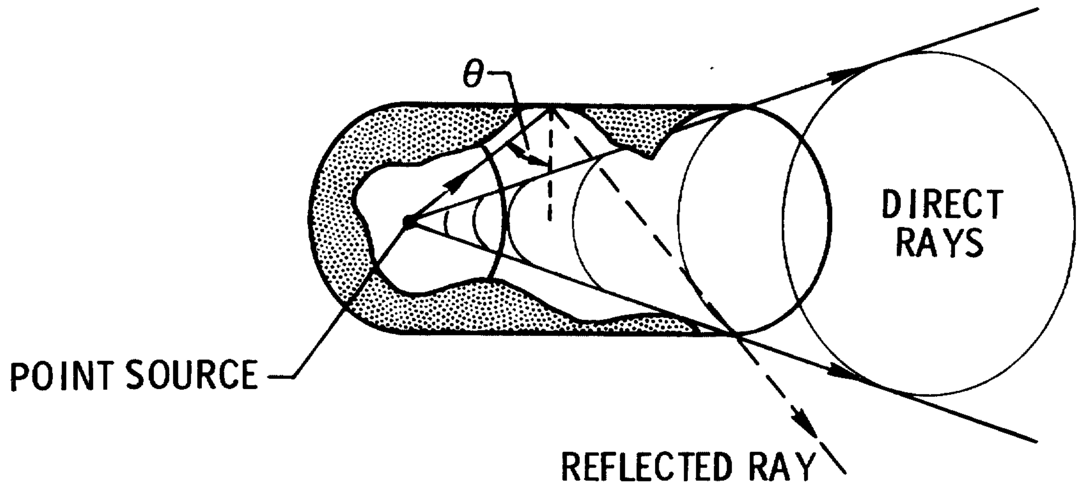
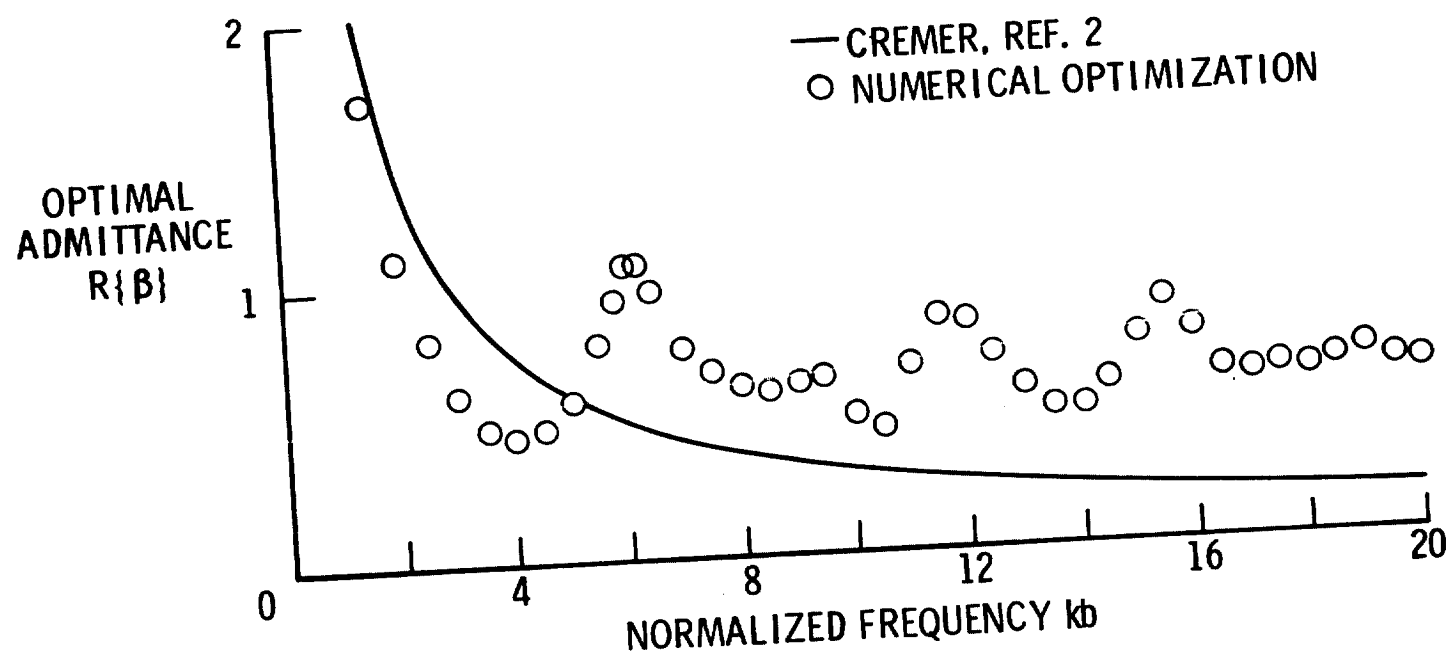


Figure 3.- Maximum transmission loss for a uniform circular liner (fig. 1-a) with a point source and L = 2b.



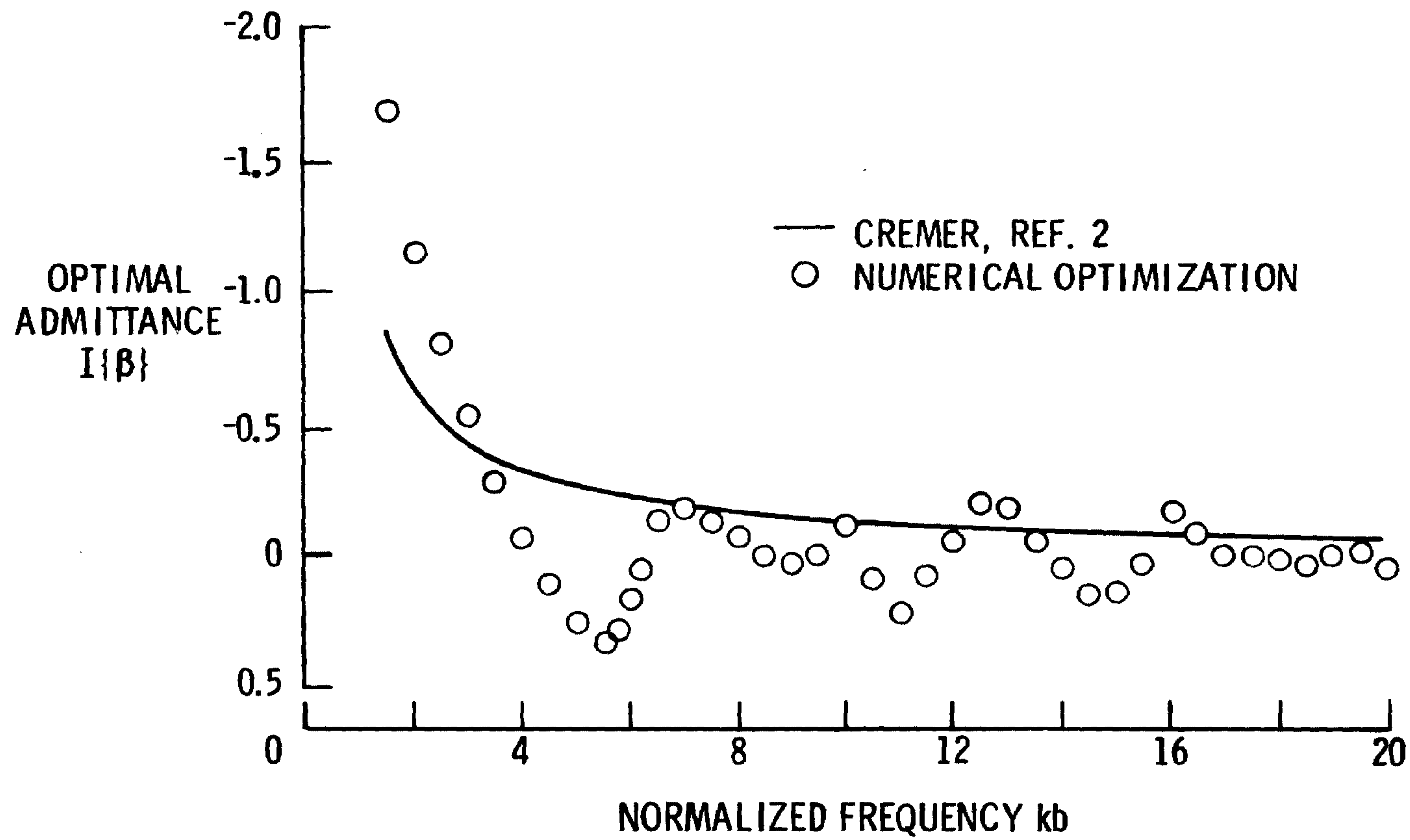
$$\text{OPTIMAL NORMAL ADMITTANCE} = \left(1.0 + j\,\frac{\cos\theta}{kb}\right)\cos\theta$$

Figure 4.- Geometrical duct acoustics.



(a) Real part of admittance, R{β}

Figure 5. - Optimal liner properties for a uniform circular liner (fig. 1-a) with a point source and L = 2b.



(b) Imaginary part of admittance, R{β}

Figure 5.- Concluded.

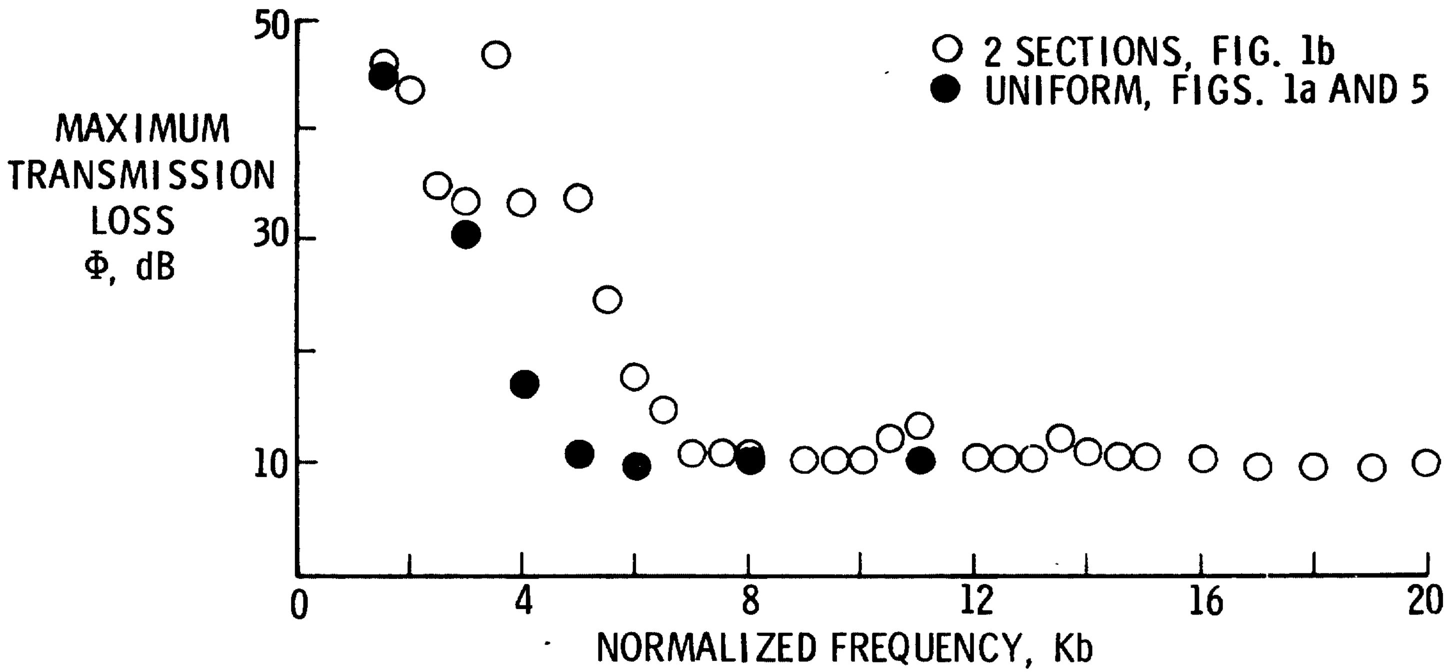


Figure 6.- Maximum transmission loss for a two-sectioned circular liner (fig. 1-b) with a point source and $L = 2b$.

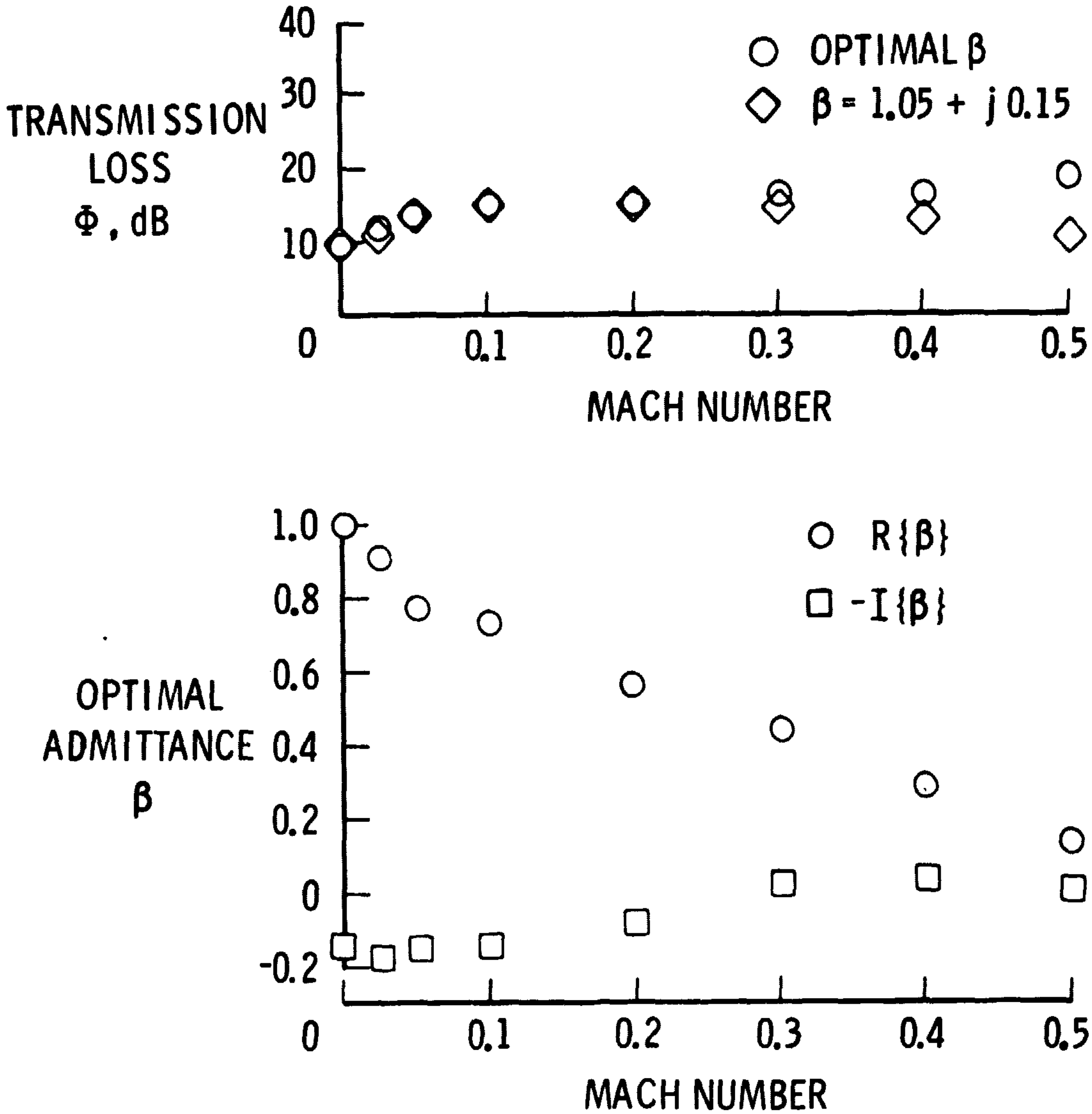
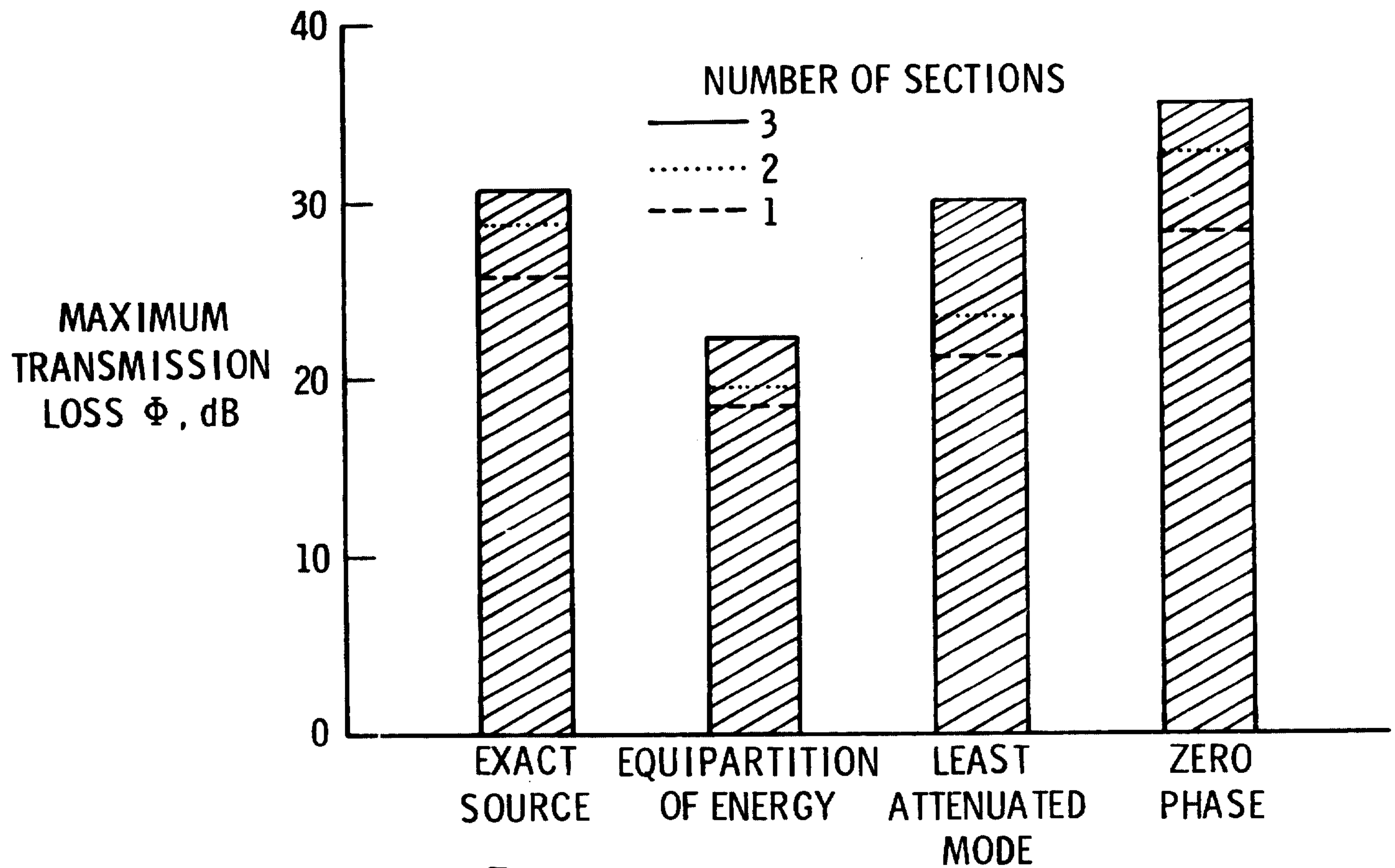


Figure 7.- Optimal properties of a uniform circular liner (fig. 1-a) with a uniform flow profile, a point source, L = 2b and kb = 6.



$$Q(r) = \sum_{\mu} A_{\mu} \psi_{\mu}(r)$$

Figure 8.- Maximum transmission loss of a research compressor for different source models - circular liners (fig. 1-c, d, e), kb = 16.53, Mach number = 0.4 and m = -7.