RADIATION OF SOUND FROM VIBRATING BEAMS
ESPECIALLY TEXTILE LOOM PICKING STICKS

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Mark William Sutterlin

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RADIATION OF SOUND FROM VIBRATING BEAMS
ESPECIALLY TEXTILE LOOM PICKING STICKS

Approved:

Allan D. Pierce, Chairman

William A. Bell

Melvin R. Corley

W. James Hadden

Date approved by Chairman: 11/17/75

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SUMMARY

Recent studies of textile loom noise suggest that the picking stick is the major contributor to the overall noise level produced by an automatic textile loom. This has led to research directed towards a better understanding of how sound is generated and radiated by the picking sticks of a loom. As a part of this effort, the present thesis is concerned with the radiation of sound from randomly vibrating beams of circular cross section.

Vibrations on the beam are considered as two traveling waves moving in opposite directions. The result is then averaged over all possible phase differences, assuming all to be equally probable. Expressions are given for the acoustic power radiated, the radiation efficiency and the normalized radiation loss factor for a beam. The radiation efficiency is approximated in the high and low frequency limits. A numerical integration technique is used to evaluate the radiation efficiency over a wide range of frequencies. These results are compared with results of the modal approach to the beam radiation problem.

The theoretical model developed is then used to predict the octave band acoustic power output of the picking sticks, and the octave band sound pressure levels at a reference point, neglecting other sources on the loom. The predicted

sound pressure levels are subsequently compared with experimental values and with the results of previous theories which predict the acoustic power output in the limits of low and high frequencies respectively.

CHAPTER I

INTRODUCTION

Recent studies of textile loom noise suggest that the picking stick is the major contributor to the overall noise level produced by an automatic textile loom.[1-4] This has led to research directed towards a better understanding of how sound is generated and radiated by the picking sticks of a loom. As a part of this effort, the present thesis is concerned with the radiation of sound from randomly vibrating beams of circular cross section. An analysis of radiation from unbaffled beams of rectangular cross section (a better approximation to the cross section of a picking stick) was considered more difficult than warranted at the present time. The theoretical model developed is then used to predict the acoustic power output of the picking sticks and the sound pressure level at a reference point, neglecting other sound sources on the loom. Theoretical calculations of expected octave band sound pressure levels, based on measured acceleration data, are subsequently compared with actual sound pressure level measurements.

Previous studies of the radiation of sound from vibrating cylindrical beams have been concerned with radiation from resonant modes of these finite beams. They consider the case of a standing wave on the beam. These include studies by Bailey and Fahy,[5] Yousri and Fahy[6] and Kuhn and Morfey.[7] The radiation efficiency or radiation loss factor determined in this manner represents the contribution of a single mode to the radiation at a given frequency. Recently, Yousri and Fahy have presented a more general derivation which shows that, in general, the radiation efficiency is a summation of terms that represent contributions from various vibrating modes.[8] This averaging over modes is necessary when more than one mode is excited in the frequency range of interest. The results of the present study are given in a form which depends only on the frequency of the beam vibrations, the physical characteristics of the beam and its surroundings, and does not require averaging over modes. Rather than considering the vibrations of a beam as a summation over excited modes, the vibrations are considered statistically, such that the final result is independent of the boundary conditions at the ends of the beam. The radiation efficiency for a given frequency band is then simply the resulting expression evaluated at the center frequency of the band.

Other studies have considered similar problems relating to the radiation of sound from beams of different types or under different conditions. Both Wallace[9] and Lyon and Maidanik[10] consider the case of radiation from baffled rectangular beams. Johnston and Barr examine experimentally acoustic damping in both cylindrical and rectangular beams, while considering theoretically the infinite beam case.[11] Blake discusses the radiation of sound from beams of elliptic cross section, in both the baffled and unbaffled configurations.[12] Junger models a beam of circular cross section and nonuniform density as a dipole array.[13] Manning and Maidanik estimate the radiation efficiency of large radius cylindrical shells.[14] The results of some of these investigations are compared with the results of the present study.

CHAPTER II

THEORY

The appropriate boundary conditions are applied to a general solution of the acoustic wave equation in cylindrical coordinates. The result is an expression for the acoustic pressure due to a vibrating beam. This pressure is used to determine the acoustic power radiated by a beam. The type of vibrations considered and the method of averaging used are then discussed. Expressions are given for the radiation efficiency and the normalized radiation loss factor for a beam of circular cross section.

Acoustic Pressure and Power Output of a Vibrating Cylinder

The acoustic wave equation in cylindrical coordinates can be written

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} + \frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2} + \frac{\partial^2 p}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 p}{\partial z^2} = 0 \qquad (2.1)$$

The solution to this partial differential equation can be written as a general linear combination of the separable solutions.[15] The coordinate system and beam location are given in Fig. 1. One can consider the solution for outgoing

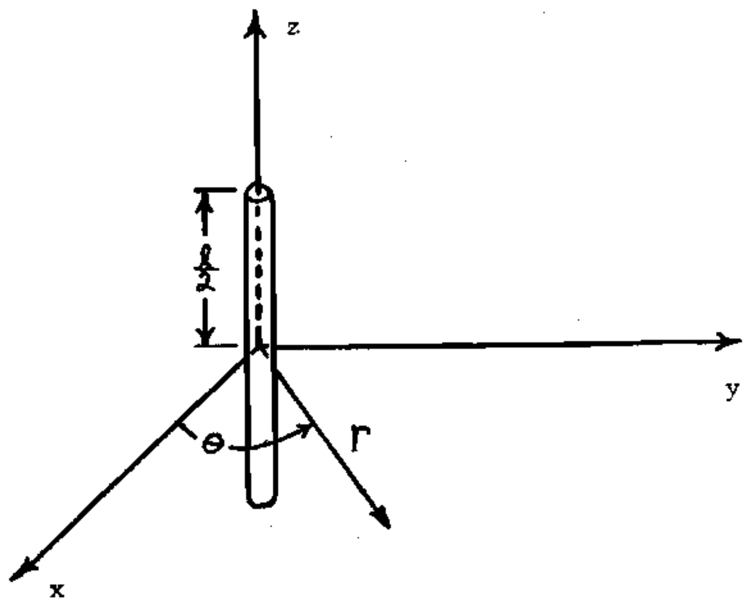


Figure 1. Beam Location and Coordinate System

waves of fixed frequency ω. With the understanding that the physical quantity under consideration (in this case the acoustic pressure) is the real part of (Re{ }) the product of a complex amplitude and an $e^{-i\omega t}$ time dependence, the solution can be represented by the complex pressure amplitude

$$P(r,\theta,z) = \int_{-\infty}^{\infty} \sum_{m=o}^{\infty} (A_m(\alpha)\cos m\theta + B_m(\alpha)\sin m\theta) H_m^{(1)}(k_r r) e^{i\alpha z} d\alpha \quad (2.2)$$

where $k_r = (k^2-\alpha^2)^{1/2}$, $k = \omega/c$ and c is the speed of sound in air. $H_m^{(1)}$ is the Hankel function of the first kind and of order m. If one considers the motion of a cylindrical beam of radius r_o vibrating in the $\theta = 0,\pi$ (x-z) plane, with the velocity of the beam at $\theta = 0$ assumed to vary sinusoidally with time,

$$v_x(z,t) = \mathrm{Re}\{v_x(z)e^{-i\omega t}\} \quad (2.3)$$

then its normal or radial velocity can be written as

$$v_r(\theta,z) = \cos\theta \int_{-\infty}^{\infty} \hat{v}(\alpha) e^{i\alpha z} d\alpha \quad (2.4)$$

where $\hat{v}(\alpha)$ is the Fourier Transform of the z dependence of the beam velocity, $v_x(z)$. The real part and the $e^{-i\omega t}$ time dependence are again understood. It is assumed that the beam is infinite in length but that beyond the points $z = \pm \ell/2$, the endpoints of a finite beam, the velocity $v_x(z)$ is zero. This assumption, used previously by others, is valid when the radius of the beam is much smaller than its length.[5]

The acoustic boundary condition comes from Euler's equation of motion for a fluid. For this specific case the boundary condition is

$$\left.\frac{\partial p}{\partial r}\right|_{r=r_o} = i\omega\rho_o v_r \tag{2.5}$$

The orthoganality of the sine and cosine functions and the above boundary condition are used to determine the coefficients $A_m(\alpha)$ and $B_m(\alpha)$. One finds that all $B_m(\alpha)$ are zero; also, all $A_m(\alpha)$ are zero, except when m is one, in which case,

$$A_1(\alpha) = i\omega\rho_o \frac{\hat{v}(\alpha)}{k_r H_1^{(1)\prime}(k_r r_o)} \tag{2.6}$$

where $H_1^{(1)\prime}$ is the first derivative with respect to its argument of the Hankel function of first order and first kind. The acoustic pressue due to a cylinder vibrating in a plane can now be written

$$P(r,\theta,z) = \cos\theta \int_{-\infty}^{\infty} Z(\alpha,r)\hat{v}(\alpha)e^{i\alpha z}d\alpha \tag{2.7}$$

with $Z(\alpha,r)$ defined as

$$Z(\alpha,r) = i\omega\rho_o \frac{H_1^{(1)}(k_r r)}{k_r H_1^{(1)\prime}(k_r r_o)} \tag{2.8}$$

The acoustic power, W, radiated by the vibrating cylinder can be found by one of two methods. Either the acoustic pressure is evaluated in the far field, where the plane wave expression for intensity may be integrated over the surface of a large sphere or, as is done here, the time average is taken of the product of the acoustic pressure at the surface of the cylinder and the normal velocity. This intensity is integrated over the surface of the cylinder. Using the latter method, one obtains

$$W = \frac{1}{2}\, \mathrm{Re}\{\int_0^{2\pi} \int_{-\frac{\ell}{2}}^{\frac{\ell}{2}} P(r_o,\theta,z) v_r^*(\theta,z) r_o \, d\theta dz\} \tag{2.9}$$

where Eqs. 2.4 and 2.7 are used for v_r and P respectively. The θ integration over cosine squared yields π. Since $\hat{v}(\alpha)$ contains the information that $v_r(\theta,z)$ is zero both above and below the beam, the limits of the z integration may be extended to plus and minus infinity, with the result of this integration being a delta function of α, or more precisely $2\pi\delta(\alpha-\alpha')$. This allows one of the α integrations to be performed by inspection, which leaves

$$W = \pi^2 r_o \int_{-\infty}^{\infty} \mathrm{Re}\{Z_o(\alpha)\} |\hat{v}(\alpha)|^2 d\alpha \qquad (2.10)$$

with

$$Z_o(\alpha) = Z(\alpha, r_o) = i\omega\rho_o \frac{H_1^{(1)}(k_r r_o)}{k_r H_1^{(1)\prime}(k_r r_o)} \qquad (2.11)$$

For $k^2 > \alpha^2$, the Wronskian relation for the Hankel functions can be used to simplify $\mathrm{Re}\{Z_o(\alpha)\}$,

$$\mathrm{Re}\{Z_o(\alpha)\} = \frac{2\omega\rho_o}{\pi r_o} \frac{1}{k_r^2 |H_1^{(1)\prime}(k_r r_o)|^2} \qquad (2.12)$$

For $k^2 < \alpha^2$, properties of the Hankel functions of imaginary argument require that $\mathrm{Re}\{Z_o(\alpha)\} = 0$.[16] Therefore Eq. 2.10 can be simplified by substituting these expressions for $\mathrm{Re}\{Z_o(\alpha)\}$ and changing the limits of integration,

$$W = 2\pi\omega\rho_o \int_{-k}^{k} \frac{|\hat{v}(\alpha)|^2}{k_r^2 |H_1^{(1)\prime}(k_r r_o)|^2} d\alpha \qquad (2.13)$$

Random Vibrations

The expression in Eq. 2.13 for the acoustic power radiated by a beam is valid for any type of vibrations on the beam in a single plane. In order to evaluate it, however, one needs to have an expression for $\hat{v}(\alpha)$, or equivalently an expression for $v_x(z)$ from which $\hat{v}(\alpha)$ can be determined. This means that something must be known or assumed about the manner in which the beam is vibrating. In general, $v_x(z)$ must be a solution to the differential equation for transverse vibrations on a beam,[17] for which a general solution is

$$v_x(z) = v_1 e^{ik_b z} + v_2 e^{-ik_b z} + v_3 e^{k_b z} + v_4 e^{-k_b z} \qquad (2.14)$$

where $k_b = \omega/c_b$ is the wave number of the beam vibrations and c_b is the wave speed of the beam vibrations. The boundary conditions at the ends of the beam determine the exact shape of beam vibrations.

The simplest and most common approach is to consider a simply supported beam vibrating at resonance with a standing wave on the beam. For this case,

$$v_x(z) = v_n \begin{smallmatrix}\cos\\ \sin\end{smallmatrix}\left(\frac{n\pi}{\ell} z\right) \qquad (2.15)$$

where n is any integer. When n is odd the cosine function is used; when n is even the sine function applies. This is the approach used by Yousri and Fahy as well as others.[6] Results derived in this manner represent the contribution to the acoustic power from a given mode at a given frequency. Unless the beam is vibrating in a single mode, the total acoustic power, octave band or one-third octave band acoustic power must be calculated from a summation of these types of terms, and the modal velocity amplitudes must be known.[8]

Another approach, the one used here, is to consider the statistical nature of the beam vibrations. Multi-modal vibrations on a beam within a narrow frequency band, which for the simple case above could be written as a summation of terms similar to Eq. 2.15, can be considered as two traveling waves moving in opposite directions with the same (average) amplitude and with a specified phase relationship. The contribution to the acoustic power from the evanescent wave solutions, the last two terms in Eq. 2.14, is considered to be negligible. The exact phase relationship between the first two terms in Eq. 2.14 is dependent on the boundary conditions at the ends of the beam and the manner of excitation of the beam. On the average, however, it is assumed that all phases are equally probable. The expression for $|\hat{v}(\alpha)|^2$ is then averaged over all possible phase relationships, to obtain the final expression for $|\hat{v}(\alpha)|^2$ which is to be used to evaluate Eq. 2.13.

With the modifications described above, Eq. 2.14 becomes

$$v_x(z) = v_o e^{i(k_b z+\eta)} + v_o e^{-i(k_b z+\psi)} \qquad (2.16)$$

where η and ψ denote arbitrary phase angles. Taking Fourier Transforms one obtains

$$\hat{v}(\alpha) = \frac{v_o}{\pi}\left[\frac{\sin(k_b+\alpha)\frac{\ell}{2}}{(k_b+\alpha)}\, e^{-i\psi} + \frac{\sin(k_b-\alpha)\frac{\ell}{2}}{(k_b-\alpha)}\, e^{i\eta}\right] \qquad (2.17)$$

Thus

$$|\hat{v}(\alpha)|^2 = \frac{{v_o}^2}{\pi^2}\left[\frac{\sin^2(k_b+\alpha)\frac{\ell}{2}}{(k_b+\alpha)^2} + \right.$$

$$\left.\frac{\sin^2(k_b-\alpha)\frac{\ell}{2}}{(k_b+\alpha)^2} + 2\cos(\eta+\psi)\ \frac{\sin(k_b+\alpha)\frac{\ell}{2}\sin(k_b-\alpha)\frac{\ell}{2}}{({k_b}^2-\alpha^2)}\right] \qquad (2.18)$$

All η and ψ being equally probable, the cross term goes to zero in an average over all possible phase differences.

Taking the time average of the square of the real part of the product $v_x(z)$ times $e^{-i\omega t}$ (the square of the physical velocity), one can show that

$$v_o^2 = \langle v_x^2 \rangle \qquad (2.19)$$

$\langle v_x^2 \rangle$ is a physical rather than a statistical quantity. From Eqs. 2.13, 2.18 and 2.19, the acoustic power radiated by the beam is

$$W = \frac{2\omega\rho_o}{\pi}\langle v_x^2 \rangle \int_{-k}^{k} \frac{1}{k_r^2 |H_1^{(1)\prime}(k_r r_o)|^2}\left[\frac{\sin^2(k_b+\alpha)\frac{\ell}{2}}{(k_b+\alpha)^2} + \frac{\sin^2(k_b-\alpha)\frac{\ell}{2}}{(k_b-\alpha)^2}\right] d\alpha \qquad (2.20)$$

Radiation Efficiency

The radiation efficiency is a useful dimensionless form in which these results can be expressed. Sometimes called the normalized radiation resistance, the radiation efficiency can be defined as the ratio of the acoustic power radiated to the acoustic power which would be radiated assuming plane wave radiation, where the acoustic pressure is related to the normal velocity, v_n, by the simple relation

$$P = \rho_o c \; v_n \tag{2.21}$$

Therefore, by definition, the radiation efficiency for plane wave radiation is unity. The radiation efficiency can be written

$$\sigma = \frac{W}{W_o} \tag{2.22}$$

where for a cylinder,

$$W_o = \rho_o c \pi r_o \ell \langle v_x^2 \rangle \tag{2.23}$$

Thus, using Eq. 2.20, one obtains

$$\sigma = \frac{2k}{\pi^2 r_o \ell} \int_{-k}^{k} \frac{1}{k_r^2 |H_1^{(1)\prime}(k_r r_o)|^2} \left[\frac{\sin^2 (k_b+\alpha)\frac{\ell}{2}}{(k_b+\alpha)^2} + \frac{\sin^2 (k_b-\alpha)\frac{\ell}{2}}{(k_b-\alpha)^2} \right] d\alpha \tag{2.24}$$

A symmetry of the integral and the change of variables $\beta = \alpha/k$ provide a more concise form for the expression,

$$\sigma = \frac{4}{\pi^2 k^2 r_o \ell} \int_{-1}^{1} \frac{1}{(1-\beta^2)\,|H_1^{(1)}(\sqrt{1-\beta^2}\,kr_o)|^2} \frac{\sin^2(\varepsilon+\beta)\frac{k\ell}{2}}{(\varepsilon+\beta)^2}\, d\beta \tag{2.25}$$

where $\varepsilon = c/c_b = k_b/k$.

The radiation resistance, which is the real part of the impedance defined by the ratio of the force to the normal velocity at the surface of the cylinder, is simply

$$R_r = \rho_o c \pi r_o \ell \sigma \tag{2.26}$$

The other common form in which results of similar beam vibration studies are expressed is the radiation loss factor. The radiation loss factor is defined as the ratio of the acoustic energy dissipated to the energy stored per cycle. For purposes of comparison, the radiation loss factor is

$$\eta_{rad} \left(\frac{\rho_m}{\rho_o}\right)\left[1 - \frac{a_i}{r_o}\right] = \frac{\sigma}{kr_o} \tag{2.27}$$

where ρ_m is the density of the beam material, and a_i is the inner radius of a hollow beam.[6]

CHAPTER III

RESULTS

The expression for radiation efficiency, Eq. 2.25, is approximated in both the high and low frequency limits. Numerical results are presented which are valid over a wide range of frequencies. These results are compared with those of other beam vibration and radiation studies.

Low Frequency Limit

In the low frequency or small radius limit, kr_o is small. An approximation may be used in place of the Hankel function in order to simplify the integral in the expression for the radiation efficiency. The first term in the series expansion for the derivative of the Hankel function gives[18]

$$|H_1^{(1)\prime}(z)|^2 \simeq \frac{4}{\pi^2}\frac{1}{z^4} \tag{3.1}$$

This approximation is valid to one tenth of one per cent for $z < 0.01$. Consistent with this approximation and a simple change of variables, $u = (\varepsilon+\beta)k\ell/2$

$$\sigma \simeq \frac{(kr_o)^3}{2}\int_{(\varepsilon-1)\frac{k\ell}{2}}^{(\varepsilon+1)\frac{k\ell}{2}} [1-(\frac{2u}{k\ell}-\varepsilon)^2]\ \frac{\sin^2 u}{u^2}\, du \tag{3.2}$$

For certain cases, further approximations can be made. Well below the coincidence frequency ($k_b >> k, \varepsilon >> 1$), u^2 in the denominator can be approximated as $u^2 = (k\ell/2)^2$. The result of this approximation is

$$\sigma \simeq \frac{2}{3}(kr_o)^2\left(\frac{r_o}{\ell}\right)\left(\frac{k}{k_b}\right)^2\left[1 - \frac{3\cos k_b\ell}{(k\ell)^2}\left\{\frac{\sin k\ell}{k\ell} - \cos k\ell\right\}\right] \quad (3.3)$$

By comparison with the numerical results below, this expression is accurate relative to Eq. 3.2 to at least four significant digits for $\varepsilon > 100$. Eq. 3.3 is directly comparable to the results of Kuhn and Morfey in their low frequency approximation of the Yousri and Fahy expression for the radiation efficiency of a simply supported beam.[7] Their expression, with some changes in notation, is

$$\sigma \simeq \frac{4}{3}(kr_o)^2\left(\frac{r_o}{\ell}\right)\left(\frac{k}{k_b}\right)^2\left[1 \pm \frac{3}{(k\ell)^2}\left\{\frac{\sin k\ell}{k\ell} - \cos k\ell\right\}\right] \quad (3.4)$$

where the plus sign applies for odd n and the minus sign is used when n is even. A graphical comparison of these results appears in Fig. 2. When evaluated at a frequency such that $k_b = n\pi/\ell$ (a requirement assumed in the case of a simply supported beam), Eq. 3.3 yields a result which is exactly one half the value given by Eq. 3.4. To help understand this phenomenon, it is helpful to note that had one used Eq. 2.18 for $|v(\alpha)|^2$ without taking an average over phase, the result

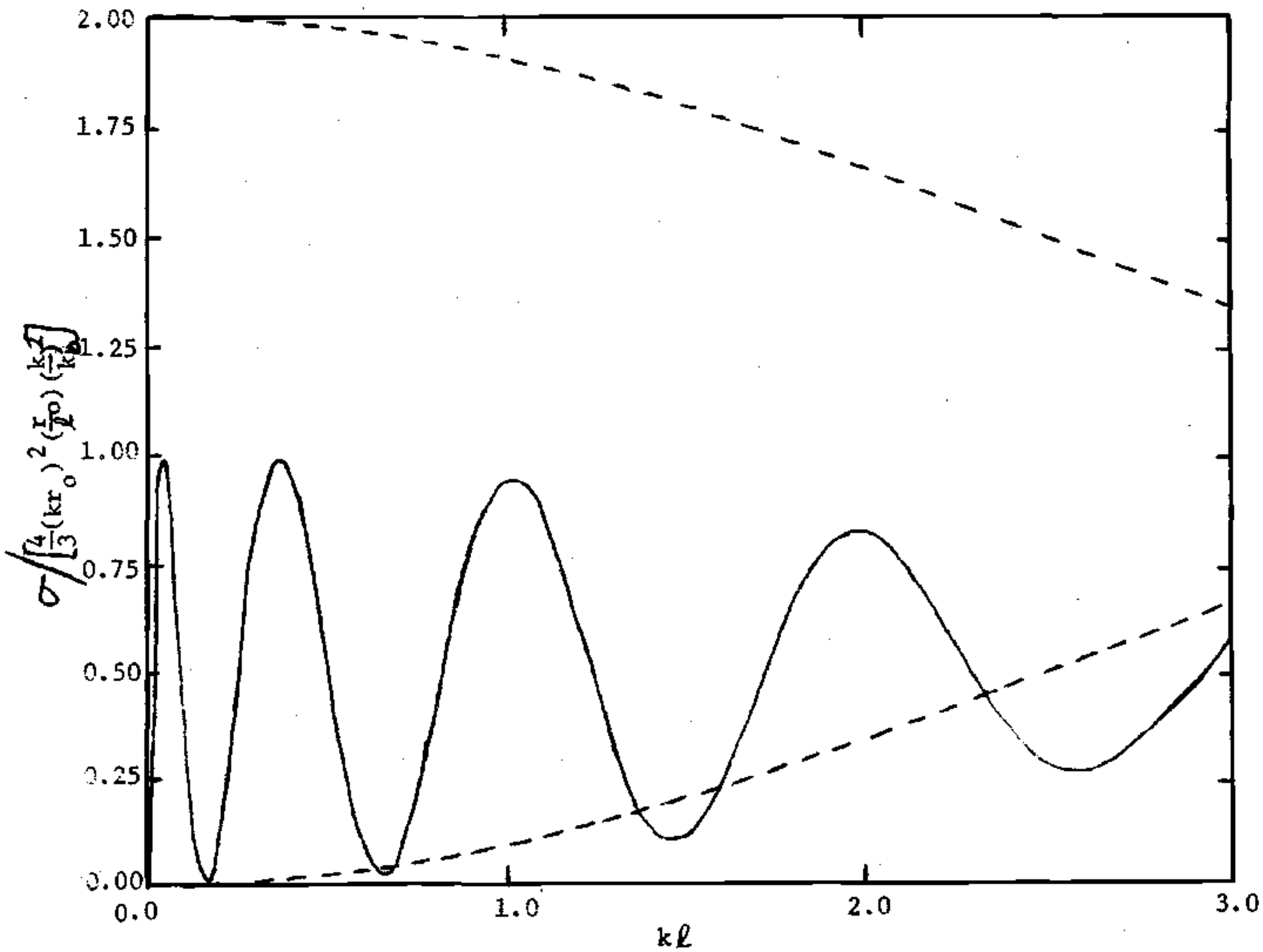


Figure 2. A Comparison of Radiation Efficiencies at Low Frequencies
—— Averaging Technique; ---- Simply Supported Beam

corresponding to Eq. 3.3 would be

$$\sigma \approx \frac{2}{3}(kr_o)^2(\frac{r_o}{\ell})(\frac{k}{k_b})^2[(1-\cos(\eta+\psi)\cos k_b\ell) +$$

$$(\cos(\eta+\psi)-\cos k_b\ell)\frac{3}{(k\ell)^2}\cdot\{\frac{\sin k\ell}{k\ell}-\cos k\ell\}] \quad (3.5)$$

An examination of this general expression for the low frequency approximation reveals that the case of a simply supported beam at resonance ($\eta+\pi = 0$ n odd, $\eta+\delta = \pi$, n even) is at each frequency an extreme case which maximizes the radiation efficiency. At the other extreme, $\eta+\psi = 0$ when n is even and $\eta+\psi = \pi$ when n is odd. It is clear that if one considers random vibrations with all phases equally probable, the result is quite properly one half of the maximum value, as is shown in Eqs. 3.3 and 3.4.

Another case in which the integral can be easily evaluated is when the beam is short compared to a wavelength ($k\ell << 1$). In this case, expanding $\sin^2u/u^2$ in a series expansion about $u = 0$ one obtains

$$\sigma \approx \frac{(kr_o)^3(k\ell)}{3}[1-\frac{(k\ell)^2}{12}\{\varepsilon^2+\frac{1}{5}\}] \quad (3.6)$$

Again, a comparison with numerical results reveals that this expression is valid (to four significant digits) for $\varepsilon k\ell < 0.4$.

High Frequency Limit

At high frequencies the major contribution to the integral in Eq. 2.25 comes from the vicinity of $\beta = -\epsilon$. Expanding the Hankel function term in a Taylor series about that point and keeping only the first term, one gets

$$\sigma \simeq \sigma_o + \sigma_1 \qquad \sigma_o = \frac{2}{\pi k r_o} \frac{1}{(1-\epsilon^2)|H_1^{(1)\prime}(\sqrt{1-\epsilon^2}\, k r_o)|^2} \tag{3.7}$$

$$\sigma_1 = -\sigma_o \frac{2}{\pi} \left[\frac{1}{(1-\epsilon^2)k\ell} + \frac{\sin(1-\epsilon)k\ell}{(1-\epsilon)^2(k\ell)^2} + \frac{\sin(1+\epsilon)k\ell}{(1+\epsilon)^2(k\ell)^2}\right] \tag{3.7}$$

where σ_o is the first term assuming infinite limits on the integral, and σ_1 is an approximate correction term to account for the finite limits. σ_o alone provides a good approximation to the radiation efficiency (less than 0.1% error) for $k\ell > 400$. Above this frequency it is clear that the finite nature of the beam is no longer significant.

If $(1-\epsilon^2)^{1/2} k r_o >> 1$, then the derivative of the Hankel function may be expressed in terms of its asymptotic limit. Ignoring the contribution from σ_1, one obtains

$$\sigma \simeq \frac{1-\epsilon^2\ (k r_o)^2}{(1-\epsilon^2)(k r_o)^2 + 1} \tag{3.8}$$

In the limit as $k r_o$ goes to infinity, this becomes

$$\sigma = \frac{1}{\sqrt{1-\epsilon^2}} \quad (3.9)$$

This is equal to the radiation efficiency for an infinite flat plate (above coincidence).[19] At these very high frequencies the curvature of the beam as well as its finite extent become insignificant due to the extremely short wavelength. As is shown in the next section, at these large frequencies ϵ is quite small; thus, the radiation efficiency is very nearly unity. Even below the extremely high frequencies, $\sigma = 1$.

Numerical Results

The expression in Eq. 2.25 was evaluated numerically to determine the radiation efficiency of a beam. The programs and subroutines used are listed in the Appendix, along with sample output. It can be seen from Eq. 2.25 that the radiation efficiency depends on four dimensionless variables: kr_o, $k\ell$, ℓ/r_o and ϵ. As it is clear that only three of these are mutually independent, it was decided to use kr_o, ℓ/r_o and ϵ. One of the computer programs calculates the radiation efficiency for different kr_o holding both ϵ and ℓ/r_o constant. However, it is not the case that ϵ remains constant with changes in frequency, or k. For most kr_o,

$$C_b = \left(\frac{B}{m}\right)^{1/4}(\omega)^{1/2} \quad (3.10)$$

where B is the bending stiffness, and m is the mass per unit length of the beam. Since this is valid over a wide range of frequencies, it is convenient to consider the radiation efficiency as a function of kr_o, ℓ/r_o and

$$\varepsilon(kr_o)^{1/2} = (\frac{m}{B})^{1/4}(cr_o)^{1/2} \tag{3.11}$$

This number depends only on the physical characteristics of the beam and its surroundings and is not a function of frequency. Eq. 3.10 is valid except at high frequencies or large radii, where for most ε and ℓ/r_o, the radiation efficiency is very nearly equal to one.

Figs. 3-6 gives the results of the numerical calculations of the radiation efficiency. Each graph shows σ as a function of kr_o for several values of $\varepsilon(kr_o)^{1/2}$ and for a given value of ℓ/r_o. One need only determine the constant $\varepsilon(kr_o)^{1/2}$ and the ratio ℓ/r_o for the particular beam in question to read the radiation efficiency for any frequency from the graph. The acoustic power output for the frequency can also be determined with the help of Eqs. 2.22 and 2.23, i.e.,

$$W = \rho_o c \pi r_o \ell \langle v_x^2 \rangle \sigma \tag{3.12}$$

These graphs cannot be directly compared with those of Yousri and Fahy or others who have considered a modal

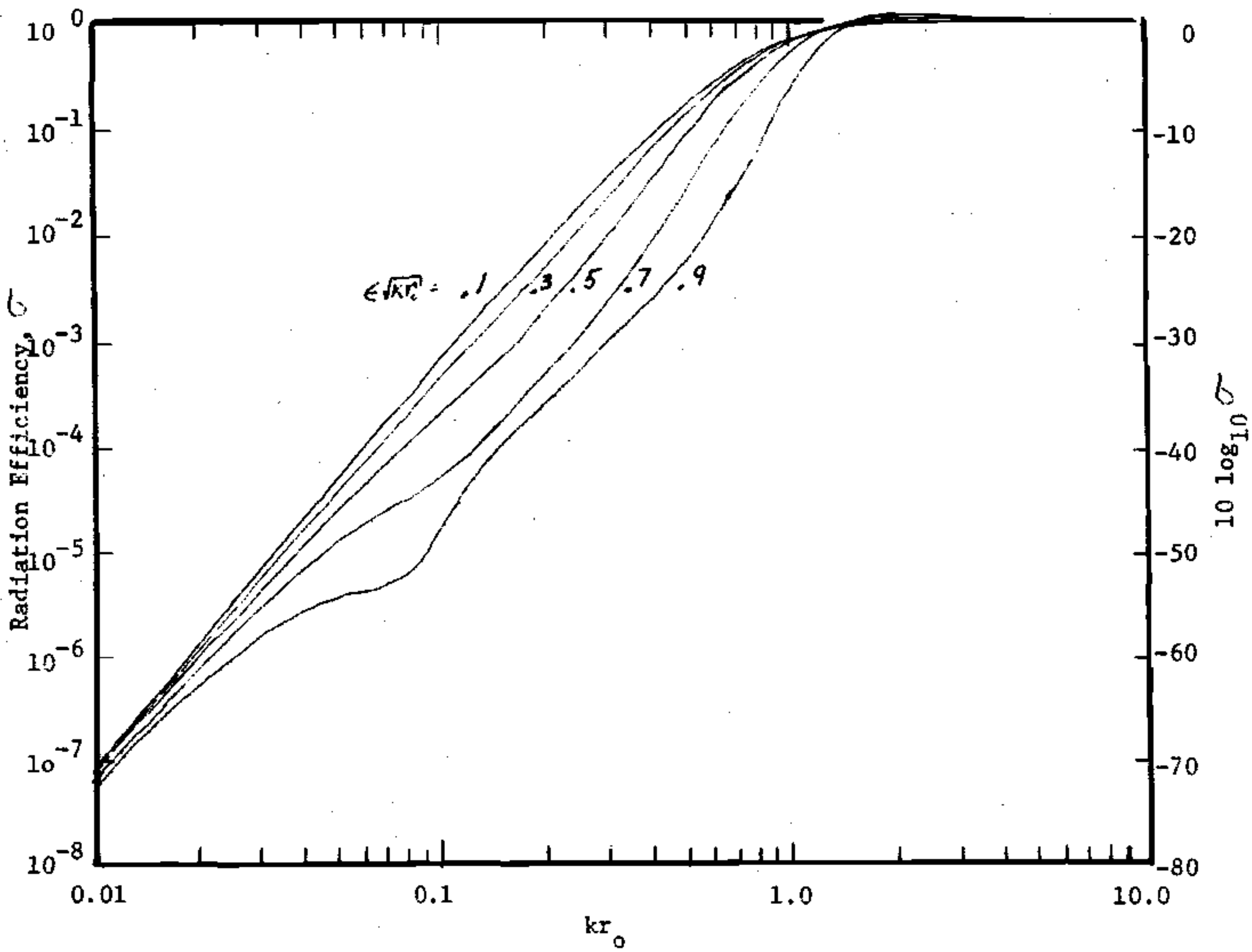


Figure 3. Radiation Efficiency of a Beam for $\ell/r_o = 25$

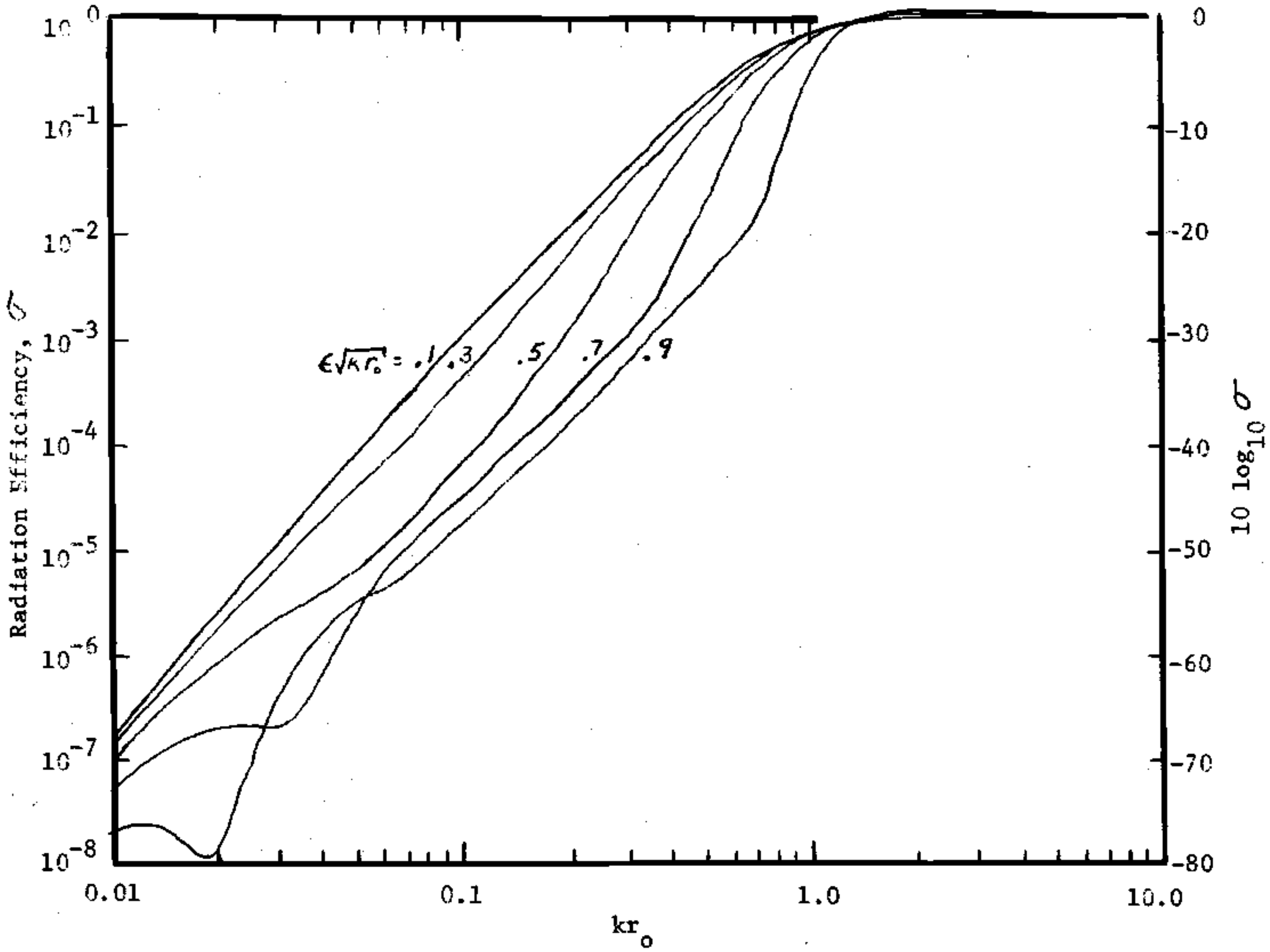


Figure 4. Radiation Efficiency of a Beam for $\ell/r_o = 50$

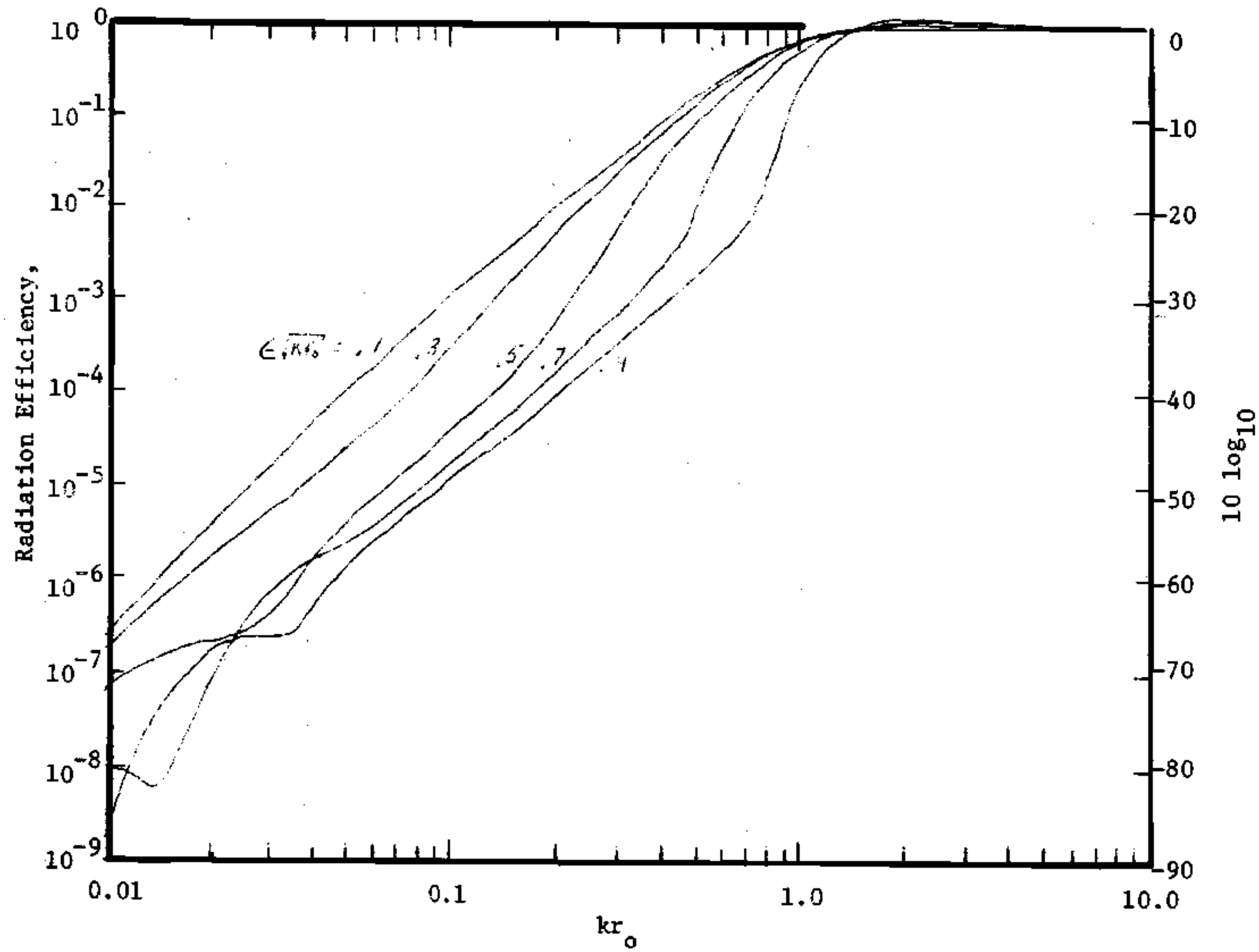


Figure 5. Radiation Efficiency of a Beam for $\ell/r_o = 75$

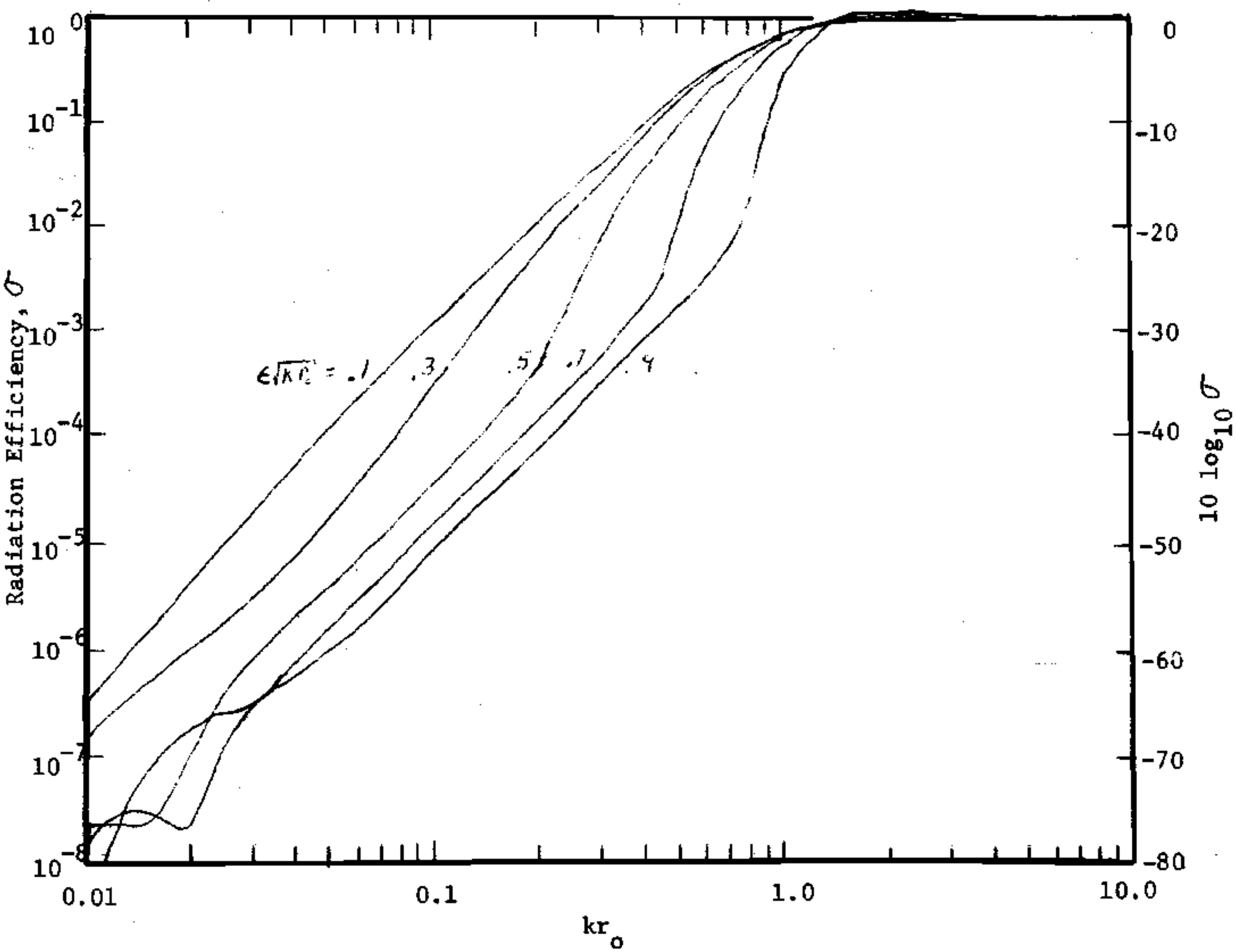


Figure 6. Radiation Efficiency of a Beam for ℓ/r_o = 100

approach without determining the mode number which corresponds to a given value of $\varepsilon(kr_o)^{1/2}$. A valid comparison can be made by leaving the phase angles in Eq. 2.18 and continuing the derivation of the radiation efficiency. The resulting radiation efficiency is

$$\sigma = \frac{4}{\pi^2 k^2 r_o \ell} \int_{-1}^{1} \frac{1}{(1-\beta^2)\,|H_1^{(1)\prime}(kr_o\sqrt{1-\beta^2})|^2} \left[\frac{\sin^2(\varepsilon+\beta)\frac{k\ell}{2}}{(\varepsilon+\beta)^2} + \right.$$

$$\left. + \cos(\eta+\psi) \cdot \frac{\sin(\varepsilon+\beta)\frac{k\ell}{2}\,\sin(\varepsilon-\beta)\frac{k\ell}{2}}{(\varepsilon^2-\beta^2)}\right] d\beta \qquad (3.13)$$

Fig. 7 gives a comparison derived in this manner using the values of $\eta+\psi$ and k_b required by the boundary conditions for a simply supported beam. A careful examination of Eq. 3.13 reveals that, just as in the previous low frequency approximation, radiation from resonances of simply supported beams represents an extreme case. The term which includes the phase angles is always positive; therefore, the radiation efficiency is somewhat higher than the average given in Eq. 2.25. At the other extreme, when $\eta+\psi = 0$ implies that n is even and $\eta+\psi = \pi$ implies that n is odd, the phase angle term in Eq. 3.13 is always negative. The radiation efficiency for this case is also shown in Fig. 7. It is clear from the figure that the contribution from the second term diminishes at higher frequencies, as the two extreme cases converge towards the average.

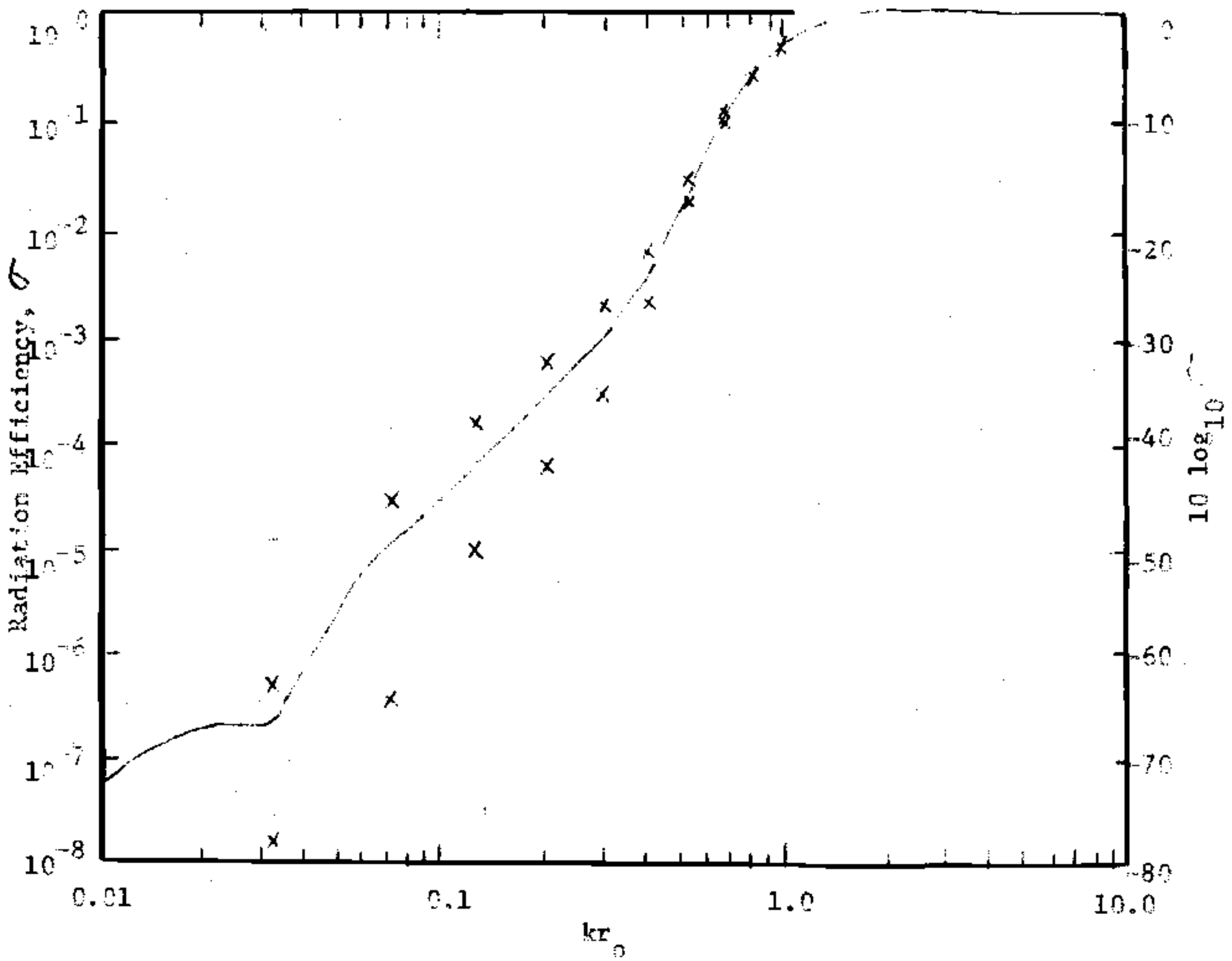


Figure 7. A Comparison of Radiation Efficiencies, —— Averaging Technique, $\ell/r_o=50$, $\epsilon\sqrt{kr_o} = 0.7$; x Modal Approach

CHAPTER IV

APPLICATION TO TEXTILE LOOM PICKING STICKS

The function of the picking stick on each side of an automatic fly-shuttle textile loom is to receive and to throw the shuttle between the threads, back and forth across the sley of the loom. Johnson presents a more detailed description of the loom, along with photographs.[4] The stick is more rectangular than cylindrical in shape, and its vibrations are not restricted to a single plane. Therefore some adjustments and modifications must be made in applying the results of the previous chapters to this specific case.

It is necessary to generalize these results to allow for vibrations in two perpendicular planes, and for the possibility of different radiation efficiencies for these perpendicular vibrations due to differences in the stiffness or the effective radius of the beam in these two planes. The total acoustic power is simply the sum of the acoustic power radiated by each of the two perpendicular vibrations. Considering vibrations in the x-z and y-z planes (see Fig. 1), one has

$$W = \rho_o c \pi \ell \; [r_{ox} \langle v_x^2 \rangle \sigma_x + r_{oy} \langle v_y^2 \rangle \sigma_y] \qquad (4.1)$$

The value of ε is critical to the determination of the correct radiation efficiency. Therefore, it is important to calculate $\varepsilon(kr_o)^{1/2}$ for a rectangular beam, and to use this value in determining the radiation efficiency of the picking stick. One finds that, for the picking stick, $B = 240$ N-m^2 for the x-z vibrations, and $B = 1000$ N-m^2 for the y-z vibrations. The mass per unit length is $m = .64$ kg/m. Thus $\varepsilon(kr)^{1/2}$ can be determined from Eq. 3.11 with the knowledge of c and r_o.

The effective radii for the stick, both r_{ox} and r_{oy}, were taken to be equal to that radius which would give the correct average cross-sectional area for the beam. This is clearly the best choice for low frequencies where radiation is dependent on the cross-sectional area of the beam. At high frequencies, the surface area that is vibrating becomes the important factor. A second method of choosing the effective radii based on the correct surface area did not significantly improve the high frequency results. Therefore the first method was used to determine r_{ox} and r_{oy} for the results which are shown here.

What is physically measured is not the velocity, as is shown in Eq. 4.1, but the root mean square accelerations, a_{xrms} and a_{yrms}, in each of the standard octave bands. Taking this into account, one gets

$$W = \frac{\rho_o c}{\omega^2} \pi \ell \; [r_{ox} \; a^2_{xrms} \; \sigma_x + r_{oy} \; a^2_{yrms} \; \sigma_y] \qquad (4.2)$$

The numerical technique used to determine the radiation efficiency was extended to calculate the acoustic power radiated from each of the two picking sticks of a loom, in each octave band from 31.5 to 31,500 Hz.

Measured acceleration data and the subroutines developed to calculate the radiation efficiency were used to determine the power output of each stick. A graph of the predicted sound power levels is shown in Fig. 8. Octave band sound pressure levels were measured at a reference point which was equidistant from the two picking sticks and one meter from the front of the loom. The distance from the picking sticks to the reference point was combined with each stick's power output to calculate predicted octave band sound pressure levels. This was done assuming symmetric cylindrical spreading,

$$SPL = 10 \log_{10} \frac{\langle P^2 \rangle}{P^2_{ref}} \qquad (4.3)$$

$$\langle P^2 \rangle = \frac{\rho_o c}{2\pi RL} \; [W_{left} + W_{right}] \qquad (4.4)$$

where R is the distance to the reference point, and P_{ref} = 2. x 10^{-5} N/m^2 is the reference pressure. The question of directivity has not yet been adequately examined. A

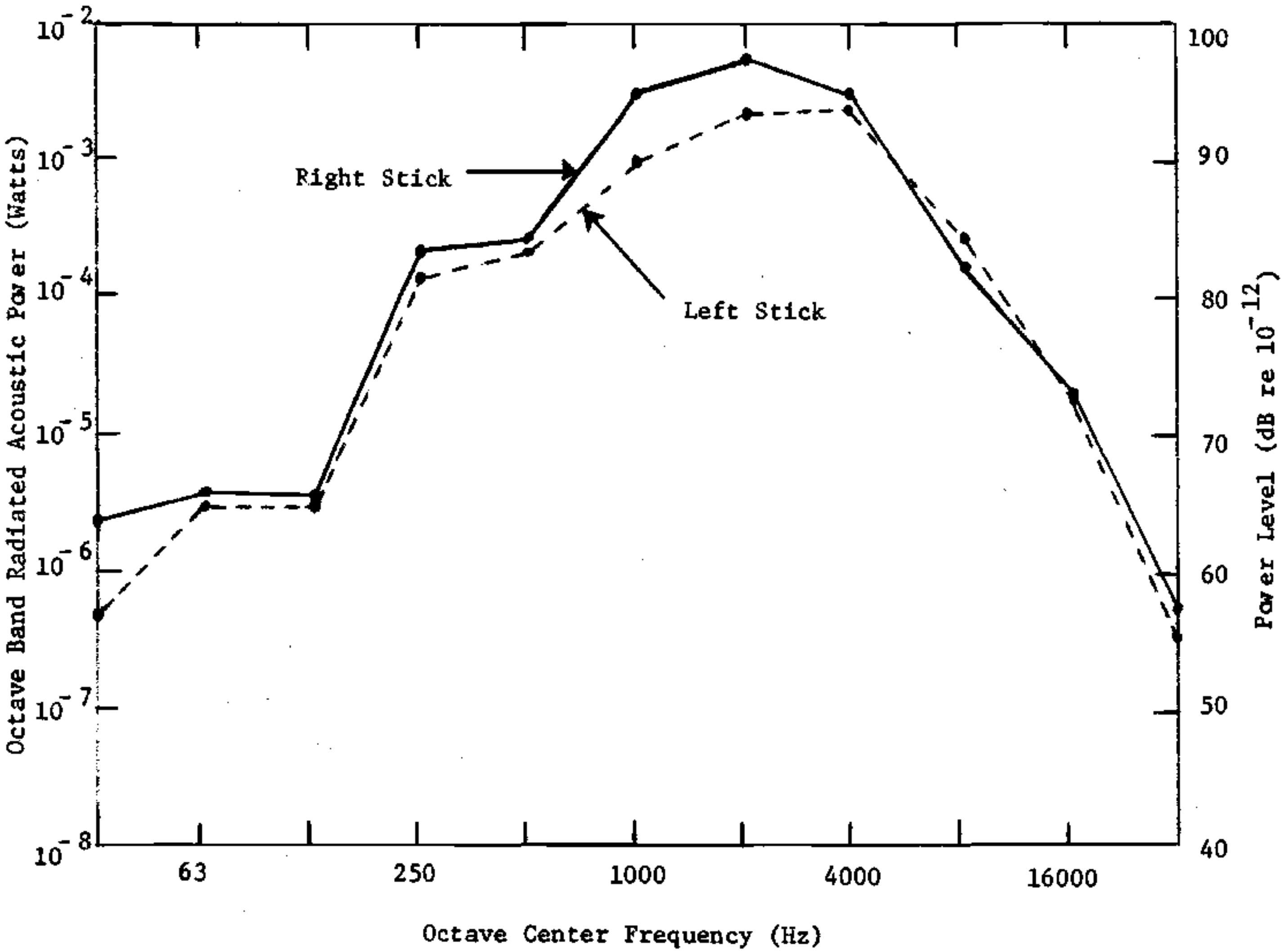


Figure 8. Theoretical Acoustic Power Output

comparison of the theoretical and experimental sound pressure levels is shown in Fig. 9.

Fig. 9 shows good agreement between theoretical and experimental results for frequencies above 125 Hz. The agreement is particularly close in the range of frequencies which have the highest sound pressure levels. There are several possible reasons for the larger discrepancies that appear at lower frequencies. A partial explanation appears to be the placement of the microphone (the reference position), 0.5 m off of the floor and 1. m from the front of the loom. Ground reflections at these lower frequencies provide positive reinforcement, causing a possible increase in the experimental values of as much as five or six decibels. Another possible explanation is the potential contributions from other sources on the loom in that frequency range. The extensive acceleration data taken by Johnson certainly do not preclude this possibility.[4]

The overall A-weighted sound pressure level can be determined from the octave band levels in Fig. 9. The result is excellent agreement between the theoretical and measured results. The A-weighted sound pressure level, rounded to the nearest tenth of a decibel, is 94.1 dBA for both the theoretical and experimental results shown in Fig. 9. Thus despite the low frequency disagreement the theory provides an extremely good prediction of the overall A-weighted sound pressure level in the vicinity of the loom.

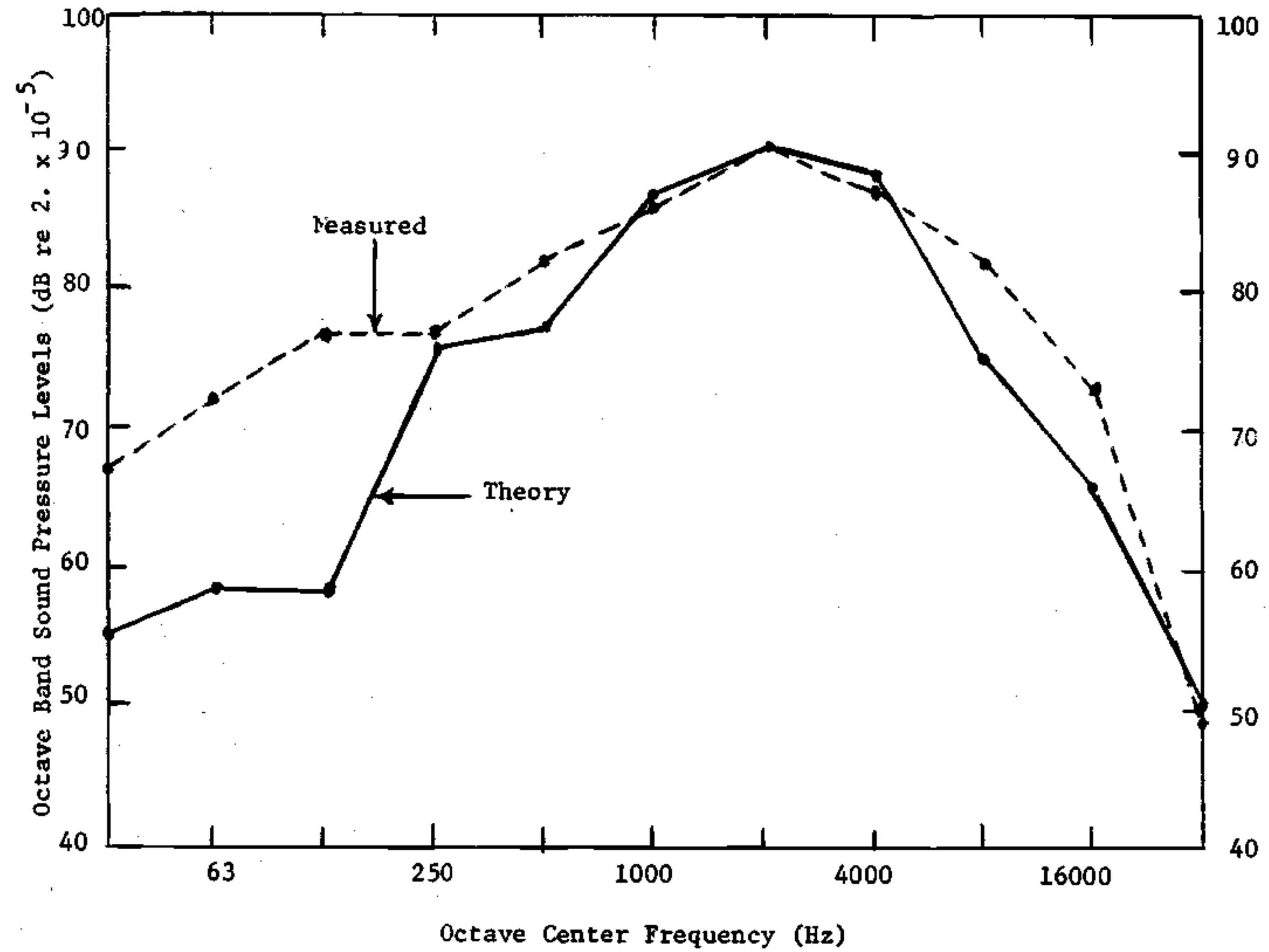


Figure 9. Theoretical and Experimental Sound Pressure Levels

CHAPTER V

CONCLUSIONS

The technique of representing beam vibrations as two traveling waves and averaging over all equally probable phase differences to determine the acoustic radiation properties of a beam has been shown to be a valid alternative to analyzing the specific boundary conditions at the ends of the beam. This technique is particularly convenient when these boundary conditions are quite complex, as in the case of a textile loom picking stick. It was possible to show that at high frequencies this method agrees with results determined for a simply supported beam vibrating at resonance. At low frequencies, this technique provides a radiation efficiency mid-way between the extremes for the modal approach. These limiting cases support the general validity of the new approach. Further support arises from the application of the theory to a specific case.

The application of this approach to the picking sticks of a textile loom provides a reasonably good model for acoustic radiation from a fly-shuttle loom, though some differences between theory and experiment still are not fully explained. More work needs to be done to determine the reasons for these discrepancies. Directivity, other sources at low frequencies and the effect of the floor are areas which require further investigation so that a more complete model of loom noise can be developed.

APPENDIX

The following is a listing of the computer programs and subroutines used in this thesis. They were written for and used on the Georgia Tech CDC Cyber 74 computer. Most of the documentation appears in the listings. Listed first are the subroutines used to calculate the radiation efficiency. QUAD, NBESJ, and RBESY are subroutines which belong to the system's math-science library, MSFLIB. Their accuracy was checked before using them.

```
      FUNCTION RADEF1(E,D,T,CRIT)
C
C     THIS FUNCTION SUBROUTINE CALCULATES THE RADIATION EFFICIENCY
C     AT A SINGLE POINT WITH E=K0/K=C/C0 ,D=KR AND T=L/R. IT MUST
C     IN CONJUNCTION WITH THE FUNCTION 'FINT' WHICH IS THE INTEGRAND
C     FOR THE 'QUAD' NUMERICAL INTEGRATION.  QUAD IS A MSFLIB LIBRARY
C     INTEGRATION ROUTINE.
C
      EXTERNAL FINT
      COMMON/RDF/EE,F,G
      PI=3.14159265459
      EE=E
      F=D
      G=.5*D*T
      N=1
      IMAP=0
      CALL QUAD(0.,1.,CRIT,REL,N,ANSW,FINT,NERR,IMAP)
      IF(NERR.GE.0.)GO TO 1
      PRINT 100,NERR
  100 FORMAT(*????INTEGRATION DID NOT MEET SPECIFIED CRITERIA*,I3)
    1 RADEF1=2.*G*D*ANSW/(PI*PI)
      RETURN
      END
      FUNCTION FSINC(X)
C
C     THIS FUNCTION SUBROUTINE CALCULATES SIN(X)/X.
C
      IF(ABS(X).LT.1.E-6)GO TO 1
      FSINC=SIN(X)/X
      RETURN
    1 FSINC=1.
      RETURN
      END
      FUNCTION FINT(BETA)
C
C
C     THIS FUNCTION SUBROUTINE CALCULATES THE INTEGRAND FOR THE RADIATION
C     EFFICIENCY INTEGRAL.  IT USES THE FUNCTION 'FSINC' AND THE MSFLIB
C     BESSEL FUNCTION ROUTINES 'NBESJ' AND 'RBESY'.
C
      REAL KL2
      COMMON/RDF/E,F,KL2
      DIMENSION BJ(2),BY(2)
      IF(BETA.EQ.1.)GO TO 3
      ARG1=F*SQRT(1.-BETA*BETA)
      SUB2=FSINC(KL2*(E+BETA))
      SUB3=FSINC(KL2*(E-BETA))
      IF(ARG1.LT.1.E-6)GO TO 1
      CALL NBESJ(ARG1,1,BJ)
      CALL RBESY(ARG1,1,BY,NERR)
      SUB1=ARG1*BJ(1)-BJ(2)
      SUB1A=ARG1*BY(1)-BY(2)
      SUB1=1./(SUB1*SUB1+SUB1A*SUB1A)
      GO TO 2
    1 SUB1=.5*3.14159265359*ARG1
      SUB1=SUB1*SUB1
    2 FINT=SUB1*(SUB2*SUB2+SUB3*SUB3)
      RETURN
    3 FINT=0.
      RETURN
      END
```

```
      SUBROUTINE PLTTS(X,Y,N,NTX,NTY,FSTVX,FSTVY,
C
C     THIS SUBROUTINE CONTAINS ALL THE PLOTTING COMMANDS FOR THE PLOTTING

C     PROGRAM 'RADPLOT'.   SEE CALCOMP MANUAL FOR FURTHER DETAILS.
C
     1DLTVX,DLTVY,NAMX,NNX,NAMY,NNY,LAST)
      DIMENSION IBUF(512),X(1),Y(1)
      CALL PLOTS(IBUF,512,2,00)
      IF(NTX.NE.1)CALL AXIS(0.,0.,NAMX,NNX,10.,0.,FSTVX,DLTVX)
      IF(NTX.EQ.1)CALL LGAXIS(0.,0.,NAMX,NNX,10.,0.,FSTVX,DLTVX)
      IF(NTY.NE.1)CALL AXIS(0.,0.,NAMY,NNY,8.,90.,FSTVY,DLTVY)
      IF(NTY.EQ.1)CALL LGAXIS(0.,0.,NAMY,NNY,8.,90.,FSTVY,DLTVY)
      ENTRY LINED
      X(N+1)=FSTVX
      X(N+2)=DLTVX
      Y(N+1)=FSTVY
      Y(N+2)=DLTVY
      IF(NTX.EQ.1.OR.NTY.EQ.1)GO TO 1
      CALL LINE(X,Y,N,1,0,0)
      GO TO 2
    1 LT=0
      IF(NTX.EQ.1.AND.NTY.NE.1)LT=-1
      IF(NTX.NE.1.AND.NTY.EQ.1)LT=1
      CALL LGLINE(X,Y,N,1,0,0,LT)
    2 IF(LAST.NE.0)CALL PLOT(0.,0.,999)
      RETURN
      END
```

```
      PROGRAM BEAM(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     THIS PROGRAM IS USED TO CALCULATE THE RADIATION EFFICIENCY
C     OF A BEAM OF CIRCULAR CROSS SECTION.  IT DOES THIS OVER A
C     SPECIFIED RANGE OF THE VARIABLE KR, FOR TEN SPECIFIED VALUES
C     OF KB/K AND ONE SPECIFIED VALUE OF L/R.  THE OUTPUT IS IN THE
C     FORM OF TEN TABLES.
C
C     LIBRARIES USED:      MSFLIB     -THE SYSTEM'S MATH-SCIENCE LIBRARY
C                          BEAMLIB    -THE LIBRARY OF SUBROUTINES USED TO
C                                      CALCULATE THE RADIATION EFFICIENCY
C
C     EXECUTION PROCEDURES:  "CALL,GGG" OR "-GGO" WILL EXECUTE THE PROGRAM
C                            AFTER IT HAS BEEN COMPILED, ASSUMING  THE BINARY
C                            FILE IS "LGO".  NAMELIST FORMAT IS USED FOR THE
C                            INPUT VARIABLES.  "CHANGES" IS THE NAMELIST.
C
C     INPUT VARIABLES:    KRMAX  - MAXIMUM VALUE OF KR TO BE INCLUDED IN
C                                  THE TABLE.
C                         KRMIN  - INITIAL VALUE OF KR.
C                         KRSTP  - INCREMENT BETWEEN SUCCESSIVE VALUES OF KR.
C                         E      - TEN VALUES  OF KB/K. ONE FOR EACH TABLE.
C                         T      - L/R.   ONE FOR ENTIRE SET OF TABLES.
C                         CRIT   - RELATIVE CRITERIA FOR NUMERICAL INTE-
C                                  GRATION.
C                         M      - THE NUMBER OF COLUMNS ON A PAGE.
C                                  NORMALLY,  M=5 FOR TTY AND M=10 FOR LPT.
C
      REAL KRMAX,KRMIN,KRSTP
      DIMENSION E(10),HD(10),RD(10)
      DATA KRMIN,KRMAX,KRSTP/0.,10.,.05/
      DATA E/.2,.4,.6,.8,1.,2.,4.,6.,8.,10./
      DATA T/50./
      DATA CRIT,M/1.E-5,5/
      NAMELIST/CHANGES/KRMAX,KRMIN,KRSTP,E,T,CRIT,M
      READ CHANGES
      N=INT((KRMAX-KRMIN)/(M*KRSTP))+1
      DO 1 I=1,M
    1 HD(I)=(I-1)*KRSTP
      DO 3 J=1,10
      IF(E(J).EQ.0.)STOP
      RD(1)=0.
      EE=E(J)
      D=KRMIN
      PRINT 200,T,EE
      PRINT 201,(HD(L),L=1,M)
      PRINT 203
      DO 3 K=1,N
      D1=D
      DO 2 L=1,M
      IF(D.EQ.0.)GO TO 2
      RD(L)=RADEF1(EE,D,T,CRIT)
    2 D=D+KRSTP
      PRINT 202,D1,(RD(L),L=1,M)
    3 CONTINUE
  200 FORMAT(///*RADIATION EFFICIENCY OF A BEAM FOR L/A =*,F6.1,
     1* AND C/CB =*,F6.2/)
  201 FORMAT(4X,*KA*,10(6X,F5.3))
  202 FORMAT(1X,F7.3,10(1X,E10.4))
  203 FORMAT(/)
      END
```

RADIATION EFFICIENCY OF A BEAM FOR L/A = 50.0 AND C/CB = .20

KA	0.000	.050	.100	.150	.200
0.000	0.	.9307E-04	.1138E-02	.4364E-02	.1102E-01
.250	.2278E-01	.3967E-01	.6384E-01	.9552E-01	.1349E+00
.500	.1815E+00	.2342E+00	.2916E+00	.3519E+00	.4132E+00
.750	.4736E+00	.5321E+00	.5870E+00	.6375E+00	.6841E+00
1.000	.7255E+00	.7630E+00	.7959E+00	.8249E+00	.8501E+00
1.250	.8722E+00	.8914E+00	.9082E+00	.9225E+00	.9355E+00
1.500	.9465E+00	.9561E+00	.9645E+00	.9716E+00	.9752E+00
1.750	.9878E+00	.9956E+00	.9929E+00	.9967E+00	.1000E+01
2.000	.1007E+01	.1008E+01	.1009E+01	.1010E+01	.1011E+01
2.250	.1017E+01	.1014E+01	.1016E+01	.1017E+01	.1015E+01
2.500	.1019E+01	.1019E+01	.1020E+01	.1021E+01	.1021E+01
2.750	.1021E+01	.1022E+01	.1022E+01	.1023E+01	.1023E+01
3.000	.1023E+01	.1023E+01	.1024E+01	.1024E+01	.1024E+01
3.250	.1024E+01	.1024E+01	.1024E+01	.1024E+01	.1024E+01
3.500	.1024E+01	.1024E+01	.1024E+01	.1024E+01	.1024E+01
3.750	.1025E+01	.1025E+01	.1025E+01	.1025E+01	.1025E+01
4.000	.1024E+01	.1024E+01	.1024E+01	.1024E+01	.1024E+01
4.250	.1024E+01	.1024E+01	.1024E+01	.1024E+01	.1024E+01
4.500	.1024E+01	.1024E+01	.1024E+01	.1024E+01	.1024E+01
4.750	.1024E+01	.1024E+01	.1024E+01	.1024E+01	.1024E+01
5.000	.1024E+01	.1024E+01	.1024E+01	.1024E+01	.1024E+01

RADIATION EFFICIENCY OF A BEAM FOR L/A = 50.0 AND C/CB = 1.20

KA	0.000	.050	.100	.150	.200
0.000	0.	.4803E-04	.2237E-03	.4602E-03	.7895E-03
.250	.1155E-02	.1600E-02	.2151E-02	.2823E-02	.3616E-02
.500	.4509E-02	.5464E-02	.6435E-02	.7378E-02	.8260E-02
.750	.9061E-02	.9781E-02	.1043E-01	.1104E-01	.1162E-01
1.000	.1219E-01	.1276E-01	.1332E-01	.1384E-01	.1430E-01
1.250	.1469E-01	.1495E-01	.1519E-01	.1532E-01	.1540E-01
1.500	.1546E-01	.1557E-01	.1561E-01	.1573E-01	.1569E-01
1.750	.1605E-01	.1619E-01	.1620E-01	.1635E-01	.1633E-01
2.000	.1625E-01	.1612E-01	.1598E-01	.1555E-01	.1576E-01
2.250	.1572E-01	.1573E-01	.1578E-01	.1584E-01	.1589E-01
2.500	.1568E-01	.1562E-01	.1570E-01	.1553E-01	.1533E-01
2.750	.1512E-01	.1497E-01	.1465E-01	.1480E-01	.1450E-01
3.000	.1483E-01	.1456E-01	.1458E-01	.1454E-01	.1474E-01
3.250	.1455E-01	.1439E-01	.1416E-01	.1396E-01	.1380E-01
3.500	.1370E-01	.1367E-01	.1366E-01	.1372E-01	.1375E-01
3.750	.1378E-01	.1370E-01	.1358E-01	.1341E-01	.1320E-01
4.000	.1299E-01	.1280E-01	.1266E-01	.1256E-01	.1257E-01
4.250	.1260E-01	.1265E-01	.1269E-01	.1269E-01	.1262E-01
4.500	.1250E-01	.1231E-01	.1211E-01	.1191E-01	.1174E-01
4.750	.1163E-01	.1158E-01	.1159E-01	.1164E-01	.1170E-01
5.000	.1173E-01	.1172E-01	.1164E-01	.1151E-01	.1133E-01

```
      PROGRAM TABLE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     THIS PROGRAM IS USED TO CALCULATE THE RADIATION EFFICIENCY
C     OF A BEAM OF CIRCULAR CROSS SECTION.  IT DOES THIS OVER A
C     SPECIFIED RANGE OF THE VARIABLE KR, FOR FIVE VALUES OF
C     KB/K*SQRT(KR) AND ONE VALUE OF L/R.  THE OUTPUT IS IN THE
C     FORM OF FIVE TABLES.
C
C     LIBRARIES USED:       MSFLIB      -THE SYSTEM'S MATH-SCIENCE LIBRARY
C                           REAMLIB     -THE LIBRARY OF SUBROUTINES USED TO
C                                        CALCULATE THE RADIATION EFFICIENCY
C     EXECUTION PROCEDURES:   'CALL,GGO' OR '-GGO', WILL EXECUTE THE PROGRAM
C                             AFTER IT HAS BEEN COMPILED, ASSUMING THE BINARY
C                             FILE IS 'LGO'.  NAMELIST FORMAT IS USED FOR THE
C                             INPUT VARIABLES.  'CHANGES' IS THE NAMELIST.
C
C     INPUT VARIABLES:    KRMAX   - MAXIMUM VALUE OF KR TO BE INCLUDED IN
C                                   THE TABLE.
C                         KRMIN   - INITIAL VALUE OF KR.
C                         KRSTP   - INCREMENT BETWEEN SUCCESSIVE VALUES OF KR.
C                         E       - TEN VALUES OF KB/K. ONE FOR EACH TABLE.
C                         T       - L/R.    ONE FOR ENTIRE SET OF TABLES.
C                         CRIT    - RELATIVE CRITERIA FOR NUMERICAL INTE-
C                                   GRATION.
C                         M       - THE NUMBER OF COLUMNS ON A PAGE.
C                                   NORMALLY, M=5 FOR TTY AND M=10 FOR LPT.
C
      REAL KRMAX,KRMIN,KRSTP
      DIMENSION E(5),HD(10),RD(10)
      DATA KRMIN,KRMAX,KRSTP/0.,10.,.2/
      DATA E/.3,.35,.4,.45,.5/
      DATA T/50./
      DATA CRIT,M/1.E-5,5/
      NAMELIST/CHANGES/KRMAX,KRMIN,KRSTP,E,T,CRIT,M
      READ(5,CHANGES)
      N=INT((KRMAX-KRMIN)/(M*KRSTP))+1
      DO 1 I=1,M
    1 HD(I)=(I-1)*KRSTP
      DO 3 J=1,5
      IF(E(J).EQ.0.)STOP
      RD(1)=0.
      D=KRMIN
      WRITE(6,200)T,E(J)
      WRITE(6,201)(HD(L),L=1,M)
      WRITE(6,203)
      DO 3 K=1,N
      D1=D
      DO 2 L=1,M
      IF(D.EQ.0.)GO TO 2
      EE=E(J)/SQRT(D)
      RD(L)=RADEF1(EE,D,T,CRIT)
    2 D=D+KRSTP
      WRITE(6,202)D1,(RD(L),L=1,M)
    3 CONTINUE
  200 FORMAT(///*RADIATION EFFICIENCY OF A BEAM FOR L/A =*,F6.1,
     1* AND C/CB SQRT(KA) =*,F4.2/)
  201 FORMAT(4X,*KA*,10(6X,F5.3))
  202 FORMAT(1X,F7.3,10(1X,F10.4))
  203 FORMAT(/)
      END
```

```
.900
? .CHANGES A=.4.0..KAMAX=5. .
```

RADIATION EFFICIENCY OF A BEAM FOR L/A = 50.0 AND C/CB SQRT(KA) = .40

KA	0.000	.200	.400	.600	.800
0.000	0.	.2290E-02	.6061E-01	.2266E+00	.4919E+00
1.000	.7157E+00	.5610E+00	.9426E+00	.9867E+00	.1010E+01
2.000	.1022E+01	.1028E+01	.1030E+01	.1031E+01	.1031E+01
3.000	.1030E+01	.1029E+01	.1029E+01	.1027E+01	.1026E+01
4.000	.1024E+01	.1023E+01	.1022E+01	.1021E+01	.1021E+01
5.000	.1020E+01	.1019E+01	.1018E+01	.1017E+01	.1017E+01

22.224 CP SECONDS EXECUTION TIME

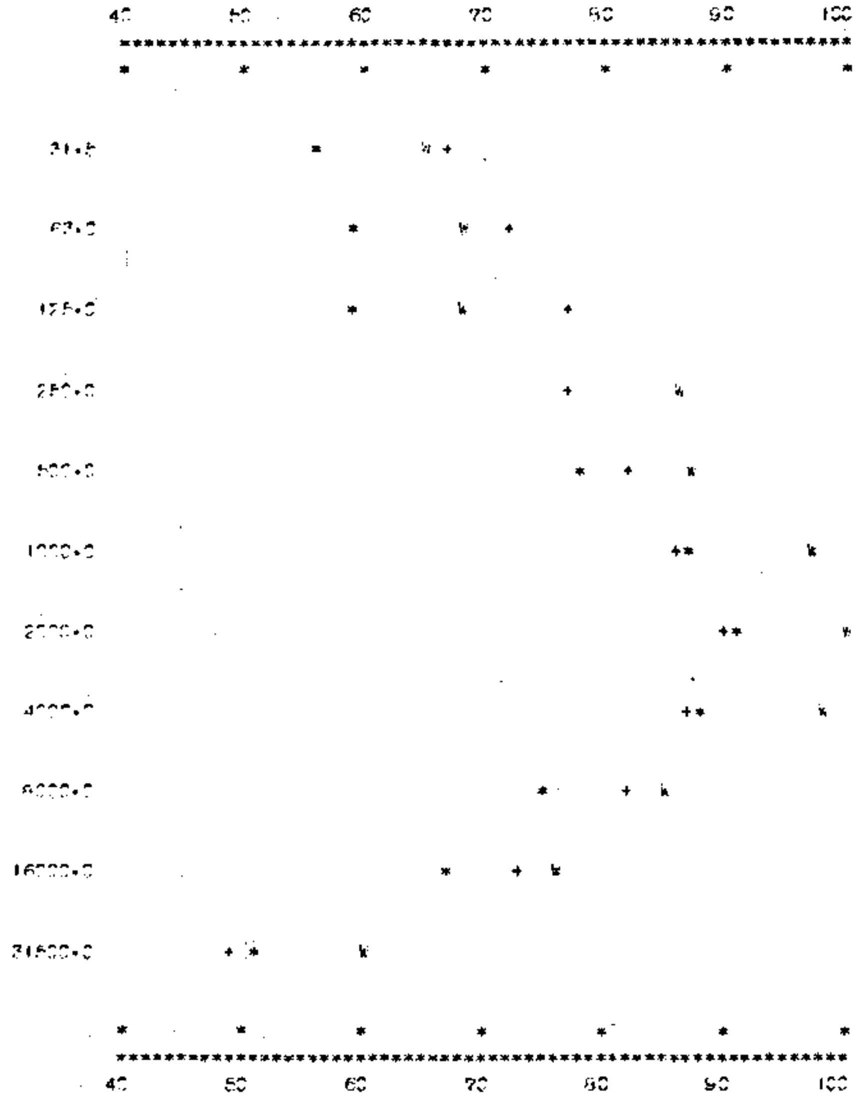
/

```
      PROGRAM RADPLOT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     THIS PROGRAM IS USED TO PLOT THE RADIATION EFFICIENCY OF A BEAM
C     OF CIRCULAR CROSS-SECTION.  IT CAN PLOT THE RAD. EFF. VS. KR OR
C     VS. K/KB.
C
C     LIBRARIES USED:      MSFLIB       - THE SYSTEM'S MATH-SCIENCE LIBRARY
C                          CALCOMP      - THE CALCOMP PLOTTER LIBRARY
C                          BEAMLIB      - THE LIBRARY OF SUBROUTINES WHICH
C                                         ARE USED IN THE RAD. EFF. CALCULATION
C
C     EXECUTION PROCEDURE:   'CALL,GO' OR '-GO'  WILL EXECUTE THE PROGRAM
C                            AFTER IT HAS BEEN COMPILED, ASSUMING THE BINARY
C                            FILE IS 'LGO'.  NAMELIST FORMAT IS USED FOR THE
C                            INPUT VARIABLES. 'CHANGES' IS THE NAMELIST.
C
C      INPUT VARIABLES:      E      - FIVE VALUES OF KB/K*SQRT(KR). MUST
C                                     BE LISTED IN DESCENDING ORDER OF
C                                     MAGNITUDE.
C                            T      - L/R.
C                            CRIT   - RELATIVE CRITERIA FOR NUMERICAL
C                                     INTEGRATION.
C                            MM     - IF MM=0, PROGRAM PLOTS  RAD.EFF. VS.
C                                     KR.  IF MM=1, THEN PROGRAM PLOTS RAD..
C                                     EFF. VS. K/KB.
C                            N      - NUMBER OF POINTS TO BE PLOTTED.
C
      REAL KRSTP,KR
      DIMENSION E(5),EP(200),KR(200),RDF(200)
      DATA E/.9,.7,.5,.3,.1/
      DATA T/50./
      DATA CRIT,MM/1.E-4,0/
      DATA N/100/
      NAMELIST/CHANGES/E,T,CRIT,MM,N
      READ(5,CHANGES)
      KRSTP=10.**(3./N)
      PRINT*,KRSTP
      DO 3 J=1,5
      IF(E(J).EQ.0.)STOP
      D=.01
      DO 2 K=1,N
      EE=E(J)/SQRT(D)
      EP(K)=1./EE
      KR(K)=D
      RDF(K)=RADEF1(EE,D,T,CRIT)
    2 D=D*KRSTP
      IF(J.EQ.1)GO TO 1
      IF(J.EQ.5)LAST=1
      IF(MM.EQ.0)CALL LINED(KR,RDF,N,1,1,.01,FY,.3,DY,0,0,0,0,LAST)
      IF(MM.NE.0)CALL LINED(EP,RDF,N,1,1,.01,FY,.3,DY,0,0,0,0,LAST)
      GO TO 3
    1 NEX=INT(ALOG10(RDF(1)))-1
      FY=10.**NEX
      DY=ABS(NEX/8.)
      IF(MM.EQ.0)CALL PLTTS(KR,RDF,N,1,1,.01,FY,.3,DY,2HKR,-2,
     120HRADIATION EFFICIENCY,20,0)
      IF(MM.NE.0)CALL PLTTS(EP,RDF,N,1,1,.01,FY,.3,DY,4HK/KB,-4
     1,20HRADIATION EFFICIENCY,20,0)
    3 CONTINUE
      END
```

```
      PROGRAM PICSTK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     THIS PROGRAM IS USED TO CALCULATE THE THEORETICAL ACOUSTIC
C     POWER RADIATED BY EACH OF THE TWO PICKING STICKS ON AN
C     AUTOMATIC TEXTILE LOOM.  IT ALSO CALCULATES THE ESTIMATED
C     OCTAVE BAND SOUND PRESSURE LEVELS AT A POINT ONE METER FROM
C     THE FRONT OF THE LOOM.
C
C     LIBRARIES USED:      MSFLIB     - THE SYSTEM'S MATH-SCIENCE LIB.
C                          BEAMLIB    - SUBROUTINES USED TO CALCULATE
C                                         THE RADIATION EFFICIENCY
C
C     EXECUTION PROCEDURE:     "CALL,GGO" OR "-GGO" WILL EXECUTE THE
C                              PROGRAM AFTER IT HAS BEEN COMPILED,
C                              ASSUMING THE BINARY FILE IS "LGO".
C                              NAMELIST FORMAT IS USED FOR THE INPUT
C                              VARIABLES. "CHANGES" IS THE NAMELIST.
C
C     INPUT VARIABLES:       FREQ   - OCTAVE BAND CENTER FREQUENCIES.
C                            ACCXL  - RMS X ACCELERATION OF LEFT STICK.
C                            ACCXR  - RMS X ACCELERATION OF RIGHT STICK.
C                            ACCYL  - RMS Y ACCELERATION OF LEFT STICK.
C                            ACCYR  - RMS Y ACCELERATION OF RIGHT STICK.
C                            SPLX   - EXPERIMENTAL OCTAVE BAND SOUND
C                                       PRESSURE LEVELS.
C                            RHO    - DENSITY OF AIR.
C                            CO     - SPEED OF SOUND IN AIR.
C                            L      - LENGTH OF STICKS.
C                            M      - MASS PER UNIT LENGTH OF STICKS.
C                            AX     - X EFFECTIVE RADIUS.
C                            AY     - Y EFFECTIVE RADIUS.
C                            BX     - X BENDING STIFFNESS.
C                            BY     - Y BENDING STIFFNESS.
C                            RR     - DISTANCE FROM RIGHT STICK TO
C                                       REFERENCE POINT.
C                            RL     - DISTANCE FROM LEFT STICK TO
C                                       REFFRENCE POINT.
C                            CRIT   - RELATIVE CRITERIA FOR NUMERICAL
C                                       INTEGRATION.
C
      INTEGER PLUS,STAR,R,W
      REAL KO,L,M,LWR(11),LWL(11),LW(11),LAX,LAY
      DIMENSION FREQ(11),ACCXL(11),ACCXR(11),ACCYL(11),ACCYR(11),
     1SPLX(11),PWRR(11),PWRL(11),PWR(11),SPL(11)
      DATA PLUS,STAR,R,LL,W/1H+,1H*,1H ,1H ,1HW/
      DATA FREQ/31.5,63.,125.,250.,500.,1.E3,2.E3,4.E3,8.E3,1.6E4,
     13.15E4/
      DATA ACCXL/70.,100.,70.,450.,220.,210.,200.,250.,80.,80.,20./
      DATA ACCYL/25.,26.,35.,40.5,90.,105.,95.,82.5,110.,45.,15./
      DATA ACCXR/150.,100.,70.,450.,240.,390.,350.,300.,100.,90.,30./
      DATA ACCYR/60.,77.5,72.5,72.5,77.5,85.,70.,53.,48.,25.,12./
      DATA SPLX/67.,72.,77.,77.,82.,86.,90.,87.,82.,73.,40./
      DATA PI,RHO,CO/3.14159265359,1.21,343./
      DATA L,M,AX,AY,BX,BY,RR,RL/.88,.636,2*.0146,1000.,240.,2*1.6/
      DATA CRIT/5.E-7/
      NAMELIST/CHANGES/FREQ,ACCXL,ACCXR,ACCYL,ACCYR,SPLX,RHO,CO,L,M,AX,
     1AY,BX,BY,RR,RL,CRIT,R,LL,W
      READ(5,CHANGES)
      WRITE(6,100)
      WRITE(6,101)
```

```
      WRITE(6,102)
      WRITE(6,103)
      WRITE(6,100)


      CP=RHO*CO/(2.*PI*L)
      C=PI*RHO*CO*L
      LAX=L/AX
      LAY=L/AY
      TMPX=SQRT(BX/M)
      TMPY=SQRT(BY/M)
      EX=SQRT(CO*AX/TMPX)
      EY=SQRT(CO*AY/TMPY)
      DO 1 I=1,11
      OMEGA=2.*PI*FREQ(I)
      KO=OMEGA/CO
      OMEG2I=1./(OMEGA*OMEGA)
      CBX=SQRT(TMPX*OMEGA)
      CBY=SQRT(TMPY*OMEGA)
      RAX=RADEF1(CO/CBX,KO*AX,LAX,CRIT)
      RAY=RADEF1(CO/CBY,KO*AY,LAY,CRIT)
      PWRR(I)=C*(AX*ACCXR(I)*ACCXR(I)*RAX+AY*ACCYR(I)*ACCYR(I)*RAY)
     1*OMEG2I
      PWRL(I)=C*(AX*ACCXL(I)*ACCXL(I)*RAX+AY*ACCYL(I)*ACCYL(I)*RAY)
     1*OMEG2I
      PWR(I)=PWRL(I)+PWRR(I)
      LW(I)=10.*ALOG10(PWR(I)*1.E12)
      LWL(I)=10.*ALOG10(PWRL(I)*1.E12)
      LWR(I)=10.*ALOG10(PWRR(I)*1.E12)
      P2=CP*(PWRL(I)/RL+PWRR(I)/RR)
      SPL(I)=10.*ALOG10(P2*2.359)
      N1=12+INT(LWR(I)-39.5)
      N2=12+INT(LWL(I)-39.5)
      N3=12+INT(LW(I)-39.5)
      N4=12+INT(SPL(I)-39.5)
      N5=12+INT(SPLX(I)-39.5)
      WRITE(6,104)FREQ(I),N1,R,N2,LL,N3,W,N4,STAR,N5,PLUS
    1 CONTINUE
      WRITE(6,103)
      WRITE(6,102)
      WRITE(6,101)
      WRITE(6,100)
      WRITE(6,105)STAR,PLUS,LL,R,W
      WRITE(6,100)
      WRITE(6,106)FREQ
      WRITE(6,100)
      WRITE(6,107) LWR
      WRITE(6,108) LWL
      WRITE(6,109) LW
      WRITE(6,110)SPLX
      WRITE(6,111)SPL
  100 FORMAT(/)
  101 FORMAT(10X,*40*,8X,*50*,8X,*60*,8X,*70*,8X,*80*,8X,*90*,7X,
     1*100*)
  102 FORMAT(11X,50H**************************************************,
     111H***********)
  103 FORMAT(11X,1H*,6(9X,,1H*))
  104 FORMAT(1X,F8.1,5(T=,A1)//)
  105 FORMAT(1X,*SPL THEORETICAL*,T20,A1/1X,*SPL EXPERIMENTAL*,T20,A1,
     1/1X,*PWR LEVEL-LEFT*,T20,A1/1X,*PWR LEVEL-RIGHT*,T20,A1
     2/1X,*PWR LEVEL-TOTAL*,T20,A1)
  106 FORMAT(5X,F6.1,9F6.0,F7.0)
  107 FORMAT(1X,3HLWR,11F6.1)
  108 FORMAT(1X,3HLWL,11F6.1)
  109 FORMAT(1X,2HLW,1X,11F6.1)
  110 FORMAT(3HSLX,1X,11F6.1)
  111 FORMAT(1X,3HSPL,11F6.1)
      END
```



SPL THEORETICAL *
SPL EXPERIMENTAL +
PWR LEVEL-LEFT
PWR LEVEL-RIGHT
PWR LEVEL-TOTAL ¥

	31.5	63.	125.	250.	500.	1000.	2000.	4000.	8000.	16000.	31500.
LWR	64.4	65.0	65.6	84.0	84.5	95.6	98.6	95.1	80.6	73.1	57.9
LWL	57.0	65.0	65.0	81.5	83.9	90.5	94.2	93.9	82.5	72.9	55.7
LW	65.2	68.5	68.3	86.1	87.1	96.8	100.0	97.5	84.7	76.0	59.9
SLV	72.0	72.0	72.0	77.0	82.0	6 .0	90.0	87.0	82.0	73.0	49.0
SPL	55.9	59.2	59.0	76.6	77.5	87.4	90.6	88.2	75.4	66.7	50.6

[illegible].756 CP SECONDS EXECUTION TIME

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