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REFLECTION AND TRANSMISSION OF ACOUSTIC WAVES FROM A MOVING LAYER

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16. Abstract

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REFLECTION AND TRANSMISSION OF ACOUSTIC WAVES FROM A MOVING LAYER

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SUMMARY

The refraction of acoustic waves by a moving medium layer is theoretically treated and the expressions for reflection and transmission coefficients are determined. The moving medium layer velocity is assumed to have a space dependence in one direction. A partitioning of the moving medium layer into constant-velocity sublayers is introduced and the number of sublayers is allowed to increase until the reflection and transmission coefficients converge to their respective values.

The introduction of the input impedance concept and the use of several dummy variables molds the equations into a form very suitable for computation. Numerical results have been obtained for several sublayer approximations of Poiseuille's flow as functions of the moving layer velocity for several angles of incidence of the acoustic wave. The refined approximations are shown to converge. The degenerate case of a single constant-velocity layer is also treated, both theoretically and by a numerical analysis.

INTRODUCTION

The investigation of reflection and transmission coefficients of an acoustic wave from a moving layer has been treated by a number of authors. (See refs. 1 to 5.) These calculations indicate that the reflection and transmission coefficients are strong functions of the velocity of the medium and the angle of incidence of the acoustic waves. However, most of these treatments have been confined to medium velocities which are constant; that is, the medium flow is both time and space independent:

$$\frac{dV}{dt} = 0$$

$$\frac{dV}{dy} = 0$$

$$\frac{dV}{dx} = \text{Constant}$$

where V is velocity, t is time, and x and y are coordinates. In many practical cases, the medium flow exhibits a space dependence. For instance, the liquid flow through cylindrical pipes has a strong velocity gradient along one space axis. This well-known case of Poiseuille's flow can be described by a second-order polynomial. A problem of this type may be approximately treated by partitioning the moving layer into a number of sublayers and considering the velocity in each sublayer to be constant.

It is the purpose of this report to define suitable computational techniques for studying the propagation of an acoustic wave through a medium moving with space-dependent velocity. The approach is, as indicated previously, to divide the moving medium into constant-velocity sublayers and use the existing theoretical solutions to propagate the wave across each of the sublayers. This procedure involves matching boundary conditions deduced from the requirements that the pressure must be continuous and the instantaneous component of the resultant velocity (stream and acoustic) locally normal to the rippled interface between the adjacent layers must be the same on both sides (ref. 6). The mathematical development is for a general n-sublayer case. Numerical results are given for a small number of sublayers (5) and for a large number of sublayers (25 to 45). An optimum number of sublayers based on convergence in the magnitudes of the reflection and transmission coefficients, as the partitioning is refined, are sought. A preliminary account of this work has been presented in reference 7.

SYMBOLS

A_n amplitude of transmitted wave

B_n amplitude of reflected wave

C speed of sound

d depth of entire medium

d_n depth of nth sublayer

$i = \sqrt{-1}$

$k_n = |k_n| = (\omega - V_n k_{n,x})/C_n$

M number of layers

n number of sublayers, $n = 1, 2, 3, \ldots, M$

p acoustic pressure

R reflection coefficient of moving layer, nondimensional

$$S_n^2 = \left(1 - \frac{V_n}{C_M} \sin \theta_M\right)^2$$

T transmission coefficient through moving layer, nondimensional

t time

$$t_n = \frac{k_{n,y}}{k_{M,y}} = \frac{1}{\cos \theta_M}\left[\left(1 - \frac{V_n}{C_n} \sin \theta_M\right)^2 - \sin^2\theta_M\right]^{1/2}$$

U_x x-component of acoustic velocity

U_y y-component of acoustic velocity

V medium flow velocity

x,y Cartesian coordinates

Z characteristic impedance of medium

Z^{in} input impedance of medium

$$\overline{Z} = \frac{Z}{\rho\omega d}$$

$$\overline{Z}^{in} = \frac{Z^{in}}{\rho\omega d}$$

α modulus of y-component of propagation vector

θ angle at which incident acoustic wave strikes medium (or leaves medium)

ρ density of fluid

σ modulus of x-component of propagation vector

ω acoustic wave frequency

PROBLEM APPROACH

Figure 1 illustrates the three-layer basic problem. Layers 1 and 3 are stationary, and layer 2 has space-dependent flow. Layer 2 is partitioned into $M - 2$ sublayers, each with a constant velocity. (Details of the partitioning technique are presented in a subsequent section.) For individual sublayers, the problem can be treated in the manner of the constant-velocity cases (ref. 2). Basic equations for the acoustic propagation for constant-velocity layers are (ref. 1) as follows:

$$\frac{\partial p_n}{\partial t} + V_n \frac{\partial p_n}{\partial x} + C_n^2 \rho \left(\frac{\partial U_{x,n}}{\partial x} + \frac{\partial U_{y,n}}{\partial y} \right) = 0 \tag{1}$$

$$\frac{\partial U_{x,n}}{\partial t} + V_n \frac{\partial U_{x,n}}{\partial x} + \frac{1}{\rho_n} \frac{\partial p_n}{\partial x} = 0 \tag{2}$$

$$\frac{\partial U_{y,n}}{\partial t} + V_n \frac{\partial U_{y,n}}{\partial x} + \frac{1}{\rho_n} \frac{\partial p_n}{\partial y} = 0 \tag{3}$$

where subscript n denotes a particular sublayer ($n = M$ and 1 represent the top and bottom stationary layers, respectively).

The general solution in a layer $n = 1, 2, \ldots, M$ is as follows:

$$p_n = \left[A_n \exp(-i\alpha_n y) + B_n \exp(i\alpha_n y)\right] \exp\left[i(\omega t - \sigma_n x)\right] \tag{4}$$

$$U_{y,n} = \left[-1/i\rho_n(\omega - \sigma_n V_n)\right]\left(\partial p_n/\partial y\right) \tag{5a}$$

or

$$U_{y,n} = \frac{\alpha_n}{\rho_n(\omega - \sigma_n V_n)}\left[A_n \exp(-i\alpha_n y) - B_n \exp(i\alpha_n y)\right] \exp\left[i(\omega t - \sigma_n x)\right] \tag{5b}$$

where A_n and B_n represent the amplitudes of the transmitted and the reflected waves, respectively. Note that for $n = 1$, $B_1 = 0$ since there is no reflected wave in that layer. The propagation vectors α_n and σ_n are defined as follows:

$$\alpha_n = k_{n,y} = \left|k_n\right| \cos \theta_n \tag{6a}$$

$$\sigma_n = k_{n,x} = \left|k_n\right| \sin \theta_n \tag{6b}$$

where

$$\left|k_n\right| = \left(k_{n,x}^2 + k_{n,y}^2\right)^{1/2} = \left(\omega - V_n k_{n,x}\right)\Big/C_n \tag{6c}$$

The boundary conditions that must be met at each sublayer interface are continuity of the acoustic pressure

$$p_{n+1} = p_n \tag{7a}$$

and the instantaneous component of the resultant velocity locally normal to the applied interface

$$U_{y,n+1}\Big/\left(\omega - \sigma_{n+1}V_{n+1}\right) = U_{y,n}\Big/\left(\omega - \sigma_n V_n\right) \tag{7b}$$

Let each layer impedance be denoted by Z_n, where

$$Z_n = \frac{\rho_n\left(\omega - V_n\sigma_n\right)^2}{\alpha_n} = \frac{\rho_n\omega^2 S_n^2}{\alpha_n} \tag{8}$$

with

$$S_n^2 = \left(1 - \frac{V_n}{C_M}\sin\theta_M\right)^2$$

After applying the foregoing boundary conditions, the input impedance Z_n^{in} is given by the following expression (ref. 5):

$$Z_n^{in} = \left(Z_{n-1}^{in} - iZ_n \tan\alpha_n d_n\right)\Big/\left(Z_n - iZ_{n-1}^{in}\tan\alpha_n d_n\right)Z_n \tag{9}$$

where d_n is the nth sublayer depth and $Z_1^{in} = Z_1$.

The reflection (at the surface of the moving medium) and transmission (through the moving medium) coefficients are then given by

$$R = \left(Z_n^{in} - Z_{n+1}\right)\Big/\left(Z_n^{in} + Z_{n+1}\right) \tag{10}$$

and

$$T = \prod_{j=1}^{j=M-1} \left[\left(Z_j + Z_j^{in}\right)\Big/\left(Z_{j+1} + Z_j^{in}\right)\right] \exp\left(i\alpha_j d_j\right) \tag{11}$$

It should be emphasized that velocity dispersion and other frequency-dependent effects have been ignored in these calculations.

ANALYSIS AND RESULTS

Let the acoustic source be located in the Mth layer and let d be the width of the moving medium. The value of $k_M d$, even though M is a variable (i.e., a function of the number of partitioned layers chosen to approximate the moving medium), is maintained constant for all values of M. (See ref. 5.) For notational convenience, a new variable t_n is defined as

$$t_n = \frac{k_{n,y}}{k_{M,y}} = \frac{1}{\cos\theta_M}\left[\left(1 - \frac{V_n}{C_n}\sin\theta_M\right)^2 - \sin^2\theta_M\right]^{1/2} \qquad (n = 1, 2, 3, \ldots, M) \tag{12}$$

The variable t_n is a complex number for selected ranges of V_n/C_n and it is either real or imaginary with the passage between the two regions yielding $t_n = 0$; t_n is imaginary if

$$\frac{1 - \sin\theta_M}{\sin\theta_M} < \frac{V_n}{C_n} < \frac{\sin\theta_M + 1}{\sin\theta_M}$$

and t_n is zero for

$$\frac{V_n}{C_n} = \left(1 \pm \sin\theta_M\right)\Big/\sin\theta_M$$

Otherwise, t_n is real.

A new impedance $\overline{Z}_n$ is now defined in terms of t_n as follows:

$$\overline{Z}_n = \frac{Z_n}{\omega^2 \rho d} = \frac{\left(\rho_n/\rho\right)S_n^2}{t_n k_M d \cos\theta_M}$$

The new input impedance is given by

$$\overline{Z}_n^{in} = \frac{S_n^2\left\{\overline{Z}_{n-1}^{in}\cos\left[t_nA\left(d_n/d\right)\right] - i(1/A)S_n^2\left(\rho/\rho_n\right)\left(1/t_n\right)\sin\left[t_nA\left(d_n/d\right)\right]\right\}}{S_n^2\cos\left[t_nA\left(d_n/d\right)\right] - i\overline{Z}_{n-1}^{in}At_n\left(\rho/\rho_n\right)\sin\left[t_nA\left(d_n/d\right)\right]} \tag{13}$$

where $A = k_M d \cos\theta_M$.

If $t_n = 0$, then limits must be taken to find the value of $\overline{Z}_n^{in}$. The appropriate limits yield

$$\overline{Z}_n^{in} = \overline{Z}_{n-1}^{in} - i\left(\rho_n/\rho\right)\left(d_n/d\right)\left(S_n^2\right) \tag{14}$$

Now, the resulting reflection and transmission coefficients are given by

$$R = \frac{\overline{Z}_{M-1}^{in} - \left(\rho_M/\rho\right)(1/A)}{\overline{Z}_{M-1}^{in} + \left(\rho_M/\rho\right)(1/A)} \tag{15}$$

and

$$T = \prod_{j=1}^{j=M-1} \frac{S_j^2\left(\rho_j/\rho\right) + At_j\overline{Z}_j^{in}}{S_{j+1}^2\left(\rho_{j+1}/\rho\right) + At_{j+1}\overline{Z}_j^{in}} \exp\left[it_jA\left(\frac{d_j}{d}\right)\right] \tag{16}$$

Assume identical media in all layers, that is, $\rho_1 = \rho_2 = \ldots = \rho_M$ and $C_1 = C_2 = \ldots = C_M$. The case of a single layer with constant velocity can be treated as a special case of the given formula.

The reflection coefficient for the special case can be shown to vanish at points of V/C for fixed incident angles θ by

$$\frac{V}{C} = \frac{1}{\sin\theta_M}\left\{1 \pm \left[\left(\frac{l\pi}{k_M d}\right)^2 + \sin^2\theta_M\right]^{1/2}\right\} \qquad (l = 1, 2, 3, \ldots) \tag{17}$$

If $l = 0$, then $t_n = 0$ and the limit process given by equation (14) must be used. Figures 2 and 3 illustrate the calculated values of the magnitudes of the reflection and transmission coefficients as functions of V/C for two values of θ.

Let the moving medium velocity now have a one-dimensional space dependence. Chosen for this example is Poiseuille's flow in which the velocity is described by the following parabolic curve:

$$\frac{V(y)}{C} = 4\left(\frac{V}{C}\right)_{max} y(1 - y) \qquad \left(0 \leqq y \leqq 1; \quad -2 \leqq \frac{V}{C} \leqq +2\right) \tag{18}$$

Let the moving medium be partitioned into three equal $\left(d_1 = d_2 = d_3\right)$ sublayers (M = 5) and the velocity in each sublayer be treated as a constant determined by the value at the midpoint of the layer. The geometry of this situation is shown in figure 4. Calculated values of the magnitudes of the reflection and transmission coefficients for the M = 5 case are shown in figures 5 and 6, respectively.

The three-equal-sublayer case (M = 5) is at best a crude approximation of the parabolic flow. Clearly, increasing the number of sublayers gives a better approximation. It appears more appropriate, however, to maintain some limiting difference between flow velocity in adjacent layers instead of a constant partition width, as has been done so far. With this new technique, a variable width partitioning was used, based on the criterion that the flow velocity difference between adjacent layers will not exceed a certain fraction of the peak flow velocity.

Two examples of this calculational refinement are presented. In the first example, the adjacent-layer velocity difference was restricted to a value ≦10 percent of the maximum velocity. The partitioning scheme is illustrated in figure 7. Note that the flow symmetry about the midstream point is preserved. The magnitudes of the reflection and transmission coefficients calculated for M = 25 are shown in figures 8 and 9, respectively. In the second example, the partitioning was refined even further by requiring that the adjacent-layer flow rates differ by ≦5 percent of the maximum flow rate. The calculated magnitudes of the reflection and transmission coefficients for the M = 45 case are illustrated in figures 10 and 11, respectively. A comparison of the results of these two examples reveals that they are almost the same, which indicates a convergence in the respective values of the reflection and transmission coefficients. It would thus appear that a criterion of $\Delta V \leqq 0.1V_{max}$ and M = 25 gives a sufficiently accurate representation of the actual flow.

DISCUSSION OF RESULTS

For the degenerate case of a single velocity layer, the magnitudes of the reflection and transmission coefficients given by equations (15) and (16) are the same as those reported in the literature (ref. 2). The graphical representations of these equations given in figures 2 and 3 agree with the zeros of $|R|$ as defined by equation (17).

The pattern of the magnitudes of the reflection and transmission coefficients exhibited in figures 5, 6, 8, 9, 10, and 11 for the cases of a partitioned y-dependent flow shows a generally similar, but distinctly different, signature from that of the case of a single constant-velocity layer. The position of zeros of $|R|$ has been altered somewhat as M is increased. For example, the zero value of $|R|$ has shifted outward to higher numerical values of $|V/C|$ for higher M values, with convergence in the highest M values. Equation (17) is not valid for any case but $M = 3$ and the method of solving for zeros of $|R|$ becomes very cumbersome for more than a single moving layer. A comparison of the results for refined partitioning with the results for the crude three-sublayer case indicates very little change in contrast to the degree of difference between the results for the single layer and multilayer cases. The difference between the two highly refined partitioned cases ($M = 25$ and $M = 45$) is hardly detectable, which indicates that the reflection and transmission coefficients have converged to their respective values at $M = 25$.

The computer solution requirements for the final equation are minimal as a result of the form in which these equations were cast. The results presented for each case in this publication represent under 45 seconds of central processing time on the Control Data 6600 computer system. Note that this processing includes three different angles of incidence and a sweep of V/C between ± 2.0 with $\Delta V/C$ of 0.01. The processing of the $M = 45$ case required a threefold increase in time over that of the $M = 5$ case.

CONCLUDING REMARKS

The reflection and transmission of acoustic waves by a medium moving with Poiseuille's flow have been treated theoretically. The moving medium was subdivided into a number of sublayers, with each sublayer having a constant velocity. The number of sublayers was allowed to increase until a saturation was achieved in the values of reflection and transmission coefficients.

With the introduction of the input impedance concept and the use of several dummy variables, the equations have been altered into a form very suitable for computer analysis.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., February 8, 1972.

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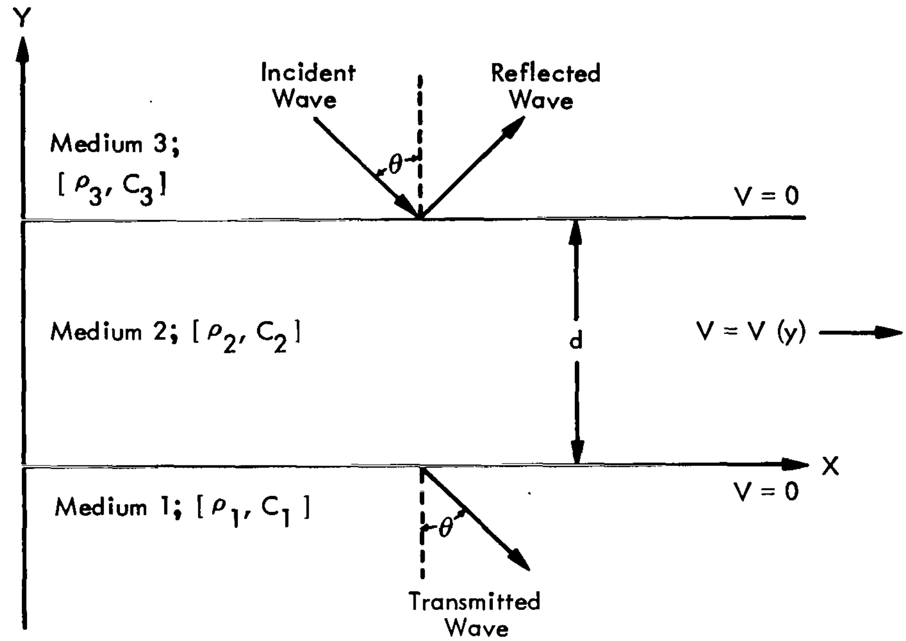

Figure 1.- Geometry of the problem.

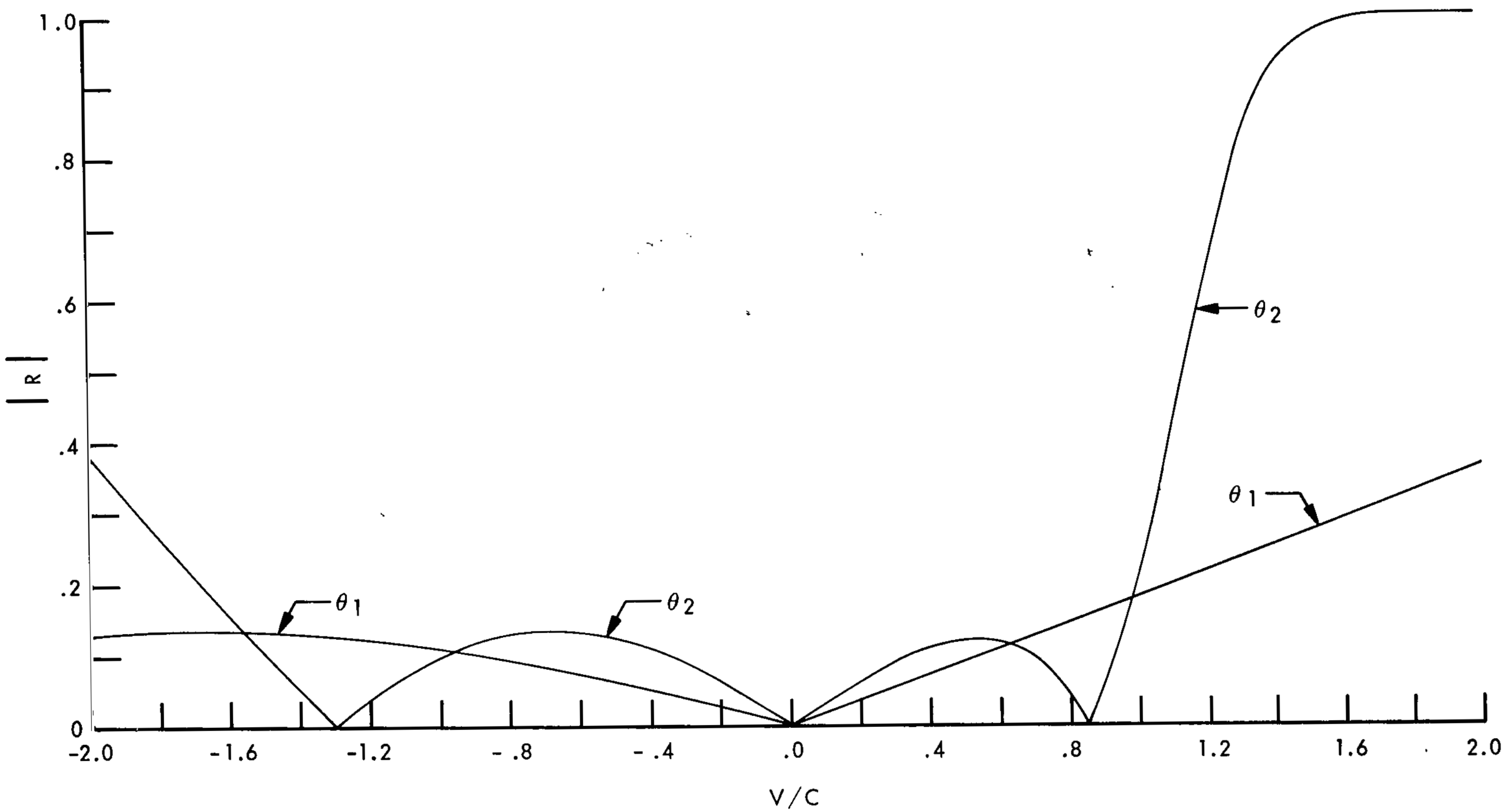

Figure 2.- Absolute values of the reflection coefficient as a function of the velocity of the moving medium for two angles of incidence. $M = 3$; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^o$; $\theta_2 = 30.0^o$.

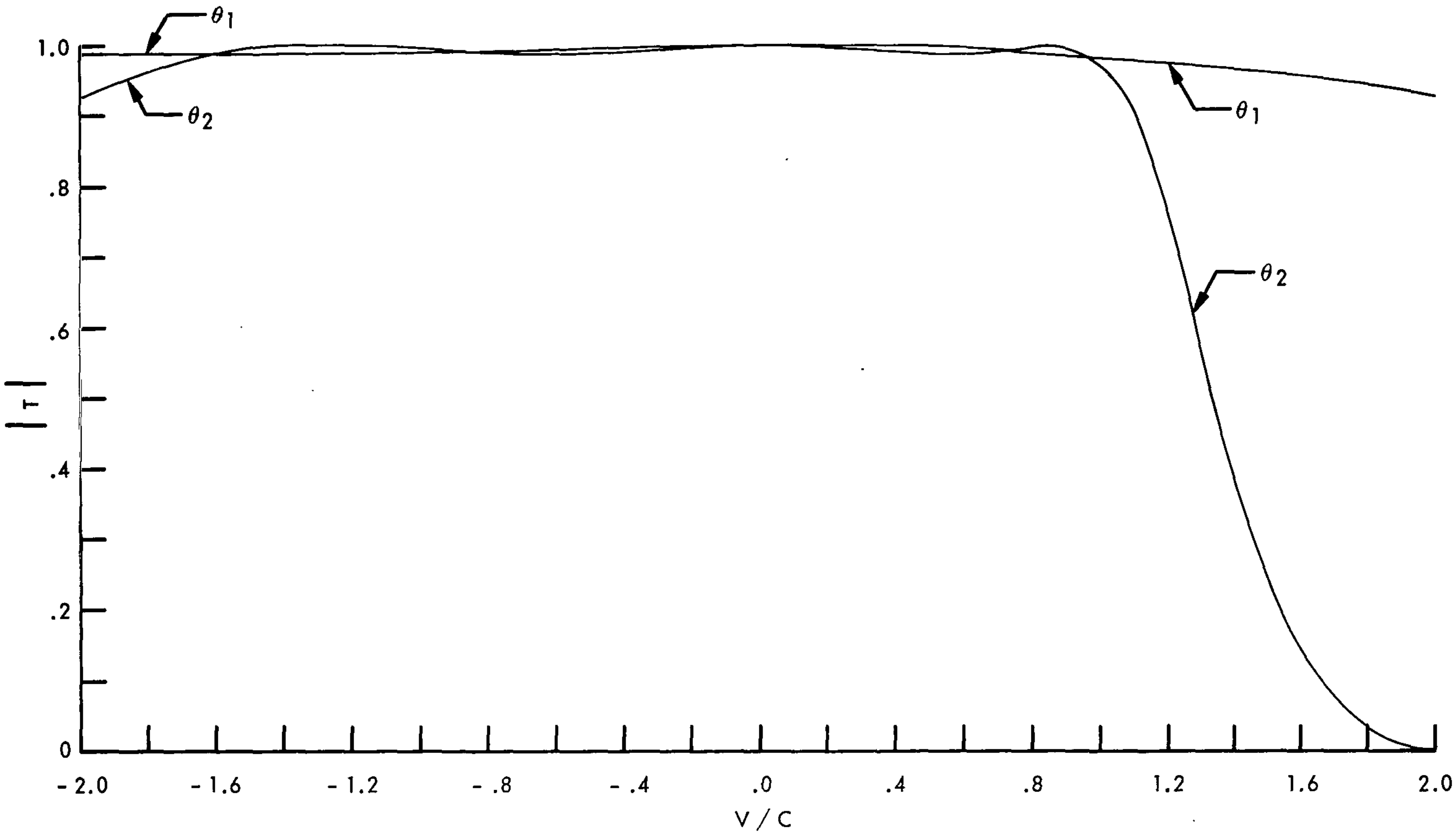

Figure 3.- Absolute values of the transmission coefficient as a function of the velocity of the moving medium for two angles of incidence. $M = 3$; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^o$; $\theta_2 = 30.0^o$.

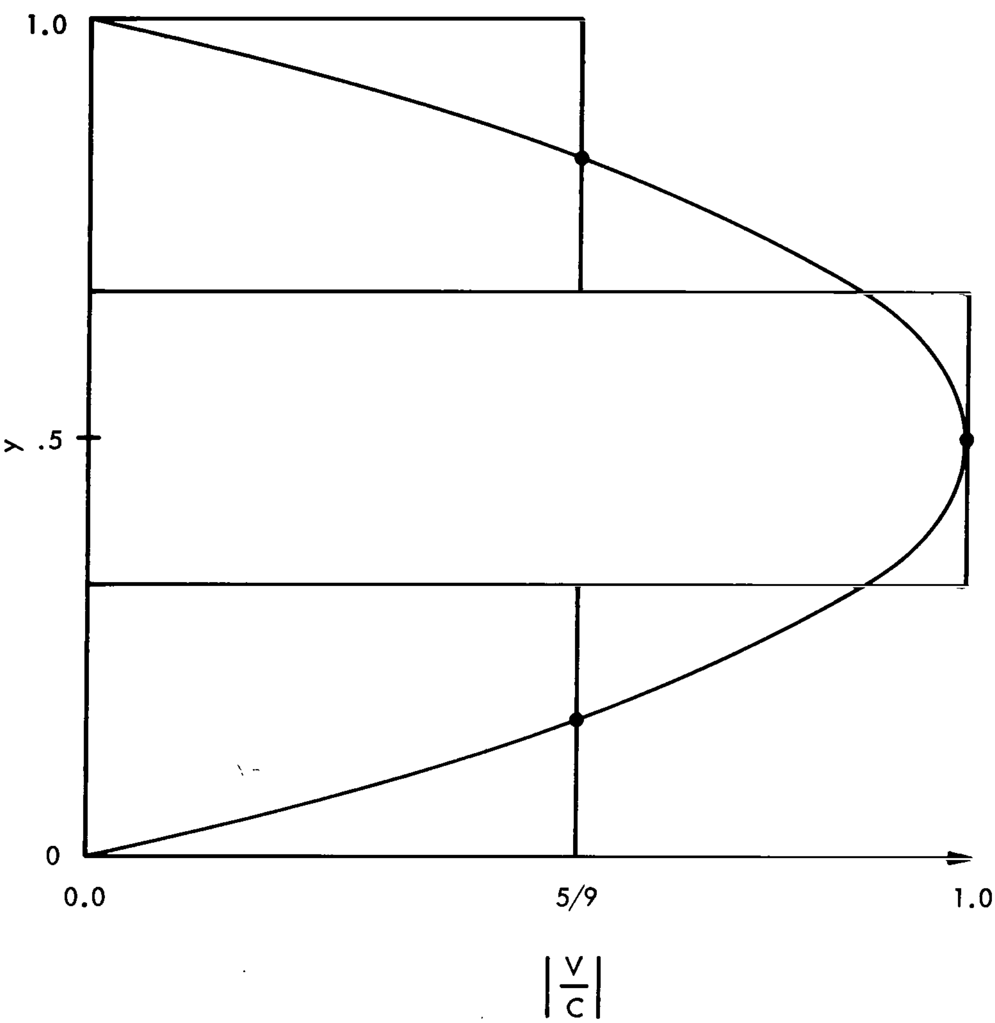

Figure 4.- Partitioning of moving medium for three sublayers.

$$\frac{V(y)}{C} = 4\left(\frac{V}{C}\right)_{max} y(1 - y) \quad \text{where} \quad y = (0 \rightarrow 1.0).$$

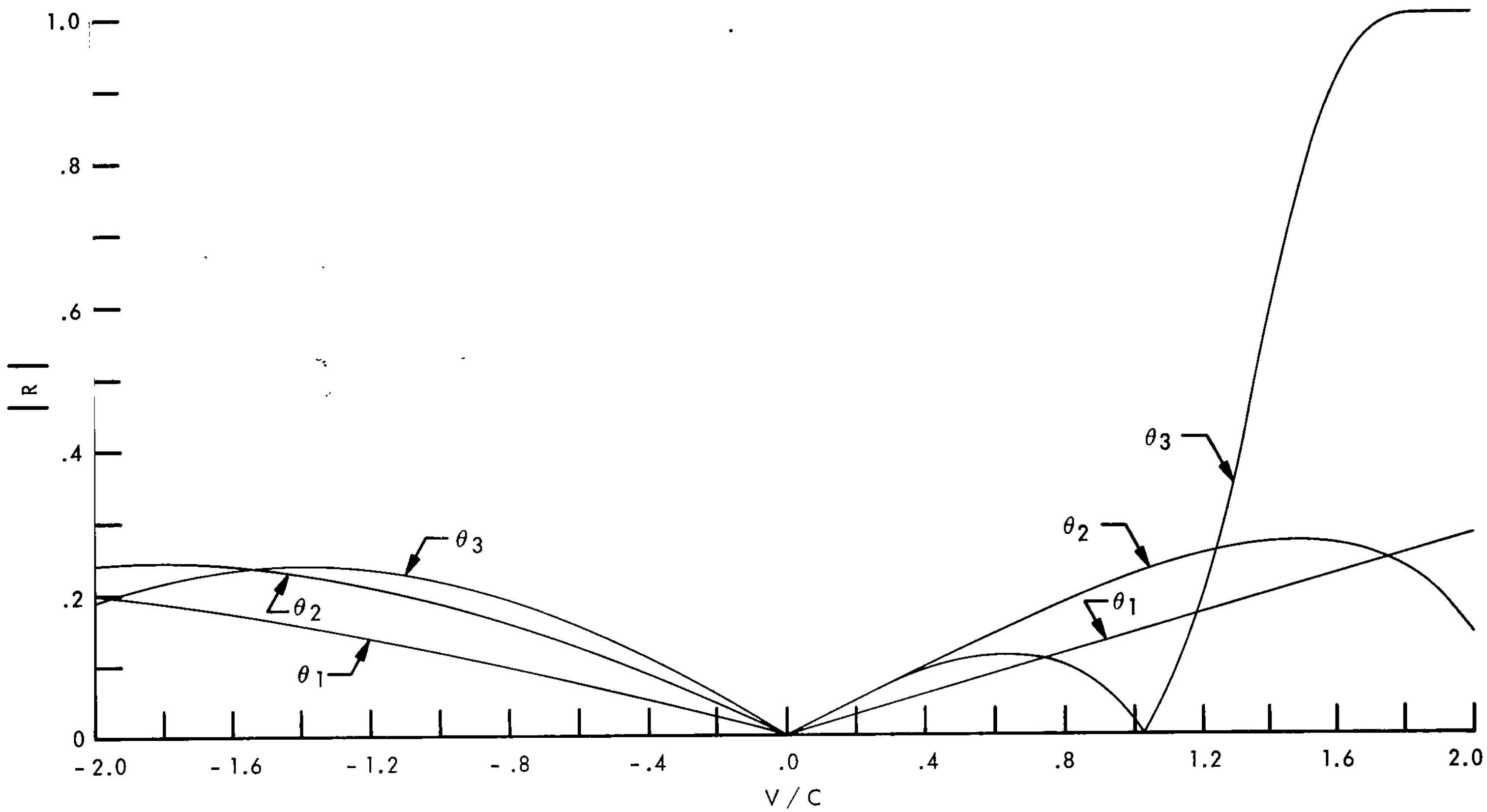

Figure 5.- Absolute values of the reflection coefficient as a function of the velocity of the moving medium for three angles of incidence. M = 5; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^{\circ}$; $\theta_2 = 20.0^{\circ}$; $\theta_3 = 30.0^{\circ}$.

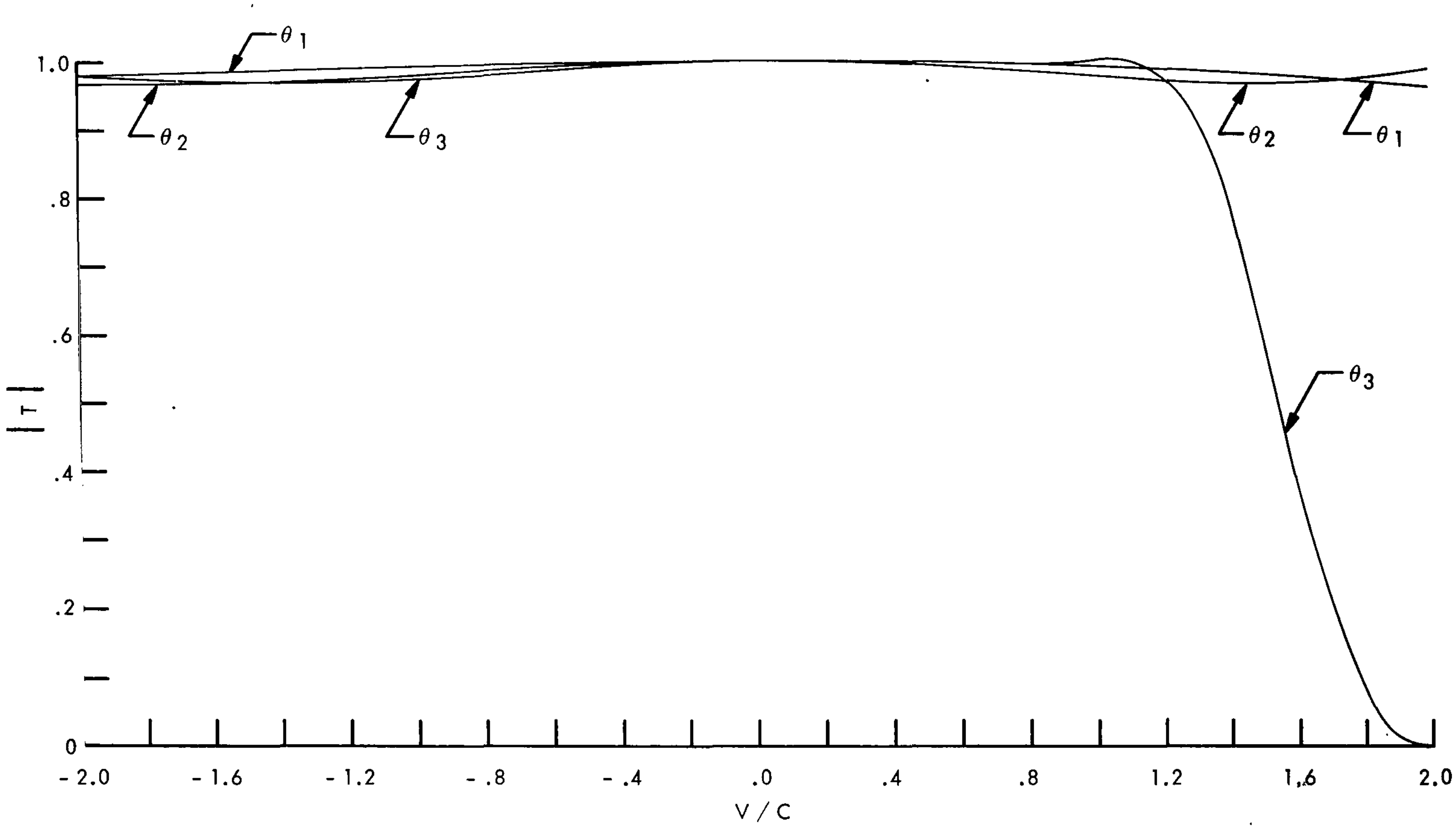

Figure 6.- Absolute values of the transmission coefficient as a function of the velocity of the moving medium for three angles of incidence. $M = 5$; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^{\circ}$; $\theta_2 = 20.0^{\circ}$; $\theta_3 = 30.0^{\circ}$.

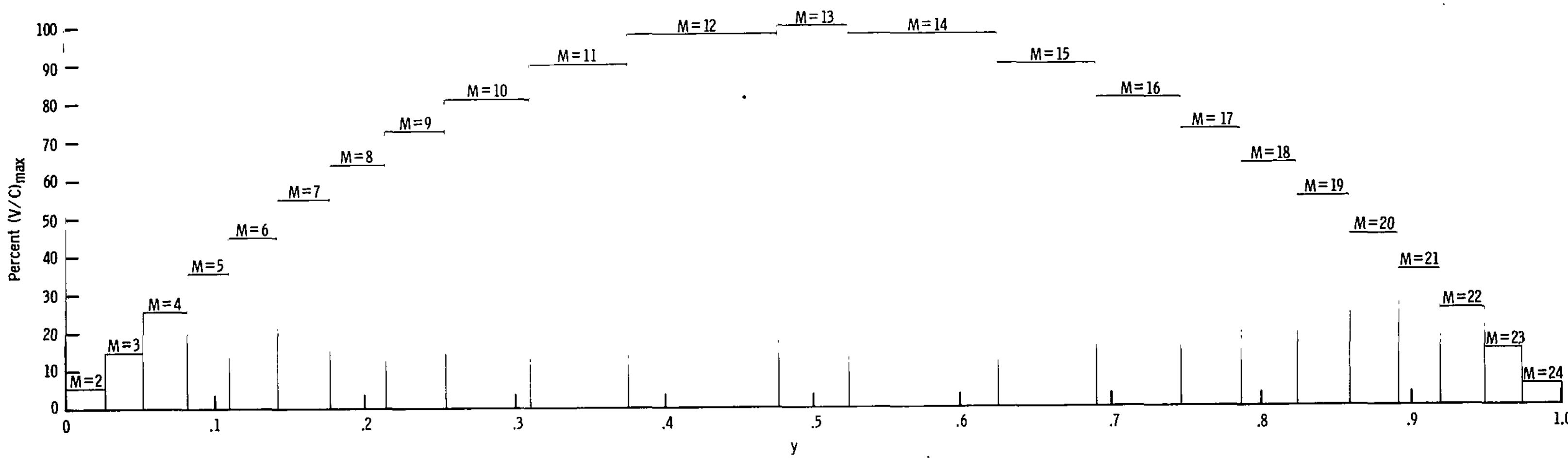

Figure 7.- Uniform velocity multilayer approximation of Poiseuille's flow (M = 25). Velocity difference between any two adjacent layers equals 10 percent of the maximum fluid flow rate.

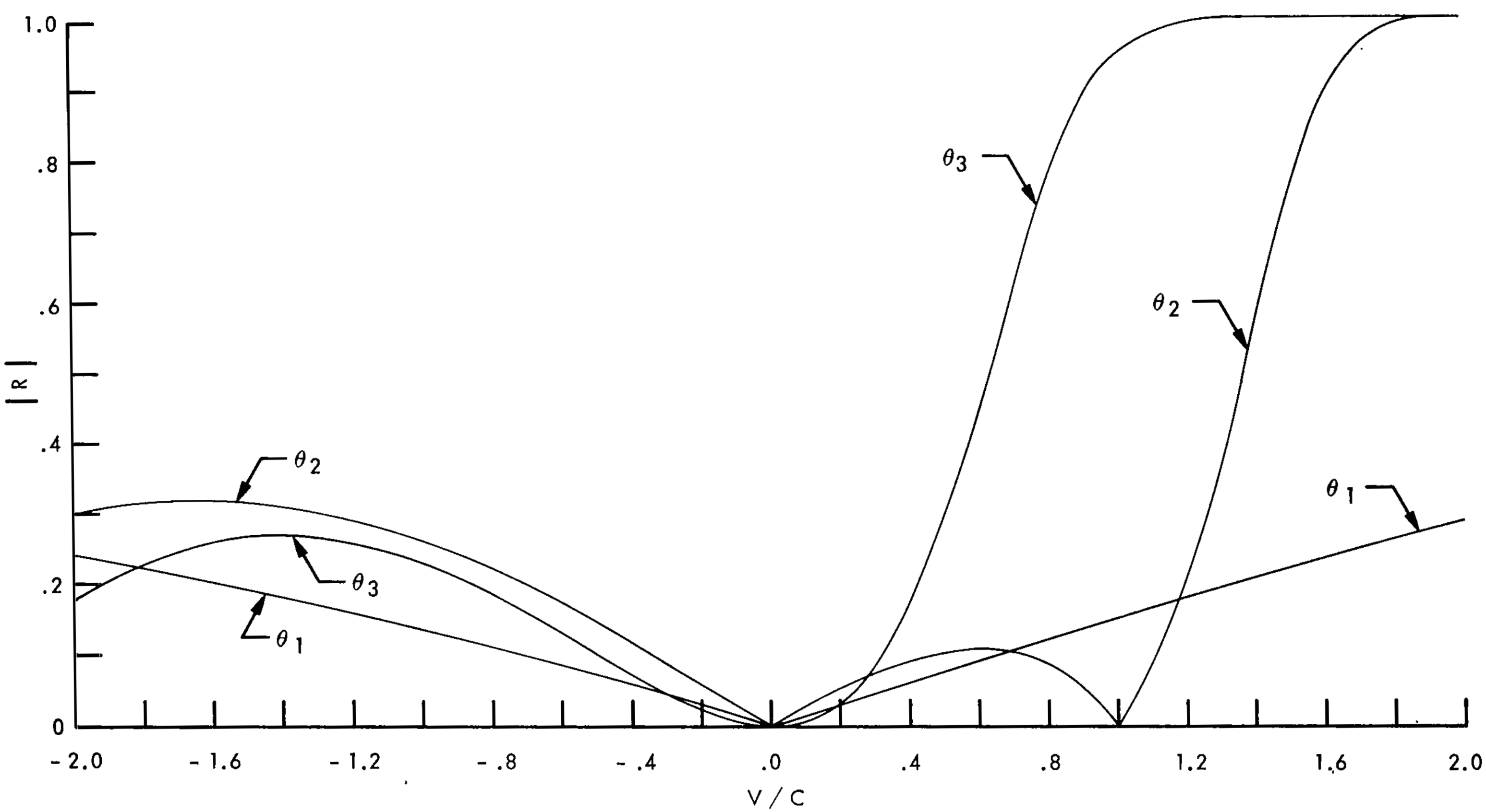

Figure 8.- Absolute values of the reflection coefficient as a function of the velocity of the moving medium for three angles of incidence. M = 25; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^o$; $\theta_2 = 30.0^o$; $\theta_3 = 45.0^o$.

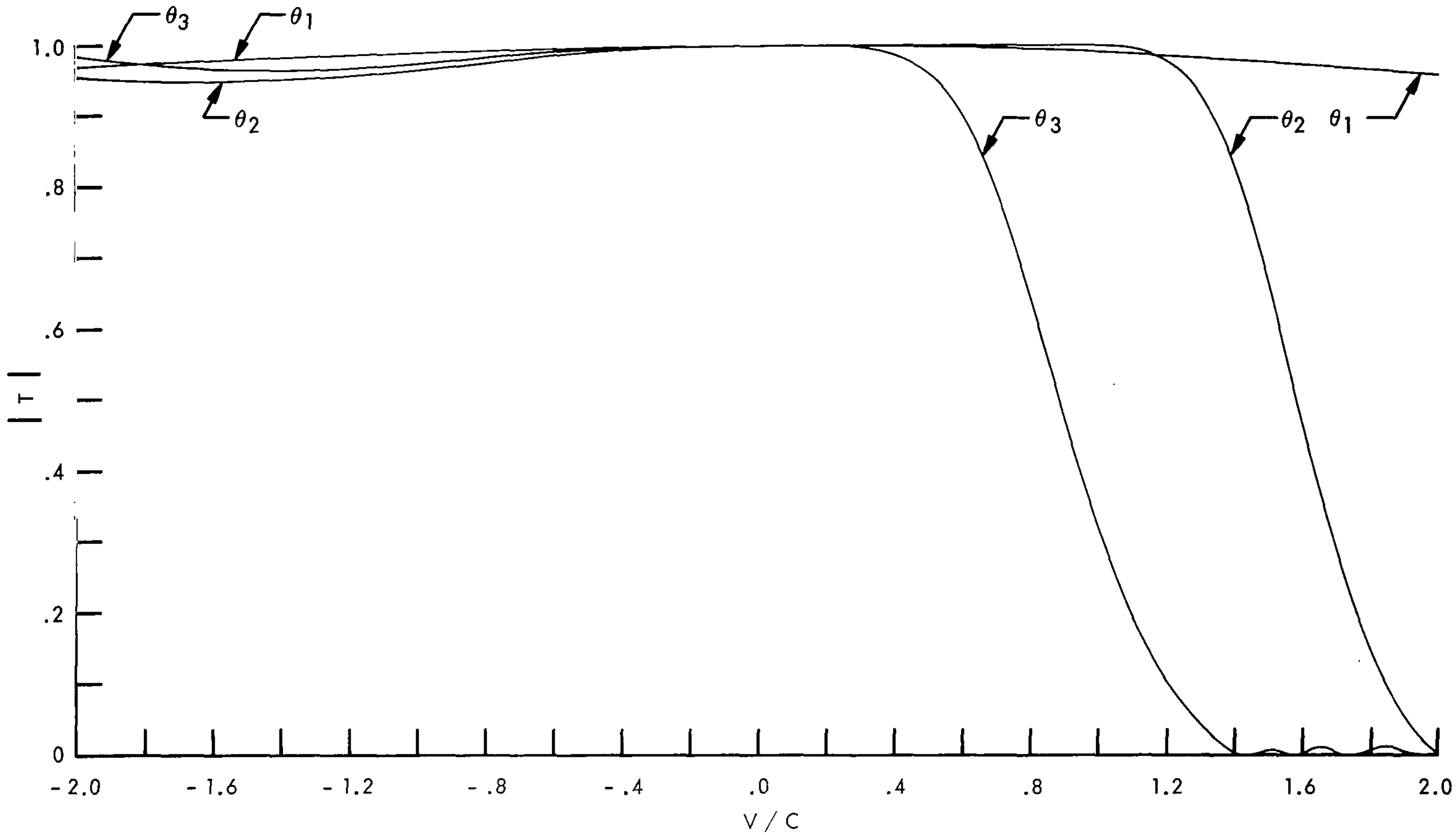

Figure 9.- Absolute values of the transmission coefficient as a function of the velocity of the moving medium for three angles of incidence. $M = 25$; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^o$; $\theta_2 = 30.0^o$; $\theta_3 = 45.0^o$.

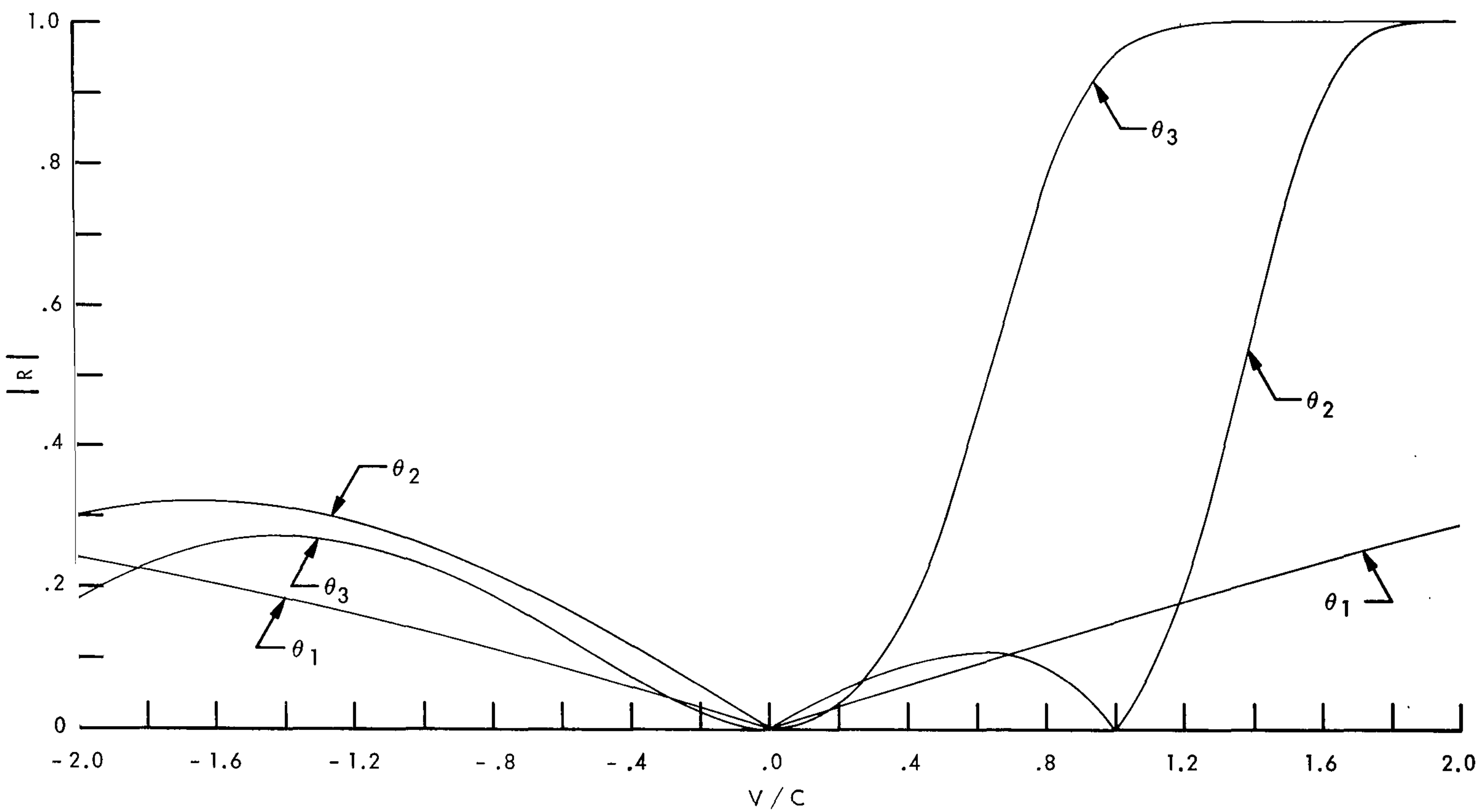

Figure 10.- Absolute values of the reflection coefficient as a function of the velocity of the moving medium for three angles of incidence. $M = 45$; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^{\circ}$; $\theta_2 = 30.0^{\circ}$; $\theta_3 = 45.0^{\circ}$.

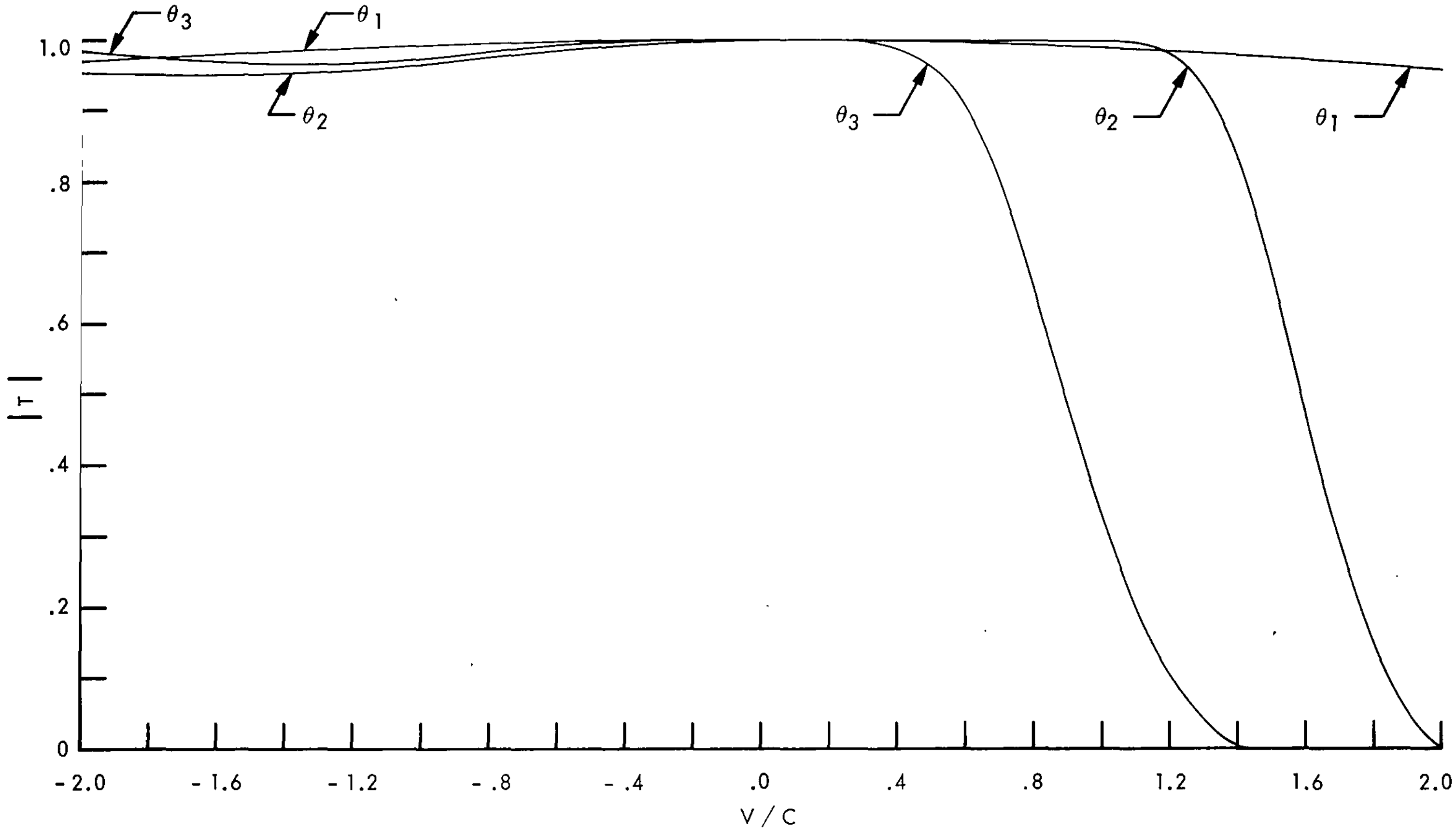

Figure 11.- Absolute values of the transmission coefficient as a function of the velocity of the moving medium for three angles of incidence. M = 45; $k_M d = 2.0$; $\rho = 1.000$; $\theta_1 = 10.0^o$; $\theta_2 = 30.0^o$; $\theta_3 = 45.0^o$.

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