UNSTEADY FLOW EFFECTS IN COMBUSTION SYSTEMS

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Some of the important results obtained recently at Caltech in Prof. Frank Marble's research group are presented here. The following research personnel at Caltech contributed to the work presented here:

Professor Frank E. Marble
Dr. Malladi V. Subbaiah
Dr. Perry Norton
Dr. Ann Karagozian

A wide variety of combustion problems, including combustion instabilities and turbulent diffusion flames, appear to involve the entrainment and deformation of laminar flames by large vortex structures in the flow field. First, we examine some details of this process of laminar flame distortion by considering the interactions of time-dependent diffusion flames with two-dimensional vortices (Figs. 1 & 2). For large values of the circulation Γ/D, the augmentation of the fuel consumption due to the vortex is proportional to $\rho\Gamma^{2/3}D^{1/3}$. When the effects of finite chemistry are included, the increase of fuel consumption rate is governed by a time scale which depends on the chemical reaction time, t_{ch} (Fig. 3). If the products of combustion occupy more volume than the original reactants, the spiral flame will appear as an unsteady volume dilatation for times on the order of chemical time. This acts as an acoustic source and the interaction of a vortex and diffusion flame results in the generation of a pressure pulse. The peak pressure is proportional to $\Gamma^{2/3}D^{1/3}/\sqrt{t_{ch}}$ and occurs after a delay proportional to the chemical time, t_{ch}. The results provide the fundamental structure for the mechanism of instability proposed by Rogers and Marble (1956) (Figs. 4-7).

In the second part of the presentation, some results on the modelling of the non-steady combustion in burners for aircraft gas turbines will be given. The general aim of the work is to develop a one-dimensional model applicable to the NASA-Lewis Non-Steady Combustion Rig. In the present discussion, we emphasize the results of the non-steady flame model, which constitutes an important module in the over all description of the system.

In an earlier investigation, a detailed model for the non-steady response of a stabilized flame in a two-dimensional duct was developed using a flame sheet description. The results showed active response by the flame region at certain well-defined frequencies and suggest a possible mechanism of low frequency instability in a combustion system.

The present model for combustion processes utilizes a two-phase combustion model which treats the flame zone as an ensemble of pockets of unburned gas and combustion products. The steady state flame development is shown in Figures 8-11. This steady state solution is perturbed by an imposed acoustic wave approaching the flame region from either the downstream or upstream region. The spectra of the reflection and transmission coefficients are shown in Figures 12-15.

Selected References:

1) Rogers D.E. and Marble F.E., A Mechanism for High Frequency Oscillations in Ramjet Combustors and Afterburners, Jet Propulsion, 26, 456-462.

2) Marble F.E., Subbaiah M.V. and Candel S.M., Analysis of Low-Frequency Disturbances in Afterburners, Proceedings, Specialists Meeting on Combustion Modelling, AGARD Propulsion and Energetic Panel, Cologne, 1979.

3) Subbaiah M.V., Non-Steady Behavior of Flame Spreading in a Two-Dimensional Duct, AIAA-81-1348, AIAA/SAE/ASME 17th Joint Propulsion Conference, July 27-29, 1981.

4) Subbaiah M.V., Non-Steady Behavior of a Flame Spreading from a Point in a Two-Dimensional Duct, Ph.D. Thesis, Caltech, Pasadena, May 1980.

5) Karagozian A.R., An Analytical Study of Diffusion Flames in Vortex Structures, Ph.D. Thesis, Caltech, Pasadena, May 1982.

6) Norton, O.P., The Effects of a Vortex Field on Flames with Finite Reaction Rates, Ph.D. Thesis, September 1982.

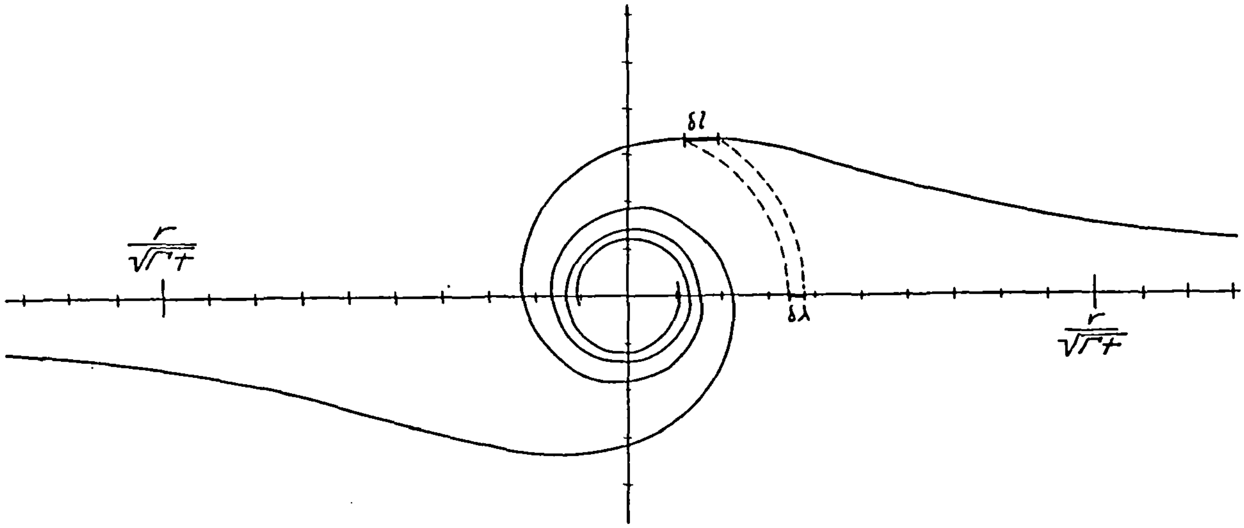

Figure 1 An initially flat flame has been wound into a spiral by a vortex; in this case the vortex is located on the flame sheet. Locally, a piece of the flame initially of length $\delta\lambda$ has been elongated to length δl. Note the similarity present in the vortex structure, the vortex grows with time as $\sqrt{\Gamma t}$.

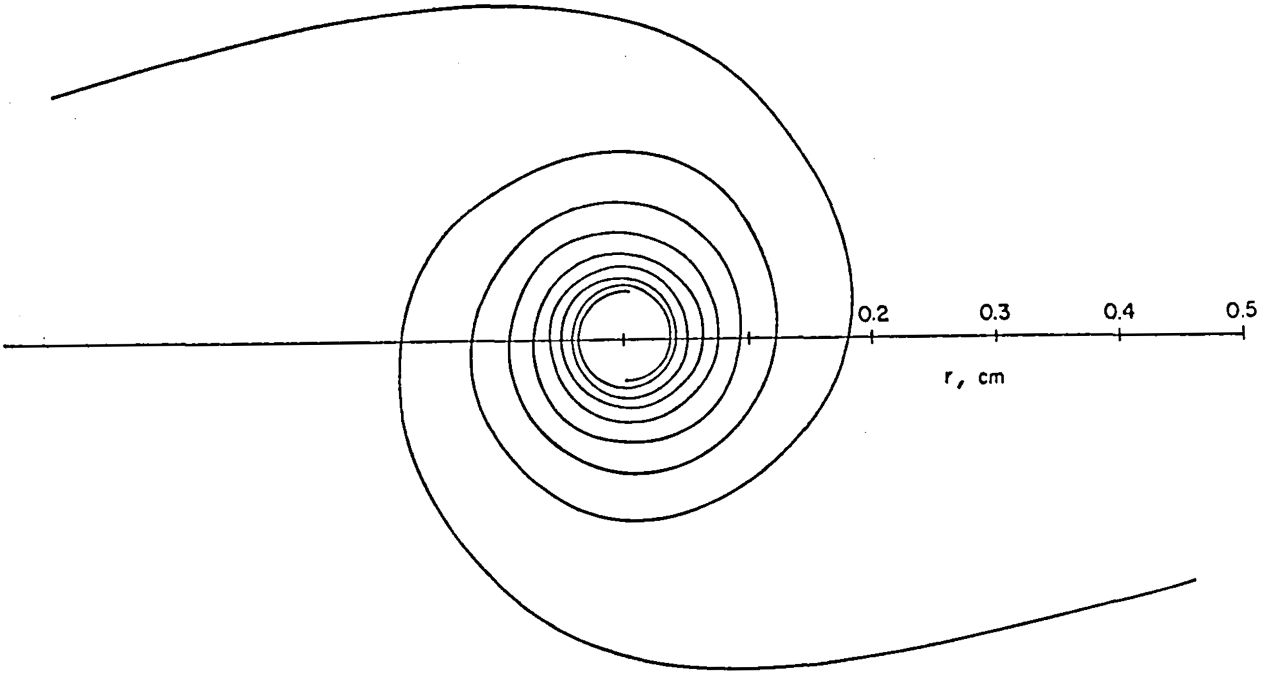

Figure 2. Core Region of Distorted Flame Sheet, $\Gamma/2\pi\nu = 40$, $\sqrt{4\nu t} = 0.1$ cm.

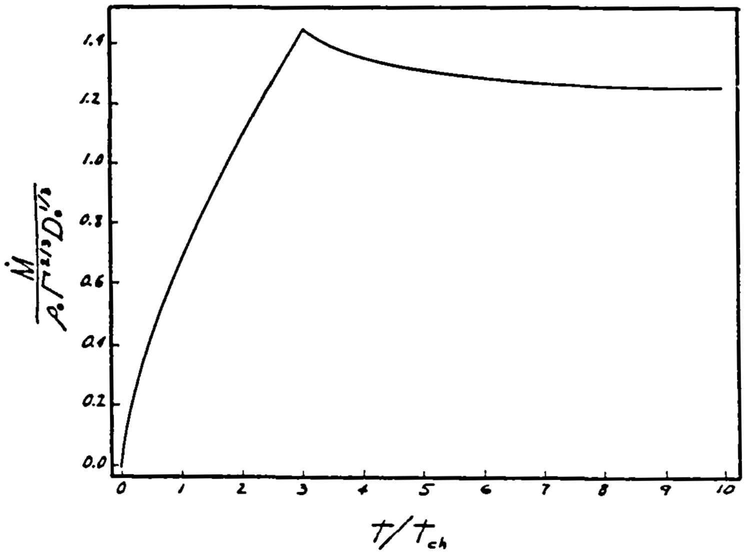

Figure 3 Here $\dot{M}$, the augmented fuel consumption rate of the flame due to the presence of the vortex, is made dimensionless by $\rho_0\Gamma^{2/3}D_0^{1/3}$ and shown as a function of t/t_{ch}.

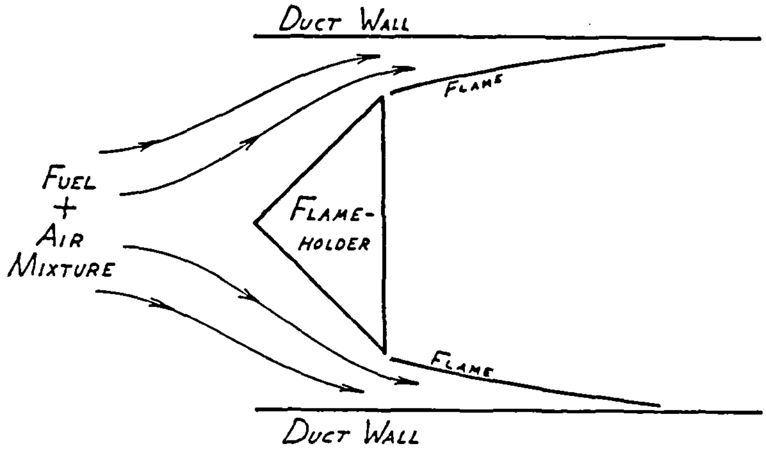

Figure 4 An idealized representation of the experimental setup of Rogers and Marble (1956). A condition of steady burning is shown here.

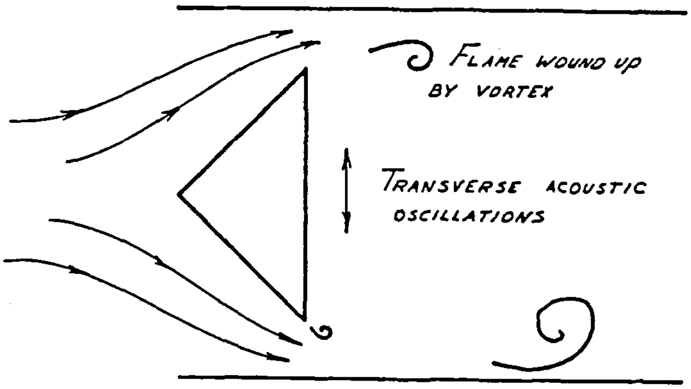

Figure 5 The same configuration as the previous figure, only under screeching conditions. The unstable oscillations corresponded to the transverse mode of the combustion chamber, thus the acoustic oscillations are from top to bottom in this figure. The flame sheets are wound up by vortices alternately shed from the top and bottom of the flameholder.

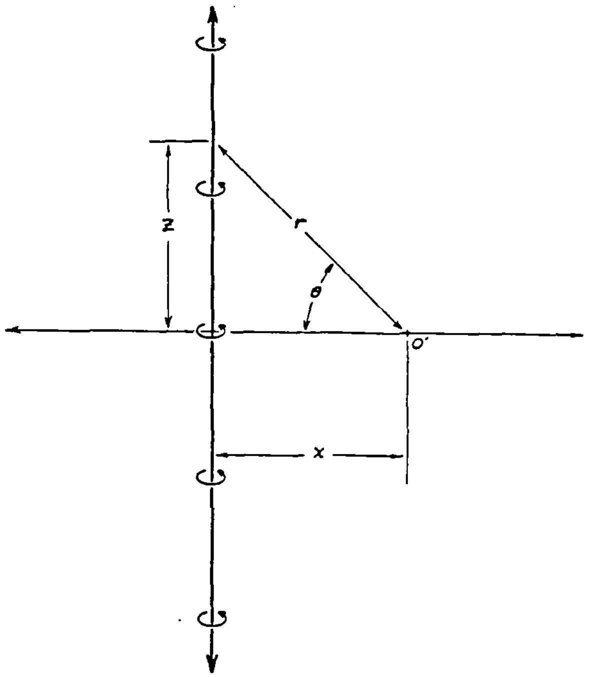

Figure 6 To calculate the two-dimensional acoustic field caused by the spiral flame, one imagines the spiral flame occupying the z axis in a three-dimensional region, and an observer at O', a distance x from the spiral flame. The pressure pulse at O' can be obtained by superimposing the pressure pulses from a line of three- dimensional sources distributed along the z axis.

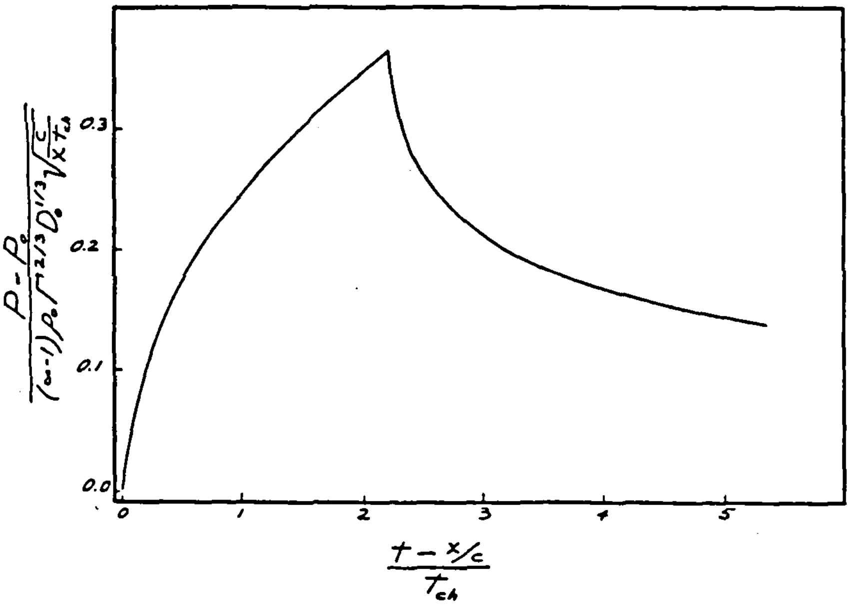

Figure 7 The pressure pulse seen at a distance x from the vortex, when x is large enough to lie in the far field, is given by equations 7.8. Here the pressure rise, $P - P_0$, made dimensionless by $(\alpha - 1)\,\rho_0\Gamma^{2/3}D_0^{1/3}\,\sqrt{c/(xt_{ch})}$ is plotted as a function of $(t - x/c)/t_{ch}$.

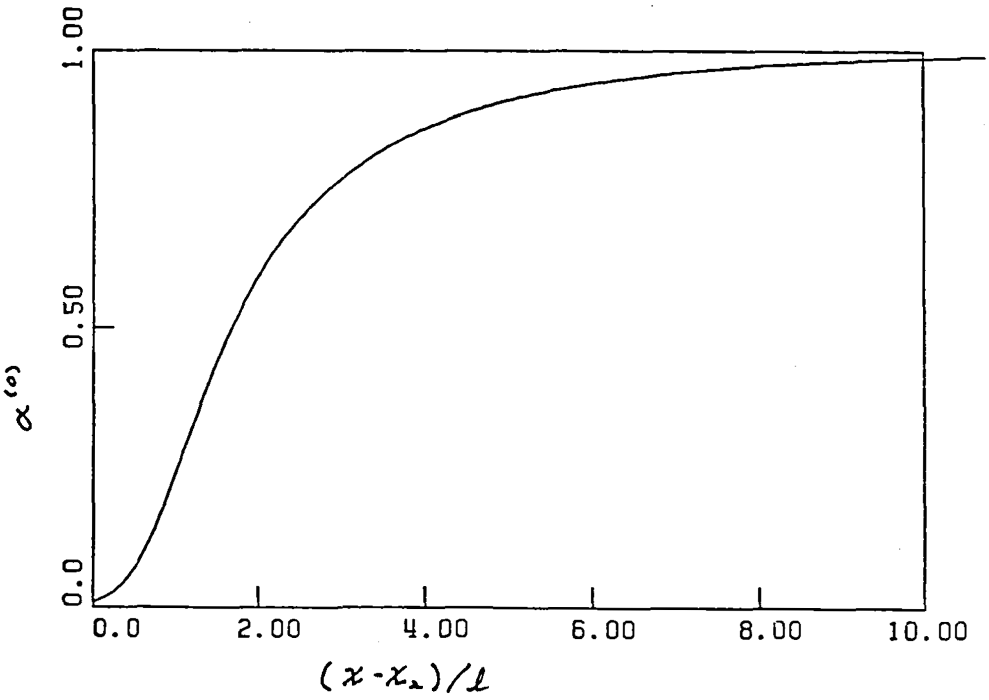

Figure 8 Distribution of Combustion Products, Steady Flow

w_1/a_1 = 0.02, ρ_1/ρ_2 = 4.5.

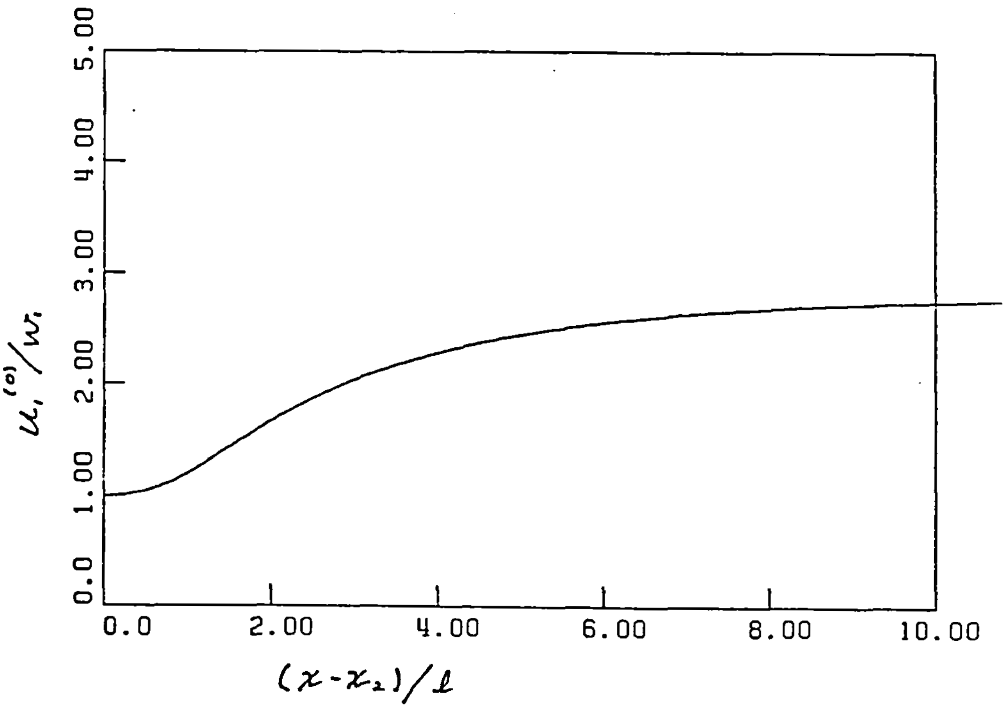

Figure 9. Velocity Distribution of Combustible Mixture, Steady Flow.

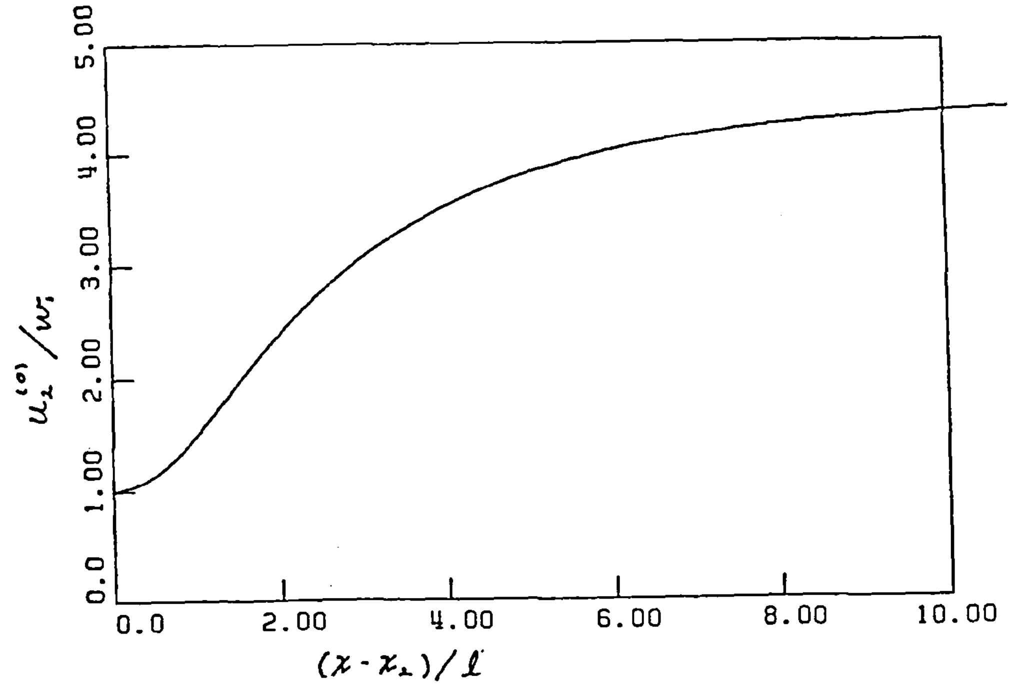

Figure 10 Velocity Distribution of Combustion Products, Steady Flow.

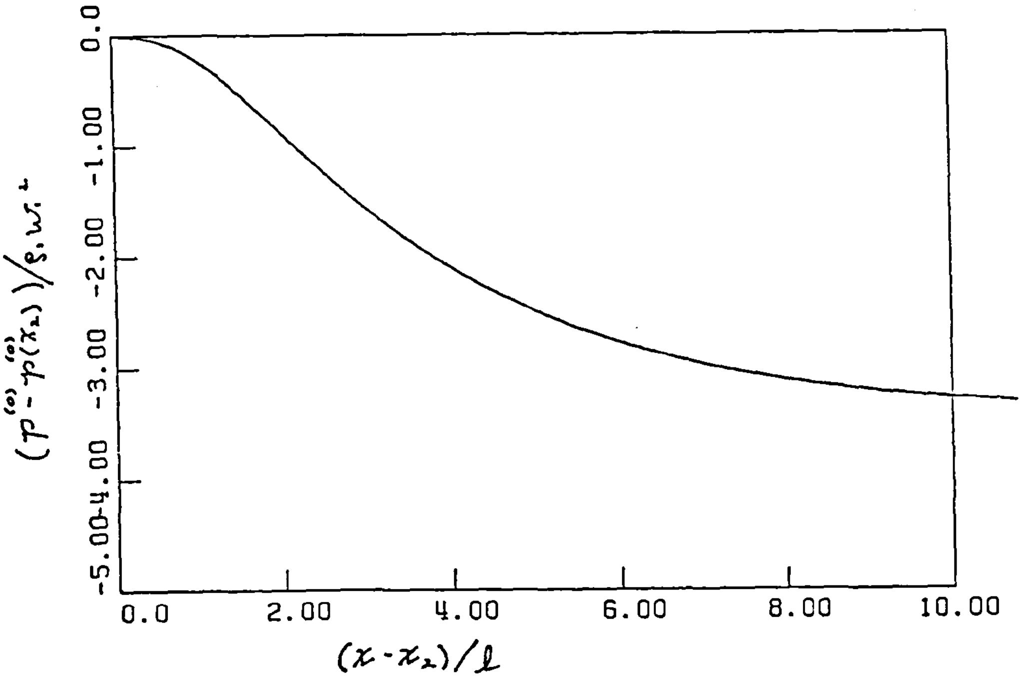

Figure 11 Pressure Distribution, Steady Flow.

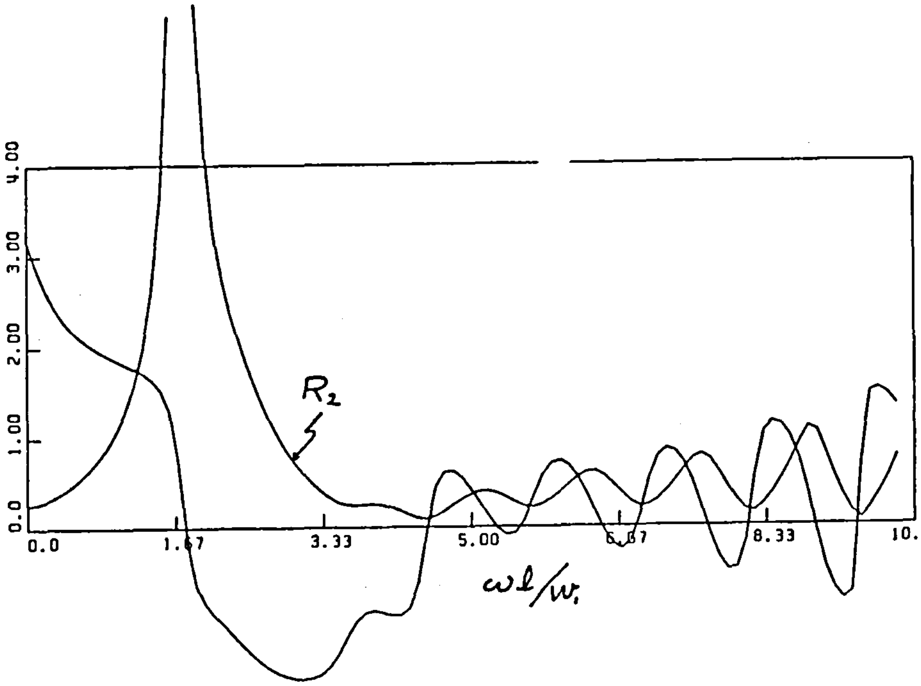

Figure 12 Pressure Wave Reflection Coefficient, R_2, Wave From Downstream.

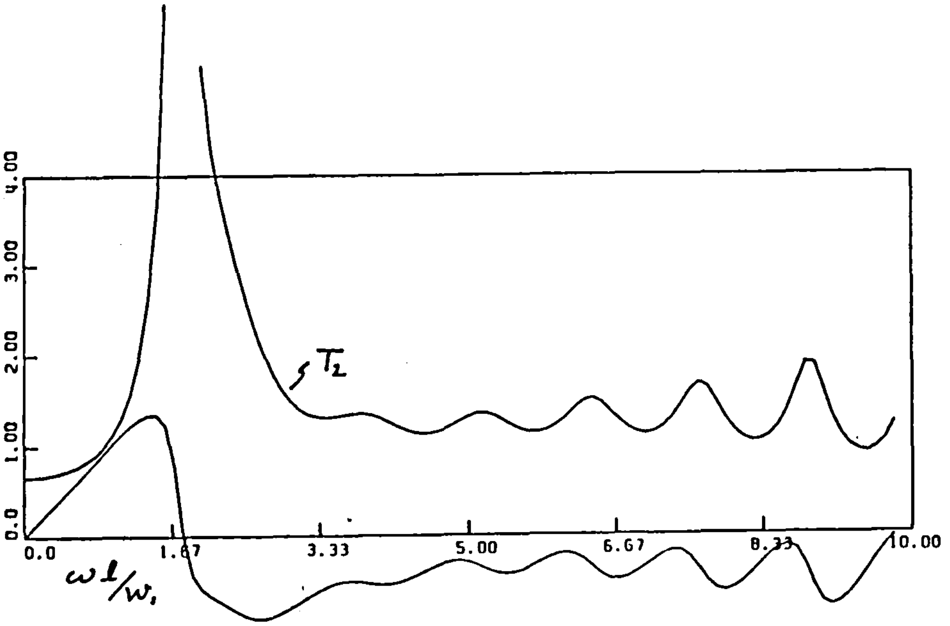

Figure 13 Pressure Wave Transmission Coefficient, T_2, Wave From Downstream.

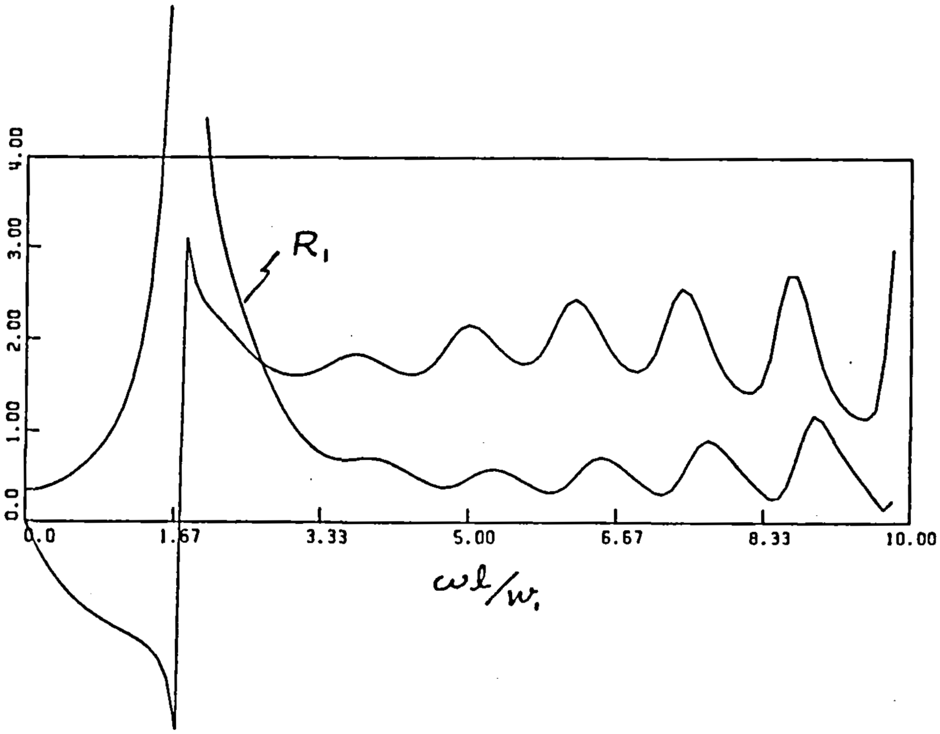

Figure 14 Pressure Wave Reflection Coefficient, R_1, Wave From Upstream.

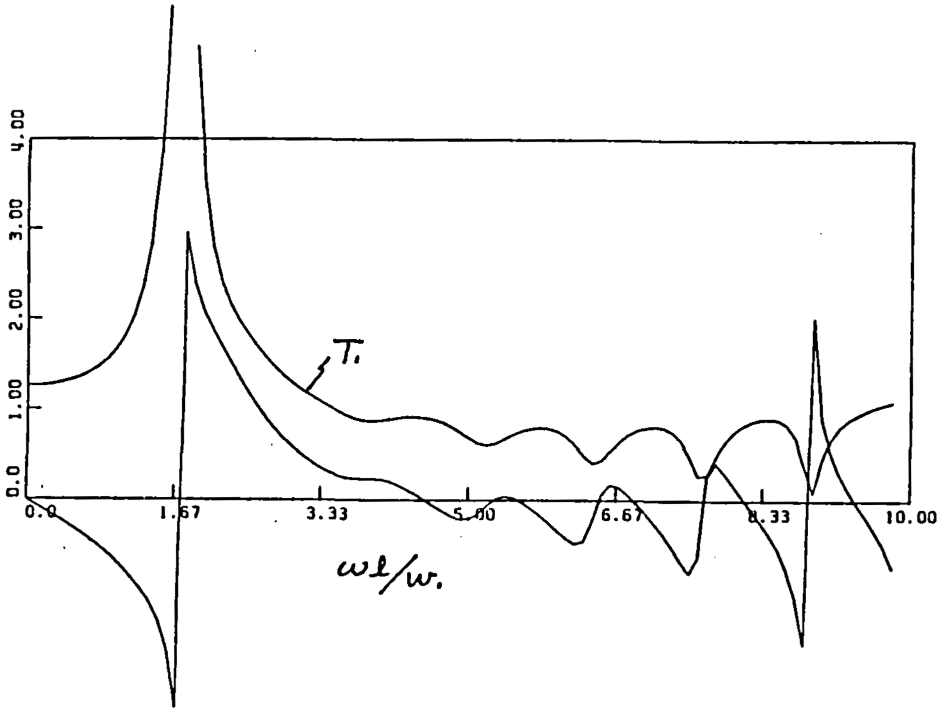

Figure 15 Pressure Wave Transmission Coefficient, T_1, Wave From Upstream.