



## **SDSU – AE&EM TR 83-01**

# Effect of an Inhomogeneous Transition Layer on the Response of a Compliant Layer Due to a Shear Fluid Disturbance

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January 1983

Research Sponsored by Office of Naval Research under Contract N00014-81-K-0424

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ABSTRACT

The amount of interaction between a fluid and a compliant coating is studied for a one dimensional shear fluid disturbance. A thin inhomogeneous viscoelastic layer is located at the interface between the fluid and the coating. The fluid is assumed to have no mean flow field. The effect of different coating properties, thickness of compliant coating and of transition layer as well as the frequency of oscillations are analyzed.

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#### I. INTRODUCTION

The drag of a body can be decreased by a compliant coating only if a considerable amount of interaction exists between the fluid and the coating. The coating has to be able to be excited by a fluid disturbance and, in turn, the coating disturbance has to change the characteristics of the fluid disturbance in such manner as to decrease the overall drag of the body.

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In typical applications, the flow field will have either a laminar or a turbulent boundary layer. For low Reynolds numbers (air application), the boundary layer will typically be laminar whereas for high Reynolds numbers (underwater application) the boundary layer will be turbulent. The interaction phenomenon required for drag reduction may be totally different in the two cases. The drag of a body with a laminar boundary layer will consist mostly of the drag due to skin friction. The drag of the same body but with a turbulent boundary layer will, however, be influenced the most by the magnitude of the Reynolds turbulent stresses. The drag due to the laminar sublayer is always smaller than the drag due to the normal Reynolds stresses acting on a wavy wall (fig. 1).

In order to properly model the fluid-structure interaction, as represented by the flow fields discussed above, two types of fluid disturbance should be analyzed: shear disturbance and normal (or longitudinal) disturbance. The shear disturbance will serve to simulate the interaction of the fluid

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with the coating for either the laminar boundary layer case or the laminar sublayer underneath the turbulent boundary layer. The longitudinal (or acoustic) disturbance result will be used to model the interaction between the Reynolds turbulent stresses and the compliant surface.

The parameters which govern the local properties of a one dimensional medium can be taken to be the density and the local wave speed of the medium. A disturbance traveling in a given direction will be partially reflected whenever a discontinuity in the properties of the medium exist. The interface between a coating and a fluid is an example of a medium discontinuity. If the effect of the discontinuity could be ameliorated then the reflection and the transmission of energy from one medium to another could be changed. A transition layer which spreads out the discontinuity between the two media, in a gradual manner, can be expected to increase the magnitude of the interaction between the two media. The properties of the transition layer may vary continuously from that of a solid on one side to that of a fluid on the other side. Alternatively, the transition layer may be assumed to be an equivalent layer whose properties are determined by the overall local motion of the surface of the coating (Fig.(2)). The transition layer will thus exhibit the properties of an inhomogeneous layer with continuously varying properties (Fig. (3)). Thus the transition layer can either be designed as part of the compliant coating or it can be thought to be an integral part of the coating with the mean transition layer properties due mainly to the

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inability to properly identify the location of the interface being forced in a random manner by the turbulence; in this context, then the transition layer will acquire average properties of the solid and the fluid and the actual magnitude of the properties will depend upon the average of the spacetime history of the surface motion at each location.

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In the two previous reports,1,2 the distribution of both shear and normal disturbances, due to a disturbance at the bottom of the compliant coating were studied (Fig. (4)). The results indicated that the transmission of shear disturbances into the fluid can be altered considerably by the presence of a thin transition layer.<sup>1</sup> For the same conditions, longitudinal (or normal) wall disturbances will be affected by the transition layer in a much reduced manner.

Pedersen et al<sup>3</sup> have shown that an inhomogeneous layer with an exponentially varying impedance at the interface varying from that of a solid to that of a fluid increases the acoustic energy transmitted from the solid into the fluid.

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#### II. ANALYSIS

The analysis consists of the derivation of the governing equations for the fluid, the elastic solid and the transition layer and the numerical technique utilized to integrate the resulting differential equations.

II.1 Fluid

Consider a one dimensional fluid disturbance located at a distance h from the lower wall (Fig (3)). The equations governing the fluid motion, in its most general form are the Navier-Stokes equations and the continuity equation.

$$p \frac{Dv_1}{Dt} = \frac{\partial \tau_{11f}}{\partial x} + \frac{\partial \tau_{12f}}{\partial y} , \qquad (1)$$

$$\rho \frac{Dv_2}{Dt} = \frac{\partial \tau_{21f}}{\partial x} + \frac{\partial \tau_{22f}}{\partial y} , \qquad (2)$$

$$\frac{D\rho}{Dt} + \rho \left(\frac{\partial v_1}{\partial x} + \frac{\partial v_2}{\partial y}\right) = 0 , \qquad (3)$$

where  $\frac{D}{Dt}$  is the material derivative and is given by

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + v_1 \frac{\partial}{\partial x} + v_2 \frac{\partial}{\partial y} . \qquad (4)$$

 $v_1$  and  $v_2$  are the local fluid velocities in the x and the y

direction respectively and  $\rho_f$  is the fluid density. The fluid stresses  $\tau_{11f}$ ,  $\tau_{12f}$ ,  $\tau_{21f}$  and  $\tau_{22f}$  are given by

$$\tau_{11f} = -p + \mu \left[ \frac{4}{3} \frac{\partial v_1}{\partial x} - \frac{2}{3} \frac{\partial v_2}{\partial y} \right] , \qquad (5)$$

$$\tau_{12f} = \tau_{21f} = \mu \left[ \frac{\partial v_1}{\partial y} + \frac{\partial v_2}{\partial x} \right] , \qquad (6)$$

$$^{\tau}22f = -p + \mu \left[-\frac{2}{3} \frac{\partial v_1}{\partial x} + \frac{4}{3} \frac{\partial v_2}{\partial y}\right] \qquad (7)$$

where  $\boldsymbol{\mu}$  is the fluid viscosity.

For a one dimensional fluid shear distrubance, the  $v_2$ component of velocity term will be zero. If the fluid disturbance is assumed to vary sinusoidally in time,

$$v_1 = v_1 \exp(-i\omega t) , \qquad (8)$$

then the governing equation reduces to

$$\frac{d}{dy}\left(\mu\frac{dv_{1}}{dy}\right) + i\rho_{f}\omega v_{1} = 0 \qquad (9)$$

II.2 Solid

The fluid disturbance will propagate from its source to the fluid-solid interface, where the no slip condition and the

continuity of stress will cause the disturbance to propagate into the fluid.

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The generalized equations for the motion of the solid are the Navier equations:

$$\rho_{s} \frac{\partial^{2} u_{1}}{\partial t^{2}} = \frac{\partial \tau_{11s}}{\partial x} + \frac{\partial \tau_{12s}}{\partial y} , \qquad (10)$$

$$P_{s} \frac{\partial^{2} u_{2}}{\partial t^{2}} = \frac{\partial^{\tau} 21s}{\partial x} + \frac{\partial^{\tau} 22s}{\partial y} , \qquad (11)$$

where  $\rho_{\rm S}$  is the density of the material. The solid particle displacements in the x and the y direction are u<sub>1</sub> and u<sub>2</sub> respectively. The solid stresses are linearly related to the particle displacements u<sub>1</sub> and u<sub>2</sub>,

$$\tau_{11s} = \frac{2G}{1-2\nu} \left[ (1-\nu) \frac{\partial u_1}{\partial x} + \nu \frac{\partial u_2}{\partial y} \right], \qquad (12)$$

$$\tilde{\tau}_{12s} = \tau_{21s} = G \left[ \frac{\partial u_1}{\partial y} + \frac{\partial u_2}{\partial x} \right] , \qquad (13)$$

$$\tau_{22s} = \frac{2G}{1-2\nu} \left[ \nu \frac{\partial u_1}{\partial x} + (1-\nu) \frac{\partial u_2}{\partial y} \right], \qquad (14)$$

where G is the shear modulus and v is Poisson ratio. In general G will be a real number if the solid is purely elastic and a complex number if the material has damping properties.

If the fluid disturbance is a shear vibration and is independent of its x location then the solid will, by necessity, vibrate in a similar fashion; thus equations 10-14 are combined into an ordinary differential equation

$$\frac{d}{dy} \left( G \frac{du_1}{dy} \right) - \rho_s \omega^2 = 0 .$$
(15)

For an inhomogeneous viscoelastic medium, the shear modulus G will be a complex function of y.

#### II.3 Unified Theory

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The differential equation governing the fluid motion (Eq. 9) and the equation governing the solid motion (Eq. 15) are seen to be very similar. For a fluid disturbance with no mean flow field, the fluid disturbance velocity  $v_1$  is related to the particle displacement  $u_1$  by

$$\mathbf{v}_1 = -\mathbf{i}\omega\mathbf{u}_1 \qquad (16)$$

The vibration of the fluid-solid system can be combined into a unified equation given by

$$\frac{d}{dy} \left( K \frac{du_1}{dy} \right) + \rho \omega^2 u_1 = 0 \quad . \tag{17}$$

The parameter K is given by

 $G \qquad \text{solid} \\ K = (18) \\ -i\omega \mu \qquad \text{fluid},$ 

and the density  $\rho$  is either the solid or the fluid density. The transition layer interposed between the fluid and the solid will be assumed to vary exponentially from the shear modulus G on one side to the fluid viscosity  $\mu$  on the other. The

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discontinuous parameter K can thus be written as

$$K(y) = -i\mu\omega + [G + i\mu\omega] \exp(-y/l)^n$$
. (19)

For values of y close to the inner wall, the elastic solid properties are recovered and for values of y far removed from the interface region (i.e. y >> l), the fluid properties are obtained. In equation 19, l is the nominal thickness of the compliant coating and n is inversely related to the thickness of the transition layer. In the limit as  $n+\infty$ , the thickness of the transition layer approaches zero and the classical elastic-solid-viscous-fluid equations are recovered.

Equations (17) and (19) can be re-cast in dimensionless form and become

$$\frac{d}{dy} \left( H \frac{du_1}{dy} \right) + \Gamma^2 R_{11} = 0 , \qquad (17a)$$

$$H(y) = -iR + (1+iR) \exp(-y/\ell)^n$$
 (19a)

H is defined to be equal to K non-dimensionalized with respect to the shear modulus G. For simplicity, it is assumed that the fluid and the solid have the same density; this is a good approximation for a rubber type of coating immersed in water. R is defined to be the square of the ratio of the speed of shear disturbances of the fluid to that of the elastic solid.  $\Gamma$ is defined as the ratio of nominal coating thickness  $\ell$  to the fluid shear wavelength  $\lambda_f$ , thus

$$R = (c_{\varepsilon}/c_{\varepsilon})^2 , \qquad (20)$$

$$\Gamma = 2\pi \ell / \lambda_{f} \qquad (21)$$

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The fluid shear wave speed  $c_f$  and the elastic solid transverse speed  $c_s$  are given by

$$c_{f}^{2} = \mu \omega / \rho$$
 , (22)

$$c_{\rm S}^2 = G/\rho$$
 (23)

The parameters R and I can also be written as

$$R = \mu\omega/G = (\lambda_f/\lambda_s)^2 , \qquad (20a)$$

$$\Gamma = \omega \ell / c_{f} = \ell \left( \rho \omega / \mu \right)^{\frac{1}{2}} \qquad (21a)$$

In the limiting conditions (i.e. y << l and y >> l ), the unified system of equations reduce to the proper equations. For y << l, H equals to unity and equation 17a reduces to

$$\frac{d^2 u_1}{dy^2} + \Gamma^2 R u_1 = 0 .$$
 (24)

For  $y >> \lambda$ , H equals -iR and the differential equation becomes

$$\frac{d^2 u_1}{dy^2} + i\Gamma^2 u_1 = 0 . (25)$$

#### II.4 Numerical Solutions

The governing unified differential equation

$$\frac{d}{dy} (H \frac{du_1}{dy}) + \Gamma^2 R u_1 = 0 , \qquad (17a)$$

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is subject to the wall boundary condition and the imposed particle velocity at y=h; thus

$$u_1(0) = 0$$
 , (26)

 $u_1(h) = 1$  . (27)

Equation 17a subject the boundary conditions 26 and 27 is a split boundary value problem. The technique utilized to solve the differential equation is the Runge-Kutta numerical integration starting at y=0 and going out to y=h. The initial value of the slope of  $u_1$  at y=0 is then iterated until the outer boundary condition  $u_1(h)=1$  is satisfied. The iteration technique used is a linear interpolation and in most cases, 6-8 iterations are required to obtain accuracy of better than 0.1%. The step size required for the numerical integration is a function of the parameters R and  $\Gamma$  and varies from y=0.01 to y=0.001. In general, the smaller step size is required for either thicker coatings, thinner transition layers or higher frequencies.

It should be noted that all the parameters are complex numbers, so that the iteration on the initial slope of  $u_1$  is really a double iteration, one on the real part of the derivative and the other on the imaginary part.

The complete copy of the computer program used to solve the system of equations can be found in the appendix.

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#### III. DISCUSSION AND RESULTS

The results from the numerical integration of the equations is presented in the form of displacement, shear stress and power distribution from the disturbance location, through the transition layer and in the elastic coating.

The dimensionless parameters that have been studied are:

1. location of disturbance - h -,

2. thickness of transition layer - n -,

3. thickness of coating -l -,

4. property of coating - R -.

The location of the disturbance is non-dimensionalized with respect to the nominal coating thickness L. Thus values of h (fig. 1) less than unity correspond to disturbances originating within the coating, while values of h greater than unity correspond to disturbances within the fluid.

Values of n are inversley related to the thickness of the transition layer. Figure 4 shows the variation of the real and imaginary part of H (Eq. 19a) for two different values of n.

A value of n equal to 8 thus corresponds to a transition layer starting at y/l = 0.75 and ending at about y/l = 1.35. The transition layer is thus seen to be about equal in thickness as the main coating itself. A value of n equal to 32 instead corresponds to a transition layer starting at y/l = 0.95 and ending ay y/l = 1.05; the thickness of the transition layer is thus equal to 10% of the compliant coating. The transition

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layer has been defined as starting where the value of the real part of H is less than 90% of its value within the compliant coating. In a similar manner, the outer edge of the transition layer is defined to be the point where the value of the imaginary part of H is within 10% of the fluid value. The point where the real part of H equals the imaginary part is the location where the transition layer switches behavior, from solid-like to fluid-like.

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Very rigid coatings with relatively large shear moduli will give rise to smaller values of the parameter R than softer coatings. The value of  $\Gamma$ , being linearly related to the dimensional coating thickness "L" will also give an indication of the relative magnitude of the thickness of the coating. As it can be verified by the corresponding definition of both R and  $\Gamma$ , higher frequencies for the disturbance will result in a simultaneous increase in both parameters. Table I gives typical values for frequencies, coating thickness and shear wave speed of the coating for the Fample of values of R and  $\Gamma$ considered in this report.

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 $c_{s} = 2500 \text{ m/s} - - \text{ f} = 10^{3} \text{Hz}$  $R = 10^{-9}$  $c_s = 250 \text{ m/s} --- \text{f} = 10 \text{ Hz}$  $c_{e} = 250 \text{ m/s} - - f = 10^{3} \text{ Hz}$  $R = 10^{-7}$  $c_s = 25 \text{ m/s} - - f = 10 \text{ Hz}$  $c_8 = 25 \text{ m/s} - - f = 10^3 \text{ Hz}$  $R = 10^{-5}$  $c_{g} = 2.5 \text{ m/s} - - f = 10 \text{ Hz}$ 10<sup>3</sup> Hz --- 2 = 0.25 mm f =  $\Gamma = 10$ 10 Hz --- £ = 1.25 mm f = 10<sup>3</sup> Hz f = --- L = 1.25 mm  $\Gamma = 10^2$ 10 Hz --- L = 12.5 mm f = 10<sup>3</sup> Hz --- l = 1.25 cmf =  $\Gamma = 10^3$  $10 \text{ Hz} --- \ell = 12.5 \text{ cm}$ f = Table 1 - Typical Values of R and  $\Gamma$  for and Elastic-Coating-Water System.

THE RESERVES

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The results of the numerical integration of the differential equation are presented in terms of particle displacement |u|, local shear stress  $|\tau|$  and local power distribution |P| for the different parameters (n, h, R,  $\Gamma$ ) considered. The power transmitted from the location of the disturbance to any point of interest is obtained from the definition

$$P = \int_0^T \tau \, du \qquad , \qquad (28)$$

where the integral is over one cycle of the disturbance and Tand u are the local shear stress and particle displacement respectively. Noting that

$$\tau = \tau(y) \exp(-i\omega t) , \qquad (29)$$

$$du = vdt = -i\omega udt , \qquad (30)$$

$$T = 1/f$$
 . (31)

equation 28 can be written as

$$P = \tau(y) u(y) \qquad (32)$$

Figures 5-7 show the particle displacement distribution for different location, h, of the disturbance and for three values of  $\Gamma$ . Only the profiles from the wall to the disturbance is shown. Values of h less than unity correspond to disturbances within the solid. The displacement distribution for all points within the solid, as expected, is thus seen to

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be linear. For all values of  $\Gamma$  considered, the shear fluid disturbance decays rapidly within the fluid and then once it has passed the transition layer, goes to zero at the wall linearly. Figure 8 shows the same type of result in both the linear and the log scale. The dotted lines shown in each of the figures correspond to the classical solution in the absence of a transition layer. Note that, while in the linear scale, the difference between the two displacement distribution seems negligible, when the results are presented on a log scale, the difference between the results with and without the transition layer is more obvious. Figure 9 shows the effect of the transition layer thickness on the displacement distribution, where it is seen that a 10% transition layer thickness (i.e. n=32) will still produce a particle displacement distribution an order of magnitude larger than the classical no transition layer solution. Note that for this particular case the displacement distribution within the solid is about 10 orders of magnitude smaller than the initial value. Figure 10 shows the effect of the elastic layer property R on the displacement distribution and is compared with the classical solution. As in the other cases the coating displacement is magnified by the transition layer.

Figures 11-16 show the shear stress distribution within the transition layer and the compliant coating for the different cases considered. Fig. 11 shows the distribution for

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three different source location. The distribution for the transition layer case is equal to the classical analysis up to the point where the visco-elastic layer switches from fluidlike to solid-like; at this point the shear stress suddenly increases by an order of magnitude and it then remains constant to the wall. The magnitude of this shift is dependent upon the thickness of the transition layer. The comparisons between the results with and without the viscoelastic layer depend upon whether in the classical solution the elastic is assumed to exist up to y=l or out to the location where the layer switches from solid-like to fluid-like (i.e. y=1.37 for  $R = 10^{-5}$ ). In either case, the present model is seen to cause larger stresses within the compliant layer. Figure 12 shows the effect of the thickness of the viscoelastic layer. Figures 13 and 14 illustrate the effect of different coating materials for two different layer thicknesses and it is seen that in both instances, the softer compliant coatings (i.e. larger values of R) will result in greater differences between the coating-fluid systems with and without the transition layer. Figures 15 and 16 show the effect of the compliant coating thickness upon the shear stress distribution. From these figures it is seen that the importance of the transition layer is more clear for thicker compliant coatings (i.e. larger values of  $\Gamma$ ). The thicker viscoelastic layer, not only causes the sharp reversal in the stress distribution, but under certain conditions, causes a double reversal to develop (see R=10<sup>-5</sup>,  $\Gamma$ = 200 case).

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The parameter that determines the magnitude of the

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interaction between the fluid and the compliant coating is the amount of power (Eq. 32) transmitted from the fluid into the coating. Figure 17 shows the effect of transition layer thickness on the power level, and figure 18 considers different coating materials. In all cases, the transition layer allows more power to be transmitted into the coating. From the results presented in figure 18 it is seen that while the transmitted power for the no transition layer varies linearly as a function of R, the presence of the transition layer reduces the dependence to about  $R^{1/2}$ .

Figures 19 and 20 compare the exponentially varying transition layer inhomogeneity with a linear inhomogeneity with the same end conditions. A stress driven fluid disturbance propagating into the coating is shown in figure 21 and 22 and as expected it is seen to have exactly the same distribution as the displacement driven disturbance. This latter result is as expected from the reciprocal theorem of linear media.

The results by Pedersen et al<sup>3</sup> are in general agreement with the results obtained in this report.

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IV. CONCLUSION

In this present analysis, the interaction between a fluid transverse disturbance, a purely elastic compliant coating and an inhomogeneous transition layer at the interface has been studied. The fluid disturbance has been assumed to take place in the absence of a mean flow field, and either a transverse displacement or a shear stress have been assumed to be one dimensional in space and sinusoidal in time.

The results obtained in this report, have shown that a thin viscoelastic inhomogeneous layer can radically alter the interaction between a fluid shear disturbance and a compliant surface. Depending upon the coating and the transition layer thickness as well as the frequency of oscillation, the presence of the transition layer lets a greater amount of energy into the coating.

Although, to more fully understand the interaction mechanism, the compliant coating was assumed to be purely elastic, the results can be carried over to the case of a damped coating. The transition layer will allow more of the energy into the coating which would then be absorbed.

The inhomogeneity of the layer can be thought as being due to one or more of four possibilities: (1) layer with continuously varying conditions, (2) a series of thinner homogeneous layers each having different properties, (3) the coating is hydrophobic (4) the costing, being forced in a random manner by

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the fluid effectively spreads out the discontinuities of the interface into a layer with finite thickness.

The greater percentage of power transfer from the fluid into the coating, achieved by means of a transition layer may stimulate new ideas which could lead to more successful compliant coatings.

#### V. REFERENCES

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Fig. 3. Variation of the Stress-Strain Coefficient as a Function of Wall Distance for (a) No Transition, (b) Inhomogeneous Transition Layer.









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Fig. 20. Comparison of Shear Stress Distribution for the Exponential and the Linear Inhomogeneity.  $R = 10^{-5}$ ,  $\Gamma = 50$ , n = 32, h = 1.25. ——— Exponential Inhomogeneity. ----- Linear Inhomogeneity.







## APPENDIX I

Computer program used to evaluate displacement, stress and power distribution due to a unit displacement (or velocity) at y=h.

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٠ DISTUREANCE IN FLUID . ٠ . \*\*\* \*\*\*\*\*\*\*\*\*\*\*\*\* \*\*\* E L I H E A A G N ۷\_ S Li A R ľ A Y O E C 1 R Ý IVEN ė G M DIMENSION Y(5), N(5), G(5), V1(3), V2(3), UU1(3), UU2(3) COMPLEX COMPY1, COMPY2, RC+F, TAU+GAM+FIFIF CCNNCN GR+G1+RF+RI, E EYTERNAL DY ASTOP=0 INPUT \*\*\*\*\* DICTIONARY NRUNS Ξ NUN1 YNUM2 NUM3 Ξ Ξ = NUM4 = ITEP Ξ NITER : PER = Y(1) Y(2) Y(3) Ξ Ξ = Y(4) 2 Y (5) н = = REAL PART OF GAMMA. CP IMAGINARY FART OF GAMMA = C PEAL FART CF R. IMAGINARY PART OF R = 0 GI PR = FI E Z Ξ Ξ VALUE OF THE ABSCISSA AT WHICH THE SOLUTIONS Ξ ARE SOLGHT. LIM = NO. OF POINTS NEEDED FOR THE RUNGE-KUTTA. CETERMINES HOW FAR OUT WE GO IN THE Y-CIRECTION FOR A CIVEN STEP SIZE. MEEG/NEND = DETERMINES THE REGION FOR WHICH H = H2. • • ٠ ٠ READ(5.2)NRUNS FORMAT(I2) REAC(5.10)NLM1.YNUM2.NUM3.NUM4.ITER.NITER.PER NSTOP=NSTCP+1 FOPMAT(I2.F5.1.J5.I5.I1.I1.F7.5) NFITE(6.20) FCPMAT(1H1.FX.YY.EX.VU(FEAL)\*.5X.VU(IMAG)\*.6X.VU(MAG)\*.4X. 1\*TAU(FEAL)\*.4Y.TAU(IMAG)\*.3X.\*TAU(MAG)\*.5X.\*WORK\*.EX. 1\*H(REAL)\*.4Y.\*H(IMAG)\*./+133(\*-\*)) \_\_\_\_ 2 5 10 2.0

APPENDIX I

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UFAC2=C48S(COMPY2) IF (b.GT. 60.C.AND.Y(1).GE.2.D)GO TO 48 ASSUME THAT AT Y=10 WE ARE OUTSIDE THE TRANSITION REGION IF (Y(1).GE.10.0)GO TO 48 F=((1.-RC)+EXP(-(Y(1)++E)))+RC GC TC 4º F=PC 48 TAU=COMFY2+F 4Š TAU=CUMPT2#F TAU=CAES(TAU) WORk=TAUM+UMAG1 IF(Y(1)+LE.YNUM2)GO TO E0 IF(MCD(N+NUM4)\*EQ\*0\*OR\*N\*EQ\*1)WRITE(6\*300)Y(1)\*Y(2)\*Y(3)\*UMAG1\* 1TAU\*TAU\*\*KCRK\*F CC TC 160 CC TC 160 CC TC 160 IF(NOD(N-NUM3)\_LQ.G.OR.N.EQ.1)WRITE(6.360)Y(1).Y(2).Y(3).UMAG1. 50 1TAU.TAUF.WOFK.F 100 CONTINUE 1F(ITER.EG.2)GO TO 150 UU1(M)=Y(2) UU2(M)=Y(3) 150 CONTINUE 4 ٠ ٠ XUYU=UM4G1 XUP 0=0%261 FCR#AT(1X+010+5+9612+6) IF(ITEF+EG+2)00 TO 500 IF THE MAGNITUDES OF VALUES USE TO LAPGE(>1+0615)+THEN WE MUST IF(XUXU+GE+1+0615)GC TC 490 300 VALUES USED IN THE ITERATION PROCESS ARE ITERATE EY HAND. 2 \* \* \* \* \* \* \* 7. ITERATION \* \* \* \* \* \* \* \* \* \* \* \* 7 COMMENTS IN CROEP TO ITEPATE. ONE MUST HAVE THREE PUNS IN A GIVEN SET. THE FIRST RUN REPRESENTS THE ZEROTH ITERATION. WHILE THE NEXT TWO ARE RUNS IN WHICH THE INITIAL GUESS FOP DU AT Y = 0 IS VARIED IN SU MANNER SO THAT SLOPES(OR DERIVATIVES). NEELED IN CROEF TO CALCULATE NEW GUESSES. CAN BE OPTAINED. THESE SLOPES ARE DETAINED AS SHOWN IN THE PROGRAM SGME THE PROGRAM BELO SLOPES OBTAINED FOR THE FIRST AND SM1.SM2 = SLOPES OBTAINED FOR THE FIRST AND SECOND RUNS. SLOPES OBTAINED FOR THE FIRST AND THIRD RUNS. THE VALUE BY WHICH THE INITIAL VALU OF THE REAL PART OF DU AT Y = 0 IN THE FIRST RUN IS TO BE INCREMENTED GRDER TO OBTAIN A NEW GUESS FOR DU SN1.SN2 = ALPHA = VALUE IR AT BETA = THE VALUE BY WHICH THE INITIAL VALUE CF THE IMAGINARY PART OF DU AT Y = THE FIRST RUN IS TO BE INCREMENTED CFDEF TO OBTAIN A NEW GUESS FOP DU VALUEY = 00 IN ÍΝ A T = 0. SLCFES ARE CALCULATED GNLY FOR EVERY OTHER ITERATION. SLCPES OBTAINED FROM THE FIRST THREE RUNS ARE USED TC OFTAIN THE NEXT TWO ITERATIONS, AFTER WHICH THE PRCGRAM AUTOMATICALLY RUNS TWO EXTRA RUNS SO THAT NEW SLOPES CAN BE CALCULATED. THESE THEN APE USED TO OBTAIN THE NEXT TWO ITERATIONS, AND SC ON. THE PARAMET NITER DETERMINES THE NUMBER OF ITERATIONS. : 03 480 F=1+NITEF ŘŘ=K

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SLOPES ARE CALCULATED FOR EVERY OTHER ITERATION AFTER THE ZEROT GC. TO (350,355,350,255,350,355,350,355,350,355),K SM1=(UU1(2)-UU1(1))/(V1(2)-V1(1)) 217:C 218 219 350 Sr1=(UU1(2)-UU1(1))/(V1(2)-V1(1))
SM2=(UU2(2)-UU2(1))/(V1(2)-V1(1))
SN1=(UU1(3)-UU1(1))/(V2(3)-V2(1))
SN2=(UU2(3)-UU2(1))/(V2(3)-V2(1))
LRITE(6,360)SM1+SM2+SN1+SM2
FCPMAT(100(\*-\*),/,1X,\*SLOPES: \_\_\_4
AAA=1.0-UU1(1)
ERP=-UU2(1) 355 \*+4614+8+/+100(\*-\*)5 36 Ŭ  $EBP = -UU_2(1)$ CENGM=(\$M1+SN2)-(\$M2+\$N1) ALPHA=((AAA+\$N2)-(BEB+\$N1))/DENOM ALPHA=((AAA+SK2)-(BEE+SK1))/DENOM GETA=((SM1+EEE)-(SM2+AAA))/DENOM V1(1)=V1(1)+ALPHA V2(1)=V2(1)+EETA THE SAMT SLOPES ARE USEL FOP TWO CONSECUTIVE ITE GC\_TG(3EG+370+3EC+370+3E0+37G+3E0+370+3E0+370)+K FOP TWO CONSECUTIVE ITERATIONS. ŇŪ=3 370 THESE VALUES ARE USED FOR THE TWO EXTRA RUNS NEEDED TO CALCULAT NEW SLOPES. V1(2)=V1(1)\*(1.0+PER) V2(2)=V2(1) V1(3)=V1(1) V2(3)=V2(1)\*(1.0+PER) CC\_TO 350 237 350 NJ=1 350 EUMMY=0.0 + . + ٠ Ľċ 470 J=1+NJ LU 470 CEIERO UEO IF(KK•EC•NITER•AND•UU•EQ•2)GC TO 500 ALL SYMEOLS FROM THIS POINT ON HAVE SPECIFIED EARLIER• Y(1)=YY1 V(2)=V20 SAME MEANING AS THAT Y(2)=YY2 Y(2)=YY2 Y(4)=V1(JJ) Y(5)=V2(JJ) Z=ZZ\_ **X X X** ITERATIO N RUNG K U T T E Δ X THIS RUNGE-KUTTA LOCP IS THE SAME AS THA UC 450 N=1+LIM IF(N.EG.1)WRITE(6+41)Y+H1+H2 IF(N.EG.1)WFITE(6+42)GP+GI+RR+RI+B+Z+LIM IS THE SAME AS THAT USED PREVIOUSLY. 265: P=H2 P=H2 IF(A.LE.NEEG.OR.N.GT.NEND)H=H1 CALL PKEE(DY.Y.Z.H.W.Q.5) CGMPY1=CMPLX(Y(2).Y(3)) UMAC1=CABS(CGMPY1) CCMFY2=CMPLX(Y(4).Y(5)) COMPT2=CMPLY(Y(4),Y(5)) UMAG2=CABS(COMPY2) IF(F.GT.EC.C.AND.Y(1).GE.2.C)GC TO ASSUME THAT AT Y=10 WE ARE OUTSIDE IF(Y(1).GE.10.D)GO TO 395 F=((1.-FC)\*EXP(-(Y(1)\*\*E)))+RC GO TO 397 F=FC 395 TRANSITION REGION THE 395 397 **F**≡FC TAU=COMPY2+F TAUM=CAES(TAU) 200:281: SORK=TAUM+UPAG1 UN K= FAUMUUPAGI IF(Y(1) +LE+YNUM2)GC TO 430 IF(MOD(N+NUM4) + EQ+O+OR+N+EQ+1)WRITE(6+300)Y(1)+Y(2)+Y(3)+UMAG1+ 1TAU+TAUN+WGKK+F CO TC 4F0 IF(MCD(N+NUM3)+LG+G+G+OR+N+EG+1)WRITE(6+300)Y(1)+Y(2)+Y(3)+UMAG1+ 1TAU+TAUN+WCRK+F CONTINUE 282 28567 430 450 28E:C

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XXXXXXXX X LU1(J) = Y(2)LU2(J) = Y(3). 470 CONTINUE **\***+ ٠ . • . ٠ 4 GO TO 500 NEITE(6:495) FORMAT(//.EX. \*MAGNITUDES TOC LARGE. ITERATE BY MAND.\*) IF (ASTOF.EG.NPURS) GO TO 550 CO TO 5 STOF END TC IF (KK.EC.NITEF) GO 500 460 CONTINUE T X 490 455 500 550 \*\* \*\*\*\*\*\*\*\*\* \*\*\*\*\*\*\* ٠ UF 1 5 - 1 EANCE IN FL UIC Đ • \*\* \*\*\*\* H E U ELN R C T k T ٤ A 0 C A Y SLY VE I I -٧ P IVEN Ó N F U N C T I O N D T THIS PRGGRAF SPECIFIES THE DIFFERENTIAL EQUATIONS TO BE SOLVED. SEE UNIVAC FATH-PACF FCR DETAILS. FUNCTION DY(Y.I) CCM MON GR.GI.FR.RI.E CCM PLEY P.U(2).THETA.A1.A2.A3.DYY.XIXIX.GAMMA LIMENSIGN Y(5) U(2)=CMPLY(Y(2).Y(3)) U(2)=CMPLY(Y(4).Y(5)) F=CMPLX(G.O.-RR) XIXIX=CMPLX(G.O.-RR) XIXIX=CMPLX(G.O.-RR) XIXIX=CMPLX(G.O.-RR) XIXIX=CMPLX(G.O.-RR) XIXIX=CMPLX(G.O.O.) GAPA F=CMPLX(G.O.O.) GAPA F=CMPLX(G.O.O.O.) GAPA F=CMPLX(G.O.O.) GAPA F=CMPLX(G.O.O.O.) GAPA F=CMPLX(G A2=THETA++2 A3=((1.-R)+EXP(-ARG))+R CYY=-(A1+U(2)+A2+U(1))/A3 GC\_TC\_E GC TC E [YY=-(THETA++2)+U(1)/R GC TG (10+2(+30+40)+I LY=Y(4) CC TO E0 CY=Y(5) GL TC 50 CY=EFAL(DYX) É Ł 10 20 EY=REAL (DYY) 30 EY=ATMAG(CYY) RETURN 40 ЪŌ I.4 ÉÑD

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REPORT DOCUMENTAT		BEFORE COMPLETING FORM
I. REPORT NUMBER	2. GOVT ACCESSION	NO. 3. RECIPIENT'S CATALOG NUMBER
SDSU/AEMEM/TR-83-01	40-4125	15C
4. TITLE (and subtitie) EFFECT OF AN INHOMOGENEOUS T	RANSITION LAYER	5. TYPE OF REPORT & PERIOD COVERS
ON THE RESPONSE OF A	COMPLIANT	March 1982 - Nov. 1982
LAYER DUE TO A SHEAR FLUID	DISTURBANCE	6. PERFORMING ORG. REPORT NUMBER
		AE&EM/TR-83-01
7. AUTHOR() Mauro Pierucci		8. CONTRACT OR GRANT NUMBER(*)
Paul Baxley		N00014-81-K-0424
. PERFORMING ORGANIZATION NAME AND AD	DRESS	10. PROGRAM ELEMENT, PROJECT, TAS
Aerospace Engineering and Engil	neering mechanics	ONP 062-693
San Diego State University San Diego, CA 92182		
11. CONTROLLING OFFICE NAME AND ADDDE	· · · · · · · · · · · · · · · · · · ·	
Department of the Navy	•	Jan. 1983
Office of Naval Research-Flui	d Dynamics	13. NUMBER OF PAGES
Arlington, VA 22217		45 + 5 (appendices)
14. MONITORING AGENCY NAME & ADDRESS(II a	illerent from Controlling Office	b) 15. SECURITY CLASS. (of this report)
		Unclassified
		154. DECLASSIFICATION/DOWNGRADING
		And Barret
17. DISTRIBUTION STATEMENT (of the ebetract e	ntered in Block 20, if different	trem Report)
17. DISTRIBUTION STATEMENT (of the obstract o	ntered in Block 20, if different	trem Report)
17. DISTRIBUTION STATEMENT (of the obstract of the solution statement of the solution statement of the solution of the solutio	ntered in Block 30, if different	tren Report)
17. DISTRIBUTION STATEMENT (of the obstract of the source	ntered in Block 20, il different	tren Report)
17. DISTRIBUTION STATEMENT (of the obstract of 18. SUPPLEMENTARY NOTES	ntered in Block 30, il dillerent	trem Report)
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