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PREFACE

The Final Report is organized in several sections, beginning with TECHNICAL REPORT< and followed by PUBLICATIONS and Activities, are listed under SEMINAR LECTURES and INVITED INTERNATIONAL VISITS.

Continued interactions between our Grant Activities and research activities at NASA/Lewis Research Center will be evidenced under (i) SEMINAR LECTURES; (ii) continued collaborative efforts, listed under PAPERS, with members of NASA/Lewis Research Center; as well as (iii) informal discussions during frequent visits to the Laboratory.

TECHNICAL REPORT

The intent of the original proposal and the work carried out under the grant was to explore the instabilities of turbulent free shear flows of an incompressible fluid. The purpose for doing so was that (1.) coherent instabilities are susceptible to control via upstream forcing and (2.) because at sufficient finite amplitudes, the coherent modes enter into nonlinear interactions with the mean motion and thus, (3.) through such nonlinear interactions, the control of mixing and of mean flow spreading can be effected through the control of the coherent structures.

(1.) Five Mode Interactions in Developing Free Shear Flows - We studied aspects of the nonlinear interactions between five interacting axisymmetric and helical modes at fundamental and subharmonic frequencies in a spatially developing round jet. Several simplifying assumptions were made in order to bring out the nonlinear interaction features: (i) the absence of dynamically participating fine grained turbulence, (ii) the mean flow is assumed "simila", thereby ruling out its distortion in its detailed distribution (but its spreading rate modifications are explicitly accounted). The integral energy method was used to study the nonlinear interactions. The streamwise development of the jet is obtained in terms of the mean flow shear-layer momentum thickness, the wave-mode kinetic energies and the wave-mode phase angles. With this method, a system of partial differential equations is reduced to a system of ordinary equations. The nonlinear differential equations are solved with initial conditions which are given at the nozzle exit. It was shown that the initial wave-mode energy densities as well as initial phase angles play a significant role in the streamwise evolution of the coherent wave modes and mean flow. More extensive studies of the five mode interaction problem in the simpler two-dimensional shear flow was also performed.

Reported in PAPERS: Lee & Liu 1989; 1993
CONFERENCES: Lee & Liu 1989, Horng & Liu 1989, 1990.

(2.) Two- and Three-Frequencies Interactions - The above five mode interactions involved only two frequencies (but more complicated geometrical modes). This work involves three frequencies but for two-dimensional modes in a two-dimensional shear flow. The frequencies include the fundamental (f), and its surrounding higher-frequency mode (3f/2) and the subharmonic (f/2). The physical rules for the mode interactions are established and the possibility of shear layer control studied.

New perspectives on the problem of two-frequency, two-dimensional mode interactions in the present of dynamically participating fine-grained turbulence were obtained through the study of nonlinear interactions in the "phase volume". This consists of trajectories in the volume occupied from the two nonlinear amplitudes and the turbulent kinetic energy; the mixing layer growth is not contained in such a three-dimensional representation.

Reported in PAPERS: Nikitopoulos & Liu 1989; Liu & Kaptanoglu 1989a, 1989b.
CONFERENCES: Nikitopoulos & Liu 1989; Liu & Kaptanoglu 1989, 1990.

(3.) Effect of Forcing in Nozzle Exit Turbulence Conditions - The question naturally arises about the effect of pulsating nozzle exit conditions, for purposes of controlling the exiting free shear layer, on the turbulence characteristics in the wall region that is about to leave the nozzle. This brings into the picture of "new" turbulence closure for the modulated turbulence quantities in the wall layer (or "turbulent Stokes layer"). Rapid distortion theory was extended to obtain ratios of modulated Reynolds shear stress and turbulent kinetic energy. Depending on the imposed frequency, turbulence structural non equilibrium could results. This has wide implications for unsteady nozzle exit conditions relevant to downstream mixing region development and control.

Reported in PAPERS: Liu & Mankbadi 1991; Mankbadi & Liu 1992.
CONFERENCES: Liu & Mankbadi 1991.

(4.) Reviews - A review of many aspects of nonlinear mode interactions and control of free shear flows was made, including possibilities of incorporating coherent structures in turbulence closure.

Reported in PAPERS: Liu 1989, 1990.
CONFERENCES: Liu 1990.

PUBLICATIONS

Liu, J.T.C. 1989 Coherent structures in transitional and turbulent free shear flows. Annual Reviews of Fluid Mechanics 21, 285-315.

Liu, J.T.C. & Kaptanoglu, H.T. 1989a Multiple large-scale coherent structures in free turbulent shear flows. In advances in Turbulence 2, (H.H. Fernholz & H.E. Fiedler, eds.), pp. 57-61. Springer-Verlag, Berlin.

Liu, J.T.C. & Kaptanoglu, H.T. 1989b Phase-volume representation of two-coherent mode transition to turbulence in a developing mixing layer. In Proc. 4th Int. Workshop

Nonlinear Processes and Turbulence in Physics. Inst. Theo. Phys., Acad. Sci. Ukrainian SSR, Kiev.

Lee, S.S. & Liu, J.T.C. 1989 Multiple coherent mode interactions in a developing round jet. A.I.A.A. Paper No. 89-0967.

Nikitopoulos, D.E. & Liu, J.T.C. 1989 Nonlinear coherent mode interactions and the control of shear layers. In structure of Turbulence and Drag Reduction, (A. Gyr, ed.), pp. 119-127. Springer-Verlag, Berlin.

Liu, J.T.C. Liu 1990 Possibilities of incorporating coherent structure models in turbulent shear flow calculations. Appl. Mech. Rev. 43, S210-S213.

Liu, J.T.C. Liu & Mankbadi, R.R. 1991 Wall-layer response in an unsteady turbulent flow. In Proc. Response of Shear Flows to Imposed Unsteadiness-Assois, France (G. Binde & D. Ronneberger, eds.).

Mankbadi, R.R. & Liu, J.T.C. 1992 Near-wall response in turbulent shear flows subjected to imposed unsteadiness. J. Fluid Mech. 238, 55-71.

Lee, S.S. & Liu, J.T.C. 1993 Multiple-coherent mode interactions in a developing round jet. J. Fluid Mech. 248, 383-401.

CONFERENCE PAPERS READ ON GRANT ACTIVITIES

AIAA 2nd Shear Flow Conference, Tempe, 12-16 March 1989: Lee, S.S & Liu, J.T.C. "Multiple coherent mode interactions in a developing round jet"

IUTAM 2nd Symposium on Structure of Turbulence and Drag Reduction, E.T.H., Zurich 25-28 July 1989: Nikitopoulos, D.E. & Liu, J.T.C. "Nonlinear coherent mode interactions and the control of shear layers"

4th International Workshop on Nonlinear Processes and Turbulence in Physics, Institute for Theoretical Physics, Academy of Sciences of the Ukrainian SSR, Kiev, 9-22 October 1989: Liu, J.T.C. & Kaptanoglu, H.T. "Phase volume representation of two-coherent mode transition to turbulence in a mixing layer"

42nd Annual Division of Fluid Dynamics Meeting, APS, Palo Alto, 19-21 November 1989: Horng, A. & Liu, J.T.C. "Five coherent mode interactions in a spatially developing mixing layer" (Abstract in Bull. Am. Phys. Soc. 34, 2301 (1989))

11th U.S. National Congress in Applied Mechanics, Symposium on Coherent Structures in Turbulent Flow, Tucson, 21-25 May 1990: Liu, J.T.C. "Possibilities of incorporating coherent structure models in calculation of turbulent shear flows"

IUTAM Symposium on Nonlinear Hydrodynamic Stability and Transition, Valbone, 3-8 September 1990: Liu, J.T.C. & Kaptanoglu, H.T. "Phase volume representation of two-coherent mode transition to turbulence in a developing free shear layer"

43rd Annual Division of Fluid Dynamics Meeting, APS, Cornell University, 18-20 1990: Horng, A. & Liu, J.T.C. "Two- and three-dimensional mode interactions in a spatially developing turbulent shear layer, II" (Abstract in Bull. Am. Phys. Soc. 35, 2281 (1990))

Euromech 272, Response of Shear Flows to Imposed Unsteadiness, Assois, 14-18 January 1991: Liu, J.T.C. & Mankbadi, R.R. "Wall layer response in unsteady turbulent flows"

SEMINAR LECTURES ON GRANT ACTIVITIES

NASA, Lewis Research Center, Cleveland, Internal Fluid Mechanics Division Seminar Series, 17 April 1989: "Applications of Coherent Structure Ideas to Heat Transfer, Transition and Coherent Flames"

NASA, Lewis Research Center, Cleveland, Internal Fluid Mechanics Seminar, 29 May 1991: "Coherent Structure Theory Applications to Problem in Propulsion Systems"

NASA, Lewis Research Center, Cleveland, Internal Fluid Mechanics Division Seminar Series, 24 February 1992: "Mode Interactions in Free Shear Flows"

Universita degli Studi di Roma "La Sapienza", Rome, Dipartimento di Idraulica, Transporti e Strade Seminari: 8 May 1992: "Two- and Three-Dimensional Mode interactions in Free Shear Flows"

INVITED INTERNATIONAL VISITS

Institute for Fundamental and Technological Research, Polish Academy of Sciences, Warsaw, 1 week, Sept. 1989

Institute of Hydromechanics, Ukrainian Academy of Sciences, Kiev, 1 1.2 weeks, Oct. 1989

CNRS, Lab. d'Aerothermique, Meudon, Dec. 1990 - Jan. 1991

Polytechnika Warszawska, Institute of Aeronautics & Applied Mechanics, Warsaw, 1 week, Jan. 1992

Universita degli Studi di Roma "La Sapienza", Dipart. di Idraulica, Transporte e Strade, Rome, 1 week, May 19921