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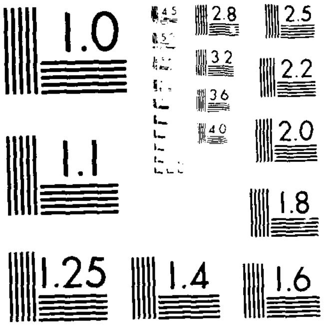

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The theoretical and experimental investigations on the instability, routes to chaos and transition to turbulence of an anisymmetric jet flow has been investigated. The first general task has involved the search for evidence of strange attractors in the unsteady dynamics of naturally (stochastically) and periodically excited jets. A special case of the periodically excited jets were ones having enhanced acoustic feedback. As part of this effort, substantial computer software was developed to analyse velocity time-series to determine attractor dimensions, Lyapunov exponents and topological entropy. Under conditions with strong feedback and without forcing, long highly sampled time-series were analyzed. Using independent measures of attractor dimension by a modified Grassberger-Procaccia algorithm and the singular decomposition method of Broomhead and King, the low-dimensional nature of the dynamics of the initial shear layer up to the point of pairing

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19. were confirmed. Phase space representations and Poincare sections were examined in order to evidence more clearly the departure of the data series from quasi-periodicity. To this point, no discernable fine scale or fractal structural has been revealed. In order to look at this in more detail, enhanced feedback conditions have been set up in the jet. This step was based on observations such as with the conditions of probe interference feedback, that such a convectively unstable flow in the presence of feedback shares the same features related to absolutely unstable (closed) flows. These measurements are nearly completed. Preliminary results point to regions of staircase-like selection of mode frequencies with Reynolds number, mode selections histerises, and two-and three-frequency mode competition and histerises loops which produce complicated dynamical behavior.

On the theoretical front, the first part of the work, now completed, dealt with the instability of thin inviscid circular shear layers. This was a needed first step towards the nonlinear analysis to follow, and showed that curvature effects and departure from axial symmetry were most strongly felt for low streamwise wave number disturbances. A non-axisymmetric secondary instability mechanism has also been investigated. This showed that the most significant parametric resonance was the one involving an axisymmetric fundamental mode and two subharmonic modes of equal-opposite signed azimuthal modes. Experiments to study this behavior are in progress.

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COUPLED EXPERIMENTAL AND THEORETICAL INVESTIGATIONS OF INSTABILITY, CHAOS AND TURBULENCE IN AN AXISYMMETRIC JET FLOW

by

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January, 1988

In the original proposal of March, 1985 (85-NA-177) and in the letter of December 16, 1985, we had chronologized the direction and focus of an investigation on the instability, routes to chaos and transition to turbulence of an axisymmetric jet flow. As described in the proposal, the choice of performing this investigation in a jet were based on a number of factors including (a) the low disturbance quality of the Jet Facility at IIT, (b) the large amount of data accumulated over the recent years in past AFOSR funded research on instability and transition in jets, (c) the fact that the jet can represent the more general class of open flow systems in which evidence of strange attractor dynamics has not been documented, and (d) a fact which was not pointed out in the original proposal but which now has come to be appreciated, which is that the the initial region of the jet can act either as a convectively unstable system, or as a result of feedback resonance, act as a globally unstable system. The implications of the latter fact will be discussed in greater length in a later part of this report.

In those two documents we had detailed three general tasks (A-C) which were intended to be performed in sequential order and which were each to encompass approximately one year of time. Within each general task were a number of subtasks which involved both experimental and theoretical analysis. These were designed to interact, enhance and build in a cumulative effort to reach the general goals of the study.

The first general task (A) involved the basic search for evidence of low-dimensional strange attractors in a naturally (stochastic) excited axisymmetric jet. The theoretical analog was the construction of low-dimensional model equations for this flow which might show periodic doubling and behavior commensurate with dynamical systems known to have strange attractors. Also part of the effort in the first year, which was explicately stated in the cited letter, was the use of numerical, theoretical and experimental 'exercises' with data series from systems with attractors of known dimensions and characteristics. These exercises were intended to provide a level of confidence for making predictions about the dynamical state of the measured systems as well as provide bench-marks for comparison to other past and ongoing similar investigations in fluid dynamics and to the more prolific number of investigations in the areas of physics and applied mathematics. This was to involve the development of the computational tools for determining such characteristic quantities as the attractor dimension, Lyapunov exponents and topological entropy.

The second general task (B) involved the 3-D (non-axisymmetric) periodic and random forcing of the jet. This was intended to produce two types of results. The first was meant to consider the basic instability processes which lead to the growth of 3-D modes in jets. The second would attempt to trace the development of quasi-periodic states which might lead to chaos.

Experimentally this would involve the use of azimuthally placed disturbance generators (piezoelectric films) capable of producing different axisymmetric and helical mode combinations. A similar approach using heating segments to produce spanwise periodic modes in boundary layers has been a great success in our laboratory. As evidenced by the boundary layer experiments, the detailed documentation of even a small number of possible combinations of controlled states was expected to take considerable time, although, we fully expected it would provide valuable new information about the initial instability and resonance conditions of such growing 2-D and 3-D mode interactions.

The theoretical analysis within task B was intended to predict the conditions for these highly controlled states. The major thrust would deal with the non-linear evolution of disturbances leading to the growth of 3-D modes. This would involve resonance mechanisms and strongly non-linear couplings leading to transition to turbulence. We expected that at this stage of the work there would be frequent comparisons between experiment and analysis in order to pinpoint similarities and differences. We further proposed, that the analysis might attempt to construct low-dimensional systems using as a basis, experimental data in the form of eigenfunction structure or frequencies brought out by interesting or unusual cases in the experiments.

The third task (C) was designed to integrate the initial work and apply it towards the active control of jets. In particular it was intended to build on the experimental and theoretical results to pinpoint important mode interactions which may have been found to lead to strong non-linear regimes and/or to random or chaotic states. Such information would then be used in a detection, feedback and control arrangement. This was intended to involve sophisticated data analysis capable of rapidly detecting 2- and 3-D modes, discriminating between them, and then generating the required system input to achieve a new more desirable state. The discrimination and system input was expected to be greatly enhanced by the theoretical analysis.

In the first 15 months of the grant period the experiments have nearly followed the chronological order laid out in the original proposal. At this point we have addressed most of the experimental tasks cited in A and approximately one half of those of B as well as some tasks which were not explicately stated in the original proposal. During this period, extensive amounts of computer software were developed for performing chaos related data analysis of time series. Some of the results of this work were presented at the 39th Annual Meeting of the American Physical Society Division of Fluid Dynamics in November, 1986 (Abstract BE 4). These exercises demonstrated that it was possible to obtain estimates of the dimension of low-dimensional attractors, with known uncertainty, at reasonable computational cost, and established a number of practical limitations which besets higher dimensional estimates. In those exercises, an approximation of the Grassberger-Procaccia dimension of known chaotic and pseudo-periodic signals was calculated. The tests were designed to simulate data series obtained from a single sensor probe, for example, what might be obtained from a single sensor hot-wire in the initial shear layer region of an axisymmetric jet. The test cases included the Henon and Lorenz attractors, and sine waves with different numbers of incommensurate frequencies. Other parameters that were varied were the relative sampling rate and the number of contiguous sample points. These exercises pointed out the large uncertainties in determining the dimension of systems with more than five degrees of freedom, and in our minds placed strong questions on results which claim to have done so.

Methods for displaying phase space representations of data series with different attractor dimensions were also developed. In particular a highly efficient algorithm based on the singular decomposition method introduced by Broomhead and King was used to produce optimum projections in phase space of low and moderate dimension systems. The method is extremely powerful for discerning deterministic behavior which might be masked by non-deterministic (incoherent) processes. As a further means for separating out deterministic behavior, methods using first-return mapping were developed and used in various numerical exercises.

At this point in the study we are now confident that we possess the basic tools for performing chaos-related analysis on data series where the outcome is not known a priori. Having achieved this we embarked on the experimental investigation of Part A of the proposed work.

Measurements were made in the initial shear layer region of the axisymmetric jet under conditions of different Reynolds numbers, with natural forcing as well as with mild forcing of axisymmetric modes using sound. The Reynolds numbers were chosen based on the experience gained in previous studies in this jet (Drubka; Shakib; Corke et al.) to produce conditions with minimum feedback and strong resonant (enhanced) feedback. Measurements were taken at a fixed azimuthal position but with different selected downstream positions where the unstable modes were primarily initial fundamental axisymmetric, primarily initial fundamental helical, a mixture of initial axisymmetric fundamental and subharmonic, and mixture of initial axisymmetric fundamental, subharmonic and fundamental helical modes. In terms of attractor dimensions these respective locations should have produced systems with attractor dimensions of one in the first two cases, one with a subharmonic, and two with a subharmonic. With the addition of far-field acoustic forcing, we could suppress the helical modes and in those cases reduce the dimension by one. Such forcing at the natural axisymmetric mode frequency could also to some extent weaken or otherwise alter the feedback and thereby modify the development of the axisymmetric subharmonic mode. Away from the preferred frequency, forcing could produce strong non-linear coupling with sum and difference interactions and a non-exact subharmonic mode. Therefore these cases represented different degrees of complexity and order of attractors under conditions which were well documented and repeatably set.

Under the conditions with strong feedback and without forcing, long highly sampled time-series at the fixed probe locations were acquired and processed using the mathematical tools for analysing the dynamical systems developed and tested earlier. In particular, independent measures of attractor dimension were obtained, using a highly efficient modified Grassberger-Procaccia algorithm and the singular decomposition method by Broomhead and King. These measures confirmed the low-dimensional nature of the dynamics of shear-layer instability, up to pairing location. The dimension was shown to increase with downstream distance, whereas mild axisymmetric forcing consistently reduced dimensionality by approximately one. Phase-space representations and Poincare sections were examined in an attempt to evidence more clearly any departure of the data from quasi-periodicity. These underlined the added complexity introduced by the presence of non-axisymmetric modes, and revealed no discernible fine or fractal structure. First return maps calculated from the Poincare sections reinforced these observations. Finally, direct measurements of the largest Lyapunov exponent (Λ) were performed using two of the available methods (due respectively to Wolf and Swinney, and Sano and Sawada). Though different in scope these methods gave convergent large positive values of Λ, but are not trusted as being sufficiently quantitative, owing to their critical sensitivity to various input parameters.

In addition to the far-field acoustic forcing, work has also been started to produce azimuthally varying 3-D forcing of the jet (Task B). The forcing was done by a thin piezoelectrically active film which was flush mounted around the trailing edge of the jet nozzle. A cavity had been milled under the film and the principle strain direction of the film was aligned so that the principle motion of the excited film would produce a radial (v) component. The feasibility of this approach was tested by using a single azimuthally continuous film to excite only axisymmetric modes. The experiment was run over a large range of Reynolds numbers, with forcing at the natural and away from the natural initial unstable frequencies and subharmonics. Based on the positive results, a second version is being constructed which will have 16 independent azimuthal segments. This will be used to seed helical mode combinations up to a mode number of eight.

In the course of this phase of the investigation, considerable time was lost as a result of the gradual degrading of a number of the facility components including the main control valve and line filters. This resulted in the production of undesirable low frequency acoustic tones which were not removed by the acoustic dampening treatment inside the settling chambers. These acoustic tones ultimately disturbed the natural feedback mechanism in the jet and resulted in a reduction of natural unstable mode amplitudes. Under these uncontrolled disturbances the jet was strongly convectively unstable, meaning that the frequency of growing modes was changing with downstream distance, commensurate with the growing shear layer and jet core.

Since the degrading of these components was gradual, the effect was brought out only through many repeatability checks over a long period of time. Under these circumstances the first tendency was to expect that the source of these disturbances resulted from uncontrolled vortical motions. In our case that meant the complete dismantling and inspection of the turbulence management devices (honeycombs, grids and screens). Only after eliminating these as the source of the problem, was the more subtle non-vortical source(s) pinpointed. These problems were subsequently eliminated and the jet was restored to its low disturbance condition. However, it further reinforced with us the important role that uncontrolled, and often unknown disturbances can have on the dynamics of these systems. In our case it was acoustic disturbances. In other cases it can result from end effects, or free-stream disturbances, or vibration.

The fundamental objective of the theoretical part of the program has been, and continues to be, to investigate the nonlinear evolution of disturbances in circular jets. The work has been structured so as to ensure that these investigations are thorough and complete. Matters of particular interest are the development and interaction of axisymmetric and helical modes, resonance mechanisms, especially the generation of subharmonic instabilities, and strongly nonlinear couplings leading to transition to turbulence. These topics most generally fall within Task B.

The first part of the work, now completed, dealt with the instability of thin inviscid circular shear layers, approximating high Reynolds-number jets. The basic flow profile was a Blasius shear layer connecting a uniform flow in the core with a quiescent external region. Linear stability calculations were performed for this profile, for both temporal and spatial instability, and for both axisymmetric and helical modes. These calculations, which were needed as a preliminary step to the nonlinear analysis, showed that curvature effects and departure from axial symmetry were most strongly felt for small values of the streamwise wave number of frequency; i.e., when the wave length of the disturbance is large compared with the shear-layer thickness.

Nonaxisymmetric secondary instability generated through a Kelly-type mechanism has been investigated. It was found that the most significant parametric resonance, in terms of the growth rate, was the one involving an axisymmetric fundamental disturbance and two subharmonic modes with equal but opposite in sign azimuthal wave numbers. In this case, it was found that the secondary growth rate increased with increasing azimuthal wave number and with curvature effects. When the fundamental is nonaxisymmetric, on the other hand, the contrary behavior was found.

A Craik-like triad interaction involving an axisymmetric fundamental and two subharmonic waves with opposite azimuthal wave numbers was also studied. This analysis has to be treated with caution since the flow under consideration is assumed to be inviscid, which means that the usual hypotheses of weakly nonlinear theory do not apply. Nevertheless, the results obtained may prove to be significant. In particular, it was found that once the subharmonic disturbances have reached a sufficient amplitude so that back-interaction to the fundamental becomes important, an explosive growth will occur within a finite time.

In the second half of the grant, the theoretical work will be devoted to viscous jet flows. A substantial program has been initiated to fully analyze this problem. All the major theoretical approaches to nonlinear instability analysis will be applied to this problem in turn. These approaches include:

1. Stuart-Watson weakly nonlinear theory; this leads to a classical Landau amplitude equation and the necessity of computing the value of the Landau constant. This is an important first step in the program, since it provides information regarding the supercritical or subcritical nature of the weakly nonlinear interactions.

2. Craik triad interaction; the interaction of an axisymmetric primary wave with a pair of oblique secondary waves will shed light on the feasibility of

this mechanism of three-dimensionality.

3. Fourier/eigenfunction expansion; a severly truncated expansion in modal form leads to a low-dimensional system of ordinary differential equations of the Lorenz type. The question of whether such a system admits chaotic solutions is to be explored.

4. Nonlinear eigenvalue problem; following the methods of Herbert, an expansion in a set of orthogonal functions will be set up, the solution of which determines the neutral surface separating the regions of stability and instability.

Topic 1 of this program is now well advanced and nearing completion.

In the second half of the grant, the experimental work will continue to follow to a major extent the tasks listed in the original proposal. However, we will exploit to an even greater extent the feedback process which remains a special feature of jet flows.

One of the conclusions of the preliminary measurements of Task A was the crucial role of "clean" experimental conditions such as core turbulence intensity (approximately 0.05%) and the need for strongly resonant axisymmetric instabilities in order to distinguish deterministic non-linear dynamics from noisy quasi-periodicity in the jet. Such conditions may be achieved by examining jet behavior at Reynolds numbers corresponding to the "column instability mode" (when the initial axisymmetric wave length is such that an integer number of pairing events coincides with the end of the potential core), and/or alternatively by the use of controlled external forcing. The existence of the column instability mode has been known for some time, however in other higher disturbance jet facilities it is only observable with strong axisymmetric forcing. In our case, with the low disturbance levels, we have Reynolds numbers at which the column instability mode exists naturally (Drubka's Re=42,000). Therefore in order to reduce the noisy quasi-periodicity in the jet, that is, the random phase modulations of the periodic initial instabilities, we will operate at this Reynolds number condition.

There are more profound reasons for setting our operating conditions to be in a strongly resonant state for studying the routes to chaotic behavior in an open fluid flow. A recent numerical study by Deissler on convective chaos in an open flow system pointed to the role of non-determinant disturbance imperfections from purely harmonic inputs in the route to chaotic behavior. He further stressed the inadequacy of presently available tools in order to study deterministic oscillations in a "true" open system. Such an analysis does not however include considerations of feedback. Therefore, a series of measurements are planned that should elucidate the role of feedback in an open flow system, since it appears that feedback or forcing can play the role of effective "boundary conditions" with respect to wave dynamics. Observations such as probe feedback and harmonic spectra indicate that a convectively unstable flow (a cold axisymmetric jet) in the presence of feedback appears to share some of the features related to absolute instability (closed flows). Such a distinction has profound implications with respect to the possible existence of deterministic chaos in jets (see for example Huerre), as well as issues of "flow controllability".

In these cases we will operate the jet in strong feedback conditions without and with periodic forcing. In the case of the periodic inputs, small deterministic imperfections will be added at precise instants in the forcing period in order to see their effect on the stability of the flow and generation of other interacted modes and spectral broadening which were observed in the numerical experiments of Deissler. The periodic inputs will include both axisymmetric and non-axisymmetric mode seeding. We expect that the low inertia input that the piezoelectric generators produce will be essential to obtaining a reliable reproduction of the computer generated and output time series patterns.

In keeping with the original objectives, these concepts will be integrated into an overall approach to controlling dynamic processes in jets.

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