ONR END-OF-THE-FISCAL-YEAR LETTER

(September 30, 1991)

CONTRACT TITLE/PRINCIPAL INVESTIGATOR: CONTROL OF TWO- AND THREE-DIMENSIONAL WAKE INSTABILITIES FROM BLUFF-BODIES/DONALD ROCKWELL
CONTRACT NUMBER: N00014-90-J1510
SCIENTIFIC OFFICER: DR. STEVE RAMBERG AND DR. EDWIN ROOD
START DATE: DECEMBER 1, 1989

(a) DESCRIPTION OF SCIENTIFIC RESEARCH GOALS

This program addresses the manipulation of flow structure and spectral content of near- and far-wake instabilities from bluff bodies by: (a) generation of varying phase shift and wavelength of vortex shedding relative to body motion by sinusoidal, amplitude-modulated, and frequency-modulated excitation; (b) alteration of mean boundary conditions at separation via boundary layer control; and (c) modification of three-dimensional (spanwise) geometry of the body surface.

In order to accomplish these technical objectives, new types of experimental systems will be developed. These systems will involve the control of the mean boundary layer thickness immediately prior to separation from a bluff body, generation of sinusoidal three-dimensional disturbances by appropriately contouring the surface of the body, and generation of amplitude-modulated and frequency-modulated perturbations of the body, in contrast to the classical type of sinusoidal excitation.

In parallel with these technical objectives, new types of experimental techniques will be developed. Emphasis will be on laser diagnostics, and interactive image display and analysis exploiting new types of graphic supercomputers. Particular effort will be devoted to the development of a high resolution particle image velocimetry (PIV) system that allows acquisition of velocity information over entire planes of the flow. Two- and three-dimensional interpretations of the flow structure in color and real time are attainable using graphics supercomputers.

(b) SIGNIFICANT RESULTS DURING PAST YEAR

Using the types of control techniques described in the foregoing section (a), the following advances have been made during the past year.

(i) Wake alteration due to modification of mean boundary conditions at separation

A unique suction facility has been constructed; it allows independent control of the boundary layer thickness at the upper and lower surfaces of a trailing-edge. When the thickness of the boundary layer at separation reaches a sufficiently low value, the near-wake instability transforms from an absolute instability to a convective instability. Existence of this convective instability allows highly two-dimensional vortex shedding to occur, in contrast to the well-known oblique or inclined shedding. Correspondingly, the fluctuation level in the near-wake decreases drastically, and therefore the loading on the edge will decrease substantially as well.

(ii) Phase shift (or timing) of vortex formation relative to body motion

The timing, or phase shift, of the vortex formation from a cylinder is related to the direction of energy transfer from the fluid to the body; it determines the conditions for onset of self-excited excitation. An adequate understanding of the near-wake vortex formation requires acquisition of not only instantaneous streamlines, but also instantaneous vorticity contours. A range of forced excitation frequencies of the cylinder has been considered, relative to the inherent vortex formation frequency from a stationary cylinder. As the excitation frequency is increased, the loci of the centers of vorticity concentrations move closer to the cylinder until a minimum distance from the cylinder is attained, at which point a change in timing of the vortex formation is effected. Instantaneous streamlines do not provide an adequate indication of the presence and location of vortices associated with this change in timing.

(iii) Locked-in and nonperiodic three-dimensional wake structure from nonuniform cylinder subjected to controlled excitation

A cylinder having very mild spanwise variation in diameter generates a sequence of locked-in and period-doubled states of vortex formation as the excitation frequency is lowered below the value corresponding to inherent vortex formation. Recently completed hydrogen bubble visualization and hot-film measurements, involving spectra and phase plane representations, define the nature of the successive states of vortex formation. Emphasis has been on high resolution particle image velocimetry (PIV), which provides the instantaneous velocity and vorticity fields in planes aligned with the span of the cylinder. The detailed mechanisms of vortex splitting, as well as the generation of vortical structures having axes orthogonal to the axis of the cylinder are characterized in detail. This approach allows, for the first time, a global and instantaneous representation of the route to chaos via period doubling, providing a basis for the fundamental flow mechanisms. Preliminary studies involving steady suction, as well as blowing/suction perturbations applied along the mid-span of the cylinder, indicate certain features of the flow structure in common with that generated from the nonuniform cylinder described in the foregoing.

(iv) Structure of wake from cylinder subjected to amplitude-modulated (AM) forcing

Whereas sinusoidal excitation at constant amplitude produces phase-locked vortex formation, employment of amplitude-modulated excitation generates a time-dependent phase between the formation of vortices and the motion of the cylinder. As a consequence, it is possible to rapidly destabilize the near-wake. This destabilization is accompanied by a period-doubled response at the modulation frequency. The consequence of these phase modulations in the near-wake is to produce a rapid spectral broadening of the far-wake. This type of rapid broadening is associated with the onset of chaotic undulations of the far-wake region, as visualized using the hydrogen bubble technique.

(v) Wake structure from cylinder subjected to frequency-modulated (FM) forcing

Frequency-modulated excitation involves forcing of the cylinder at constant amplitude, but continuously varying frequency. This type of excitation can produce either an enhancement or destabilization of the organized vortex street. For this type of excitation, the primary control parameters are the modulation frequency and the frequency deviation. By properly tuning these parameters, it is possible to enhance the degree of organization of the near-wake, and to produce regions of lock-in that are substantially wider than those arising from purely sinusoidal excitation. On the other hand, destabilization, or a decrease in the degree of organization of the vortex street, is also attainable by proper choice of excitation parameters. Both the processes of enhancement and destabilization extend into the far-wake region, and have been characterized by spectral measurements and flow visualization.

(vi) Development of new laser-diagnostic techniques

In addition to the conventional technique of laser illumination employed in particle image velocimetry (PIV), several types of laser scanning techniques have been developed. These scanning approaches allow rapid implementation of a laser system. Three approaches have been developed recently in our laboratory. They involve deflection of the incident laser beam by: an oscillating mirror driven by a galvanometer system; a rotating mirror having a large number (72) of facets; and an acousto-optic (Bragg cell) deflector. Corresponding optical trains involving use of telescopic and singlet lens arrangements allow focussing the beam on a laser deflector as well as attainment of minimum beam width within the field of interest.

Emphasis has also been on development of a video system for real-time, on-line characterization of flows using the particle image velocimetry (PIV) technique. Development of this system has required design of a computer-controlled shutter system external to the video and corresponding synchronization with the deflected laser beam from the rotating mirror system.

(vii) Development of new graphics and image construction techniques

In order to provide rapid feedback of the observations of particle image velocimetry, on-line methods for determining streamlines and basic topological features of complex flows have been developed in our laboratory. Moreover, methods for rapid construction of contours of constant vorticity also have been developed.

Detailed interpretation of the instantaneous velocity, vorticity and topological fields is attainable in multiple color and overlay formats using the graphics supercomputer system in our Computer-Aided Design laboratory. This approach allows establishing the interrelationship between the topology and underlying vorticity fields.

(c) PLANS FOR NEXT YEAR'S RESEARCH

Over the coming year, the foregoing investigations will be continued, and several of them brought to completion.

Concerning the *wake alteration due to modification of mean boundary conditions at separation*, emphasis will be on interrelating the flow visualization of the near-wake structure with quantitative measurements of the fluctuating amplitude and frequency. The structure of the wake as a function of dimensionless boundary layer thickness at separation will be related to the dimensionless frequency of oscillation, involving boundary layer thicknesses on either side of the trailing-edge, in contrast to the usually-employed trailing-edge thickness. A universal frequency law will be sought.

Regarding the *phase shift of the near-wake vortex formation, relative to the motion of the oscillating cylinder*, attention will be focussed on characterizing the instantaneous vorticity and streamline patterns for a range of excitation frequencies. This will be accomplished by use of a phase-referencing technique whereby the patterns are compared at, for example, the maximum amplitude of the cylinder motion. Moreover, the variation of these patterns during a typical cycle of the cylinder oscillation will also be addressed. Applying these approaches and overlay techniques to interpret the instantaneous velocity and vorticity fields simultaneously, the basic physics associated with the change in timing, or phase shift, vortex formation will be addressed.

With respect to the *locked-in and nonperiodic three-dimensional wake structure from a nonuniform cylinder subjected to controlled excitation*, further emphasis will be given to the particle image velocimetry (PIV) technique for characterizing the instantaneous velocity fields, streamline patterns, and vorticity fields. The successive, period-doubled states leading to the onset of chaotic motion will be characterized on the basis of patterns of out-of-plane vorticity distributions, as well as streamline patterns in various reference frames. The objective is to determine the detailed flow physics that controls the locked-in and low-order chaotic wake from nonuniform cylinders. These objectives will be carried out along with further studies of use of localized mean suction, as well as unsteady suction/blowing to control the vortex formation from the cylinder. Exploratory efforts will also be made at relatively high Reynolds numbers in order to determine generic phenomena in relation to the observations at low Reynolds numbers.

Regarding the *structure of the wake from a cylinder subjected to amplitude-modulated (AM) and frequency-modulated (FM) forcing*, attempts will be made to generalize the overall response of the near- and far-wake structure on the basis of the nominal amplitude of excitation, frequency deviation, and modulation frequency. These generalized maps will illustrate the possible routes to low order chaotic behavior as, for example, the dimensionless modulation frequency or amplitude is increased. The possibility of multiple routes to chaotic behavior will be explored and interpreted in conjunction with flow visualization and laser-Doppler measurements of the spectral content of the near- and far-wake regions. In turn, this approach will allow more universal interpretation of the concepts of enhancement and destabilization of the wake through AM and FM forcing.

Continued development of *new types of laser-diagnostic techniques, as well as new graphics and image construction methods* will be pursued. Emphasis will be on development of systems that allow construction of the entire three-dimensional image, using phase-referenced characterizations of the flow structure. Methods for rapid identification of critical points in the flow will provide a basis for pattern recognition methods.

(d) ONR DATA BASE INFORMATION

(a) *Number of papers submitted to refereed journal but not yet published* — 7

(b) Number of papers published in refereed journals (list attached): — 6

(c) Number of <u>books</u> or chapters submitted but not yet published: — 1

(d) Number of books or chapters published (list attached): — --

(e) Number of printed technical reports and non-refereed papers (list attached): — --

(f) Number of patents — --

A-1

(g) Number of patents granted (list attached): --

(h) Number of invited presentations at workshops or professional society meetings (list attached): 2

(i) Number of presentations at workshops or professional society meetings (list attached) 1

(j) Honors/awards/prizes for contract/grant employees: (list attached, may include society awards/offices, promotions, faculty awards/offices, etc.) 2

(k) Providing the following information will assist with statistical purposes

PI/CO-PI:	TOTAL	1	Grad Students:**	TOTAL	3
	Female	--		Female	--
	Minority*	--		Minority*	--
			Post Doc:**	TOTAL	2
				Female	--
				Minority	1

(l) Degrees granted (list attached): 2

* Underrepresented or minority groups include Blacks, Hispanics, and Native Americans.
Asians are not considered an underrepresented or minority group in science and engineering.

** Supported at least 25% this year on contract/grant.

(e) LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS/PATENTS/GRADUATES

1. Articles published in refereed journals:

Publications (in print)

"On Interpretation of Flow Visualization of Unsteady Shear Flows", *Experiments in Fluids*, Vol. 9, pp. 257-266 (1990) (with I. Gursul and D. Lusseyran).

"Effect of Concentration of Vortices on Streakline Patterns", *Experiments in Fluids*, Vol. 10, pp. 294-296 (1991) (with I. Gursul).

"Decoupling of Locked-In Vortex Formation by Amplitude-Modulated Excitation", *Journal of Fluids and Structures*, Vol. 5, pp. 455-458 (1991) (with M. Nakano).

"Destabilization of the Karman Vortex Street by Frequency-Modulated Excitation", *Physics of Fluids*, Vol. 3, pp. 723-725 (1991) (with M. Nakano).

"Period-Doubling in the Wake of a Three-Dimensional Cylinder", *Physics of Fluids*, Vol. 3, pp. 1477-1478 (1991) (with F. Nuzzi and C. Magness).

"Unsteady Crossflow on a Delta Wing Using Particle Image Velocimetry", *AIAA Journal of Aircraft*, (in press) (1991) (with C. Magness and O. Robinson).

Publications (submitted)

"Construction of Three-Dimensional Images of Flow Structure Via Particle Tracking Techniques", submitted to *Experiments in Fluids* (with O. Robinson).

"Laser-Scanning Particle Image Velocimetry Applied to a Delta Wing in Transient Maneuver", submitted to *Experiments in Fluids* (with C. Magness and O. Robinson).

"The Near-Wake of an Oscillating Trailing-Edge: Mechanisms of Periodic and Aperiodic Response", submitted to *Journal of Fluid Mechanics* (with A. Lotfy).

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"Instantaneous Topology of the Unsteady Leading-Edge Vortex at High Angle of Attack", submitted to *AIAA Journal* (with C. Magness and O. Robinson).

"Three-Dimensional Vortex Formation from an Oscillating, Nonuniform Cylinder", submitted to *Journal of Fluid Mechanics* (with F. Nuzzi and C. Magness).

"Control of the Spanwise Structure of a Bluff-Body Wake by Changes in Boundary Layer Thickness at Separation", submitted to *Physics of Fluids* (with S. Konak).

2. Books Submitted for Publication:

An Engineering Guide to Flow-Induced Vibrations, submitted to Balkema Press, Rotterdam (with E. Naudascher). This book provides an overview of the wide variety of mechanisms associated with flow-induced vibration and noise generation. It is to appear in Spring, 1992.

3. Technical Reports:

Several progress and final reports to ONR; essential advances are described in the foregoing journal articles.

4. Presentations:

a. Invited

"Flow-Induced Oscillations in Engineering Systems", two-day seminar at NASA Marshall Space Flight Center, Huntsville, Alabama, January, 1991.

"Control of Two- and Three-Dimensional Wake Instabilities from Bluff-Bodies", Invited Lecture at MIT Sea Grant Marine Industry Collegium Symposium on Interactions of Flow Fields with Cables, Flexible Risers, and Tethers, Massachusetts Institute of Technology, April 23-24, 1991.

(Unable to accept a number of invited seminars and lectures at various universities and technical meetings due to research commitments.)

b. Uninvited

"Period-Doubled Wake from a Nonuniform Cylinder", presented at the Meeting of the American Physical Society, Division of Fluid Dynamics, Cornell University, November, 1990, Abstract CB-2.

5. Patents Granted

No patents were granted during the past fiscal year.

6. Degrees Granted:

C. L. Magness, Doctor of Philosophy in Mechanical Engineering, June, 1991
S. Konak, Master of Science in Mechanical Engineering, June, 1991

(f) LIST OF HONORS/AWARDS

Name of Person Receiving Award	Recipient's Institution	Name of Award	Sponsor of Award
Donald Rockwell	Lehigh University	Paul B. Reinhold Professorship of Mechanical Engineering and Mechanics	Paul B. Reinhold Endowment
Donald Rockwell	Lehigh University	Joseph and Eleanor Libsch Research Award	Libsch Endowment

(g) OTHER SPONSORED RESEARCH

- Volkswagen Foundation (1982-1991) "Flow-Induced Vibrations of Structures", $214,000. Corresponding funds allocated to University of Karlsruhe for International Research Collaboration.
- Office of Naval Research (1989-1992) "Unsteady Flow Distortion Past Blades: Sources of Noise Generation in Rotating flows", $350.000.
- National Science Foundation (1990-1993) "Forced Excitation of Globally-Unstable Flow Systems", $280,000.
- National Science Foundation (1988-1991) "Development of Particle Image Velocimeter" ($120,000)

- Air Force Office of Scientific Research (1990-1993) "Unsteady Structure of Leading-Edge Vortices on a Delta Wing" ($363,000)
- Pratt and Whitney (1990-1991) "Control of Wakes from Turbomachinery Blading" ($70,000)

Enclosure (1)

OFFICE OF NAVAL RESEARCH
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT
1 October 1990 through 30 September 1991

R&T Number: N00014-90-J1510

Contract/Grant Title: "Control of Two- and Three-Dimensinal Wake Instabilities from Bluff-Bodies"

Scientific Officer: Dr. Steve Ramberg and Dr. Edwin Rood

Principal Investigator: Professor Donald Rockwell

Mailing Address: Department of Mechanical Engineering and Mechanics, 354 Packard Laboratory #19, Lehigh University, Bethlehem, Pennsylvania 18015

Phone Number: (215) 758-4107

FAX Number: (215) 758-4041

E-Mail Address:

a.	Number of Papers Submitted to Refereed Journal but not yet Published:	7
b.	Number of Papers Published in Refereed Journals: (List Attached):	6
c.	Number of Books or Chapters Submitted but not yet Published:	1
d.	Number of Books or Chapters Published (List Attached):	--
e.	Number of Printed Technical Reports and Non-Refereed Papers (List Attached):	--
f.	Number of Patents Filed:	--
g.	Number of Patents Granted (List Attached):	--
h.	Number of Invited Presentations at Workshops or Professional Society Meetings (List Attached):	2
i.	Number of Presentations at Workshops or Professional Society Meetings (List Attached):	1
j.	Honors/Awards/Prizes for Contract/Grant Employees: (List Attached, may include Society Awards/Offices, Promotions, Faculty Awards/Offices, etc.	2

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