Control of Two- and Three-Dimensional Wake Instabilities from Bluff-Bodies

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PROJECT ABSTRACT

Research Goals:

The long-range goals of this investigation are to:

1. Determine the effects of various active and passive control techniques on the instantaneous and time-averaged structure of the three-dimensional wake of a cylinder at low and high Reynolds number.

2. Characterize the unsteady loading on the cylinder, including the phase shifts between the cylinder motion, the forces acting on the cylinder, and the three-dimensional structure of the near-wake.

3. Develop new types of experimental techniques, focusing on high-image-density particle image velocimetry (PIV), image processing and pattern recognition, and methods of instantaneous force measurement.

Objectives:

The immediate objectives are to:

1. Determine the effect of active (open-loop) control of the cylinder motion, in the form of sinusoidal, amplitude-modulated and frequency-modulated excitation, on the quasi-two-dimensional and three-dimensional flow structure.

2. Investigate the effect of imposed three-dimensionality in the form of surface nonuniformities or, equivalently, localized suction/blowing on the flow structure.

3. Develop integrated PIV-force measurement systems, including PIV cinematography, high-speed digital processing of images, and multicomponent force transducers.

Approach:

An integrated, active (open loop) control – quantitative flow visualization system has been implemented. It involves digital computer control of the cylinder motion, the localized fluid injection, and the phase angle between them. Moreover, this integrated system allows simultaneous firing/scanning of lasers, image shifting systems, camera systems and other related instrumentation. Use of a high-image-density PIV approach allows characterization of the instantaneous streamline pattern and vorticity field over an arbitrary plane in a highly three-dimensional flow at high values of Reynolds number. Concepts of flow topology based on critical point theory are employed to identify crucial features of the instantaneous flow structure. These approaches will be integrated with techniques of instantaneous force measurement, in order to provide direct, wholefield correlations of the near-wake and the loading on the cylinder.

Tasks Completed:

The quasi-two-dimensional wake structure has been addressed, with emphasis on the phase shift between the cylinder motion and the large-scale vortices, as well as the rapid destabilization and restabilization of the vortices for sinusoidal, amplitude- and frequency-modulated excitation. The three-dimensional structure of the near-wake, in the presence of localized disturbances, has been characterized quantitatively in terms of projections of the three-dimensional streamline patterns and vorticity distributions.

Results:

The quasi-two-dimensional flow structure from a uniform cylinder subjected to sinusoidal excitation shows the well-known phenomenon of locked-in vortex formation. For amplitude-modulated and frequency-modulated excitation, new types of locked-in response have been revealed. Moreover, away from the locked-in region, it is possible to attain rapid destabilization of the large-scale vortex formation or, in certain cases, to restabilize the vortex formation to a periodic state. All of these features require consideration of AM and FM parameters such as modulation frequency and frequency deviation. Even in the presence of purely sinusoidal excitation, higher Reynolds number flows that are usually assumed to be in a locked-in state actually exhibit large instantaneous excursions of the flow pattern from one cycle to the next. These excursions can be viewed as amplitude- and frequency-modulated phenomena occurring in a system subjected to pure sinusoidal excitation; they are not revealed by classical ensemble-averaged

representations of the flow structure.

The three-dimensional flow structure from a uniform cylinder at higher values of Reynolds number (5,000 to 10,000) involves pronounced three-dimensional vorticity concentrations ω_x and ω_y, relative to the classical Kármán vortices having only ω_z vorticity. The circulation Γ_x and Γ_y of vortices can be of the same order as the Kármán vortices Γ_z.

At low values of Reynolds number, the three-dimensional structure from an oscillating cylinder having a geometrical nonuniformity shows not simply distorted patterns of quasi-two-dimensional vortex formation having nominal vorticity ω_z, but very pronounced clusters of vorticity concentrations ω_y. It is possible to generate values of circulation Γ_y of the same order as the dimensionless circulation Γ_z of the Kármán vortices. These patterned clusters of vorticity, arising from the localized nonuniformity of the cylinder, provide the basis for similar studies at higher values of Reynolds number. In a related study focusing on the three-dimensional structure at low Reynolds number from a uniform cylinder with localized suction/blowing, patterns of vorticity clusters ω_y are analogous to those attained for the geometrical nonuniformity. Moreover, ω_y concentrations at the end of the cylinder can be drastically attenuated by localized blowing.

Recent developments in high-image-density particle image velocimetry have focused on techniques for characterizing the instantaneous structure in the near-wake at high-Reynolds number. Techniques of correlation of instantaneous vorticity over an entire plane provide a basis for linking the flow structure to the instantaneous surface loading on the cylinder. Moreover, new approaches to high speed image acquisition in the form of PIV cinematography have been initiated. Complete time histories of the flow will be obtained using this approach.

Accomplishments:

1. Patterns of three-dimensional vorticity concentrations have been defined in the near-wake at low and high Reynolds number; these vortices can have strengths of the same order as the classical Kármán vortices.

2. Quantitative techniques for characterizing the instantaneous structure of the near-wake at high Reynolds number have been developed; they provide new types of velocity and vorticity correlations that can link the flow patterns to the loading on the cylinder.

Contours of constant streamwise vorticity (top image) and superposition of sectional streamlines and vorticity contours (bottom image) on a plane cutting across turbulent wake ($Re = 5000$). Plane is perpendicular to the freestream and located one diameter downstream of the base of the cylinder. Images are obtained via high-image-density particle image velocimetry.

PUBLICATIONS FROM ONR SPONSORED WORK - FY91/FY92
DR. DONALD ROCKWELL
DECEMBER 1992

91-P Nakano, M. and Rockwell, D., "Decoupling of Locked-In Vortex Formation by Amplitude-Modulated Excitation", *Journal of Fluids and Structures* 5 (1991) 455-458.

91-P Nakano, M. and Rockwell, D., "Destabilization of the Kármán Vortex Street by Frequency-Modulated Excitation", *Physics of Fluids* 3 (1991) 723-725.

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

91-P Gursul, I. and Rockwell, D., "Effect of Concentration of Vortices on Streakline Patterns", *Experiments in Fluids* 10 (1991) 294-296.

92-P Nuzzi, F., Magness, C., and Rockwell, D., "Three-Dimensional Vortex Formation from an Oscillating, Nonuniform Cylinder", *Journal of Fluid Mechanics* 238 (1992) 31-54.

92-P Robinson, O. and Rockwell, D., "Construction of Three-Dimensional Images of Flow Structure Via Particle Tracking Techniques", *Experiments in Fluids* (1992) (in press).

92-P Nakano, M. and Rockwell, D., "The Wake from a Cylinder Subjected to Amplitude-Modulated Excitation", *Journal of Fluid Mechanics* (1992) (in press).

92-P Rockwell, D. and Konak, S., "Control of the Spanwise Structure of a Bluff-Body Wake by Changes in Boundary Layer Thickness at Separation", *Physics of Fluids* (1992) (in press).

92-P Lotfy, A. and Rockwell, D., "The Near-Wake of an Oscillating Trailing-Edge: Mechanisms of Periodic and Aperiodic Response", *Journal of Fluid Mechanics* (1992) (in press).

92-P Rockwell, D., Magness, C., Towfighi, J, Akin, O. and Corcoran, T., "High-Image-Density Particle Image Velocimetry Using Laser Scanning Techniques", *Experiments in Fluids* (1992) (in press).

92-P An Engineering Guide to Flow-Induced Vibrations, submitted to Balkema Press, Rotterdam (with E. Naudascher). This book provides, for the first time, a comprehensive overview of the wide variety of mechanisms associated with flow-induced vibration and noise generation. It is to appear in Fall, 1993.

92-PS Nakano, M. and Rockwell, D., "Flow Structure in the Frequency-Modulated Wake of a Cylinder", submitted to *Journal of Fluid Mechanics* (1992).

92-PI Gu, W., Robinson, O., and Rockwell, D. "Timing of Vortex Formation from an Oscillating Cylinder: Instantaneous Topology and Vorticity Field Characterization", to be submitted to *Journal of Fluids and Structures* (1992).

92-PI Towfighi, J. and Rockwell, D., "Instantaneous Structure of the Locked-In and Period-Doubled Wake from an Oscillating, Nonuniform Cylinder via Particle Image Velocimetry: Topology and Vorticity Fields", to be submitted to *Physics of Fluids* (1992).

92-PI Rockwell, D., Chyu, C., and Lin, J.-C., "Three-Dimensional Structure of the Near-Wake of a Stationary and Oscillating Cylinder at High Reynolds Number", to be submitted to the *Journal of Fluid Mechanics* (1992).

92-PI Rockwell, D., Chyu, C., and Lin, J.-C., "Structure of the Near-Wake of a Cylinder with Helical Surface Windings at High Reynolds Number", to be submitted to *Journal of Fluids and Structures* (1992).

92-PI Rockwell, D., Kuryla, J., and Konak, S., "Variations of Boundary Layer Thickness at a Blunt Trailing-Edge: Near-Wake Structure and Scaling of Frequency of Oscillation", to be submitted to *Journal of Fluids and Structures* (1992).

92-PI Rockwell, D. and Chow, G., "Generation of Out-of-Plane Vorticity in the Near-Wake of a Stationary Cylinder", to be submitted to *Journal of Fluids and Structures* (1992).

92-PI Rockwell, D. and Kuo, C.-H., "Vortex Street Incident Upon a Cylinder in a Near-Wake Structure and Surface Loading", to be submitted to *Journal of Fluids and Structures* (1992).

92-PI Rockwell, D. and Gu, W., "Three-Dimensional Structure of a Bluff-Body Wake Due to Localized Fluid Perturbations at the Surface of a Cylinder", to be submitted to *Physics of Fluids* (1992).

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

91-C Rockwell, D., Magness, C., Towfighi, J., Corcoran, T. and Akin, O., "High Resolution Particle Image Velocimetry Using Scanning Techniques", presented at the Meeting of the American Physical Society, Division of Fluid Mechanics, Arizona State University, November, 1991. Also in *Bulletin of the American Physical Society,*

Abstract ED2, 36 (10) (1991) 2663.

91-C Rockwell, D., Towfigh, J. and Robinson, O., "Structure of the Three-Dimensional and Period-Doubled Wake from an Oscillating Cylinder", presented at the Meeting of the American Physical Society, Division of Fluid Mechanics, Arizona State University, November, 1991. Also in *Bulletin of the American Physical Society,* Abstract IE4, 36 (10) (1991) 2701.

92-C Rockwell, D., Akin, O., Lin, J.-C., Chow, G., Cipolla, K., Chyu, C., Evans, M., Laudenslager, A., Mayori, M., and Towfighi, J., "Structure of Unsteady Vortical Flows via High-Image Density Particle Image Velocimetry", presented at the Meeting of the American Physical Society, Division of Fluid Mechanics, November, 1992. Also in *Bulletin of the American Physical Society,* Abstract AH2 , 37 (8) (1992) 1710.

91-IC Rockwell, D., "Instantaneous Structure of Unsteady Wakes", Seminar in Department of Mechanical and Aerospace Engineering, Princeton University, October 1991.

91-IC Rockwell, D., "Unsteady Flow Distortion Past Blades: Sources of Noise Generation and Rotating Flows", Presentation at Office of Naval Research Workshop, Naval Ship Research and Development Center, Annapolis, Maryland, October 1991.

92-IC Rockwell, D., "Control of Two- and Three-Dimensional Wake Instabilities from Bluff Bodies", Presentation at Office of Naval Research Workshop, Ohio State University, May, 1992.

92-IC Rockwell, D., "Quantitative Visualization of Wakes via Particle Image Velocimetry", Invited Lecture at International Union of Theoretical and Applied Mechanics Symposium on Bluff-Body Wakes, Goettingen, Germany, Sept. 6-11, 1992, to be published by Springer-Verlag (eds. H. Eckelmann and J. M. R. Graham).

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

OFFICE OF NAVAL RESEARCH
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT
1 October 1991 through 30 September 1992

R&T Number: N00014-90-J1510
Contract/Grant Number:
Contract/Grant Title: "Control of Two- and Three-Dimensional Wake Instabilities from Bluff-Bodies
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a. Number of Papers Submitted to Refereed Journal not yet Published: 1

b. Number of Papers Published in Refereed Journals: 10
(List Attached):

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): 3

j. Honors/Awards/Prizes for Contract/Grant Employees: (List Attached, this might include Scientific Soc. Awards/Offices, Promotions/ Faculty Awards/Offices, etc.) 2

k. Total Number of Graduate Students and Post-Docs Supported at Least 25% This Year on This Contract/Grant

Grad Students 3 and Post-Docs 2 including
Grad Student Female -- and Post-Doc Female --
Grad Student Minority -- and Post-Doc Minority --

Minorities include Blacks, Aleuts, AmIndians, Hispanics, etc.
NB: Asians are not considered an under-represented or minority group in science and engineering.

Enclosure (3)