

**WAKE STRUCTURE, LOADING AND VIBRATION OF CYLINDERS:
EFFECTS OF SURFACE NONUNIFORMITIES AND UNSTEADY INFLOW**

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ABSTRACT

The flow structure from stationary and oscillating cylinders, both with and without surface treatment, has been characterized in steady currents and waves using techniques of high-image-density particle image velocimetry. This quantitative imaging has led to new insight into the quasi-two-dimensional and three-dimensional features of the near-wake, which are intimately related to the loading on the cylinder, for cases where the cylinder is either stationary or elastically mounted. This program has resulted in a total of 46 publications in leading journals and the support of 15 graduate students.

OVERVIEW OF ADVANCES

Detailed insight into the instantaneous and averaged flow structure from stationary and oscillating cylinders is necessary for a full understanding that leads to development of effective control techniques, simplified models for description of the cylinder response, and guidance for large-scale numerical simulations.

For the case of a stationary cylinder, the strong dependence of the near-wake structure on Reynolds number has been characterized in detail. Furthermore, the onset and development of small-scale Kelvin-Helmholtz instabilities in the separating shear layers leading to large-scale Kármán vortex formation has been experimentally defined, for the first time, using quantitative imaging techniques. When the cylinder is in a deep water wave, as opposed to a steady current, the patterns of vortex formation take on a variety of complex forms. Again, the present program represents the first quantitative characterization of these vortex patterns in an experimental setting.

Regarding the three-dimensional structure of the near-wake, use of orthogonal plane, cinema imaging approaches has allowed definition, for the first time, of the space-time volumes of streamwise vorticity that are an inherent feature of the near-wake structure over a broad range of Reynolds numbers. This range extends from the initial onset of vortex formation to much higher values, at which Kelvin-Helmholtz instabilities occur in the separating shear layers.

When the cylinder is subjected to controlled vibration, either at the Kármán frequency or the frequency at which Kelvin-Helmholtz instabilities are formed, it is possible to generate highly coherent vortical structures. These types of control have allowed insight into the optimal response characteristics over the entire near-wake region, as well as the individual, separating shear layers. Quantitative imaging has pointed to fallacies in classical interpretation of streamline patterns, in favor of patterns of vorticity.

In the situation where the cylinder is elastically mounted, such that the vortex formation initiates, and is eventually strongly coupled with, the motion of the cylinder, detailed representations of the near-wake have been attainable using imaging approaches. Design and construction of novel, low mass-damping elastic systems have provided realistic conditions in accord with the ocean environment, and the types of vortex patterns revealed using the imaging approaches has been important in an well-defined, quantitative interpretation of the wake pattern.

In the event that the cylinder has a small-scale surface disturbance(s), it has been demonstrated that large changes in the near-wake structure are attainable. These changes are associated with, in most cases, dramatic alteration of the process of vortex shedding from the cylinder. Innovative analysis techniques, based on quantitative imaging, have involved, for example, global spectral and cross-spectral analysis of the near-wake. In essence, this involves evaluation of spectra and cross-spectra at thousands of points in the near-wake structure via cinema sequences of high resolution PIV images.

Finally, extensive collaboration with the numerical simulation group of Professor George Karniadakis at Brown University has led to enhanced capabilities for computation of complex flow patterns, and a new approach that uses results from quantitative imaging as input to a computation has been advanced.

JOURNAL PUBLICATIONS (IN PRESS/IN PRINT) (Total of 46)

Ozgoren, M. and Rockwell, D. 2007 "Interaction of a Deep Water Wave with a Vertical Cylinder: Effect of Self-Excited Vibrations on Quantitative Flow Patterns", (in press) *Journal of Fluid Mechanics*.

Carberry, J., Sheridan, J., and Rockwell, D., 2005 "Controlled Oscillations of the Cylinder: Forces and Wake Modes", *Journal of Fluid Mechanics*, Vol. 538, pp. 31-69.

Fu, H. and Rockwell, D. 2005 "Shallow Flow Past a Cylinder: Control of Near-Wake" *Journal of Fluid Mechanics*, Vol. 539, No. 1, pp. 1-24.

Fu, H. and Rockwell, D. 2005 "Shallow Flow Past a Cylinder: Transition Phenomena at Low Reynolds Number" *Journal of Fluid Mechanics*, Vol. 540, No. 1, pp. 75-97.

Yang, Y. and Rockwell, D. 2004 "Interaction of a Deep Water Wave with a Vertical Cylinder: Flow Structure and Loading", *Journal of Fluid Mechanics*, Vol. 520, December, pp. 267-295.

Ozgoren, M. and Rockwell, D. 2004 "Interaction of a Deep-Water Wave with a Vertical Cylinder at Low KC Number: Transition from Phase-Locked Modes of Vortex Formation", *Physics of Fluids*, Vol. 16, No. 7, pp. 2700-2703.

Sirisup, S., Karniadakis, G. E, Saelim, N. and Rockwell, D. 2004 "DNS and Experiments of Flow Past a Wired Cylinder at Low Reynolds Number", *European Journal of Mechanics B/Fluids*, Vol. 23, No. 1, pp. 181-188.

Carberry, J., Govardhan, R., Sheridan, J., Rockwell, D. and Williamson, C. H. K. 2004 "Wake States and Response Branches of Forced and Freely Oscillating Cylinders", *European Journal of Mechanics B/Fluids*, Vol. 23, No. 1, pp. 89-97.

Carberry, J., Sheridan, J., and Rockwell, D. 2004 "Cylinder Oscillations beneath a Free Surface", *European Journal of Mechanics B/Fluids*, Vol. 23, No. 1, pp. 81-88.

Downes, K. and Rockwell, D., 2003 "Oscillations of a Vertical Elastically-Mounted Cylinder in Waves: Imaging of Vortex Patterns", *Journal of Fluids and Structures*, Vol. 17, Issue 7, June, pp. 1017-1033.

Carberry, J., Sheridan, J. and Rockwell, D. 2003 "Controlled Oscillations of a Cylinder: A New Wake State" *Journal of Fluids and Structures*, Vol. 17, Issue 2, pp. 337-343.

Lin, J.-C., Yang, Y. and Rockwell, D. 2002 "Flow Past Two Cylinders in Tandem: Instantaneous and Averaged Flow Structure", *Journal of Fluids and Structures*, Vol. 16, Issue 8, December, pp. 1059-1071.

Kahraman, A., Sahin, B. and Rockwell, D. 2002 "Control of Vortex Formation from a Vertical Cylinder in Shallow Water: Effect of Localized Roughness", *Experiments in Fluids*, Vol. 33, pp. 54-65.

Akilli, H. and Rockwell, D. 2002 "Vortex Formation from a Cylinder in Shallow Water", *Physics of Fluids*, Vol. 14, No. 9, pp. 2957-2967.

Yang, Y. and Rockwell D. 2002 "Wave Interaction with a Vertical Cylinder: Spanwise Flow Patterns and Loading", *Journal of Fluid Mechanics*, Vol. 460, June, pp. 93-129.

Chyu, C.-K. and Rockwell, D. 2002 "Near-Wake Flow Structure of a Cylinder with a Helical Surface Perturbation", *Journal of Fluids and Structures*, Vol. 16, No. 2, February, pp. 263-269.

Carberry, J., Sheridan, J. and Rockwell, D. 2001 "Forces and Wake Modes of an Oscillating Cylinder", *Journal of Fluids and Structures*, Vol. 15, No. 3-4, April, pp. 523-532.

Lin, J.-C., Cetiner, O., Downes, K., Yang, Y. and Rockwell D. 2001 "Quantitative Imaging of the Wake of a Cylinder in a Steady Current and a Wave", *Journal of Fluids and Structures*, Vol. 15, Issues 3-4, April, pp. 427-444.

Cetiner, O. and Rockwell, D. 2001 "Streamwise Oscillations of a Cylinder in Steady Current. Part I: Locked-On States of Vortex Formation and Loading", *Journal of Fluid Mechanics*, Vol. 427, pp. 1-28.

Cetiner, O. and Rockwell, D. 2001 "Streamwise Oscillations of a Cylinder in Steady Current. Part II: Free-Surface Effects on Vortex Formation and Loading", *Journal of Fluid Mechanics*, Vol. 427, pp. 29-59.

Zhu, Q., Lin, J.-C., Unal, M.-F. and Rockwell, D. 2000 "Motion of a Cylinder Adjacent to a Free-Surface: Flow Patterns and Loading", *Experiments in Fluids*, Vol. 28, pp. 559-575.

Shiang, A., Öztekin, A., Lin, J.-C. and Rockwell, D. 2000 "Hydroelastic Instabilities in Viscoelastic Flow Past a Cylinder", *Experiments in Fluids*, Vol. 28, No. 2, pp. 128-142.

Oshkai, P. and Rockwell, D. 1999 "Free Surface Wave Interaction with a Horizontal Cylinder", *Journal of Fluids and Structures*, Vol. 13, Issues 7-8, October, pp. 935-954.

Gaydon, M. and Rockwell, D. 1999 "Vortices Incident upon an Oscillating Cylinder: Flow Structure and Loading", *Journal of Fluids and Structures*, Vol. 13, Issue 6, August, pp. 709-722.

Lin, J.-C. and Rockwell, D. 1999 "Horizontal Oscillations of a Cylinder Beneath a Free-Surface: Vortex Formation and Loading", *Journal of Fluid Mechanics*, Vol. 389, pp. 1-26.

Sheridan, J., Carberry, J., Lin, J.-C. and Rockwell, D. 1998 "On the Near-Wake Topology of an Oscillating Cylinder" Note in *Journal of Fluids and Structures*, Vol. 12, Issue 2, February, pp. 215-220, 1998.

Shiang, A. H., Lin, J.-C., Öztekin, A. and Rockwell, D. 1997 "Viscoelastic Flow Around a Confined Circular Cylinder: Measurements Using High-Image-Density Particle Image Velocimetry" *Journal of Non-Newtonian Fluid Mechanics*, Vol. 73, pp. 29-49.

Sheridan, J., Lin, J.-C. and Rockwell, D. 1997 "Flow Past a Cylinder Close to a Free-Surface", *Journal of Fluid Mechanics*, Vol. 330, pp. 1-30.

Lin, J.-C. and Rockwell, D. 1997 "Quantitative Interpretation of Vortices from a Cylinder Oscillating in Quiescent Fluid", *Experiments in Fluids*, Vol. 23, pp. 99-104.

Lin, J.-C., Sheridan, J. and Rockwell, D. 1996 "Near-Wake of a Perturbed, Horizontal Cylinder at a Free-Surface", *Physics of Fluids*, Vol. 8, No. 8, pp. 2107-2116.

Chyu, C.-K. and Rockwell, D. 1996 "Evolution of Patterns of Streamwise Vorticity in the Turbulent Near-Wake of a Circular Cylinder", *Journal of Fluid Mechanics*, Vol. 320, pp. 117-137.

Chyu, C.-K. and Rockwell, D. 1996 "Near-Wake Structure of an Oscillating Cylinder: Effect of Controlled Shear-Layer Vortices", *Journal of Fluid Mechanics*, Vol. 322, pp. 21-49.

Mahir, N. and Rockwell, D. 1996 "Vortex Formation from a Forced System of Two Cylinders. Part I: Tandem Arrangement", *Journal of Fluids and Structures*, Vol. 10, Issue 5, July, pp. 473-490.

Mahir, N. and Rockwell, D. 1996 "Vortex Formation from a Forced System of Two Cylinders. Part II: Side-By-Side Arrangement", *Journal of Fluids and Structures*, Vol. 10, Issue 5, July, pp. 491-500.

Lin, J.-C., Phetkong, N., Sheridan, J. and Rockwell, D. 1996 "Controlled Motion of a Cylinder through a Free-Surface: Effect of Depth of Penetration", *Journal of Fluids and Structures*, Vol. 10, Issue 4, May, pp. 309-317.

Brede, M., Eckelmann, H. and Rockwell, D. 1996 "On Secondary Vortices in the Cylinder Wake", *Physics of Fluids*, Vol. 8, No. 8, pp. 2117-2124.

Sheridan, J., Lin, J.-C. and Rockwell, D. 1995 "Metastable States of a Cylinder Wake Adjacent to a Free-Surface", *Physics of Fluids*, Vol. 7, No. 9, pp. 2099-2101.

Gu, W. and Rockwell, D. 1995 "Flow Structure from an Oscillating Cylinder with a Localized Nonuniformity: Patterns of Coherent Vorticity Concentrations", *Physics of Fluids*, Vol. 7, No. 5, pp. 993-998.

Lin, J.-C., Towfighi, J. and Rockwell, D. 1995 "Instantaneous Structure of Near-Wake of a Circular Cylinder: On the Effect of Reynolds Number", *Journal of Fluids and Structures*, Vol. 9, Issue 4, May, pp. 409-418.

Chyu, C., Lin, J.-C., Sheridan, J. and Rockwell, D. 1995 "Kármán Vortex Formation from a Cylinder: Role of Phase-Locked Kelvin-Helmholtz Vortices", *Physics of Fluids*, Vol. 7, No. 9, pp. 2288-2290.

Lin, J.-C., Towfighi, J. and Rockwell, D. 1995 "Near-Wake of a Circular Cylinder: Control by Steady and Unsteady Surface Injection", *Journal of Fluids and Structures*, Vol. 9, Issue 6, August, pp. 659-669.

Lin, J.-C., Vorobieff, P. and Rockwell, D. 1995 "Three-Dimensional Patterns of Streamwise Vorticity in the Turbulent Near-Wake of a Cylinder", *Journal of Fluids and Structures*, Vol. 9, Issue 2, February, pp. 231-234.

Gu, W., Chyu, C. and Rockwell, D. 1994 "Timing of Vortex Formation from an Oscillating Cylinder", *Physics of Fluids*, Vol. 6, No. 11, pp. 3677-3682.

Nakano, M. and Rockwell, D. 1994 "Flow Structure in the Frequency-Modulated Wake of a Cylinder", *Journal of Fluid Mechanics*, Vol. 266, pp. 93-119.

Takmaz, L. and Rockwell, D. 1994 "Unsteady Flow Structure and Surface Pressure Due to Translation of a Cylinder Past an Elliptical Leading-Edge", *Journal of Fluids and Structures*, Vol. 8, Issue 6, August, pp. 583-600.

Towfighi, J. and Rockwell, D. 1994 "Flow Structure from an Oscillating Nonuniform Cylinder: Generation of Patterned Vorticity Concentrations", *Physics of Fluids*, Vol. 6, No. 2, pp. 531-536.

GRADUATE STUDENTS SUPPORTED (Total of 15)

Student	Degree	Year
Carberry, Josie	Ph.D. (Monash University)	2004
Cetiner, Oksan	Ph.D.	1998
Chyu, C.-K.	Ph.D.	1995
Downes, Keith	M.S.	1999
Gaydon, Matthew	M.S.	1997
Haojun Fu	Ph.D.	2004
Mahir, Necati	Ph.D.	1993
Oshkai, Peter	Ph.D.	2002
Phetkong, Nonglak	M.S.	1996
Saelim, Nattapong	Ph.D.	2003
Towfighi, Joseph	M.S.	1994
Unal, M. Fevzi	Ph.D.	1985
Vorobieff, Peter	Ph.D.	1996
Yingchen Yang	Ph.D.	2005
Zhu, Qing	M.S.	1998

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