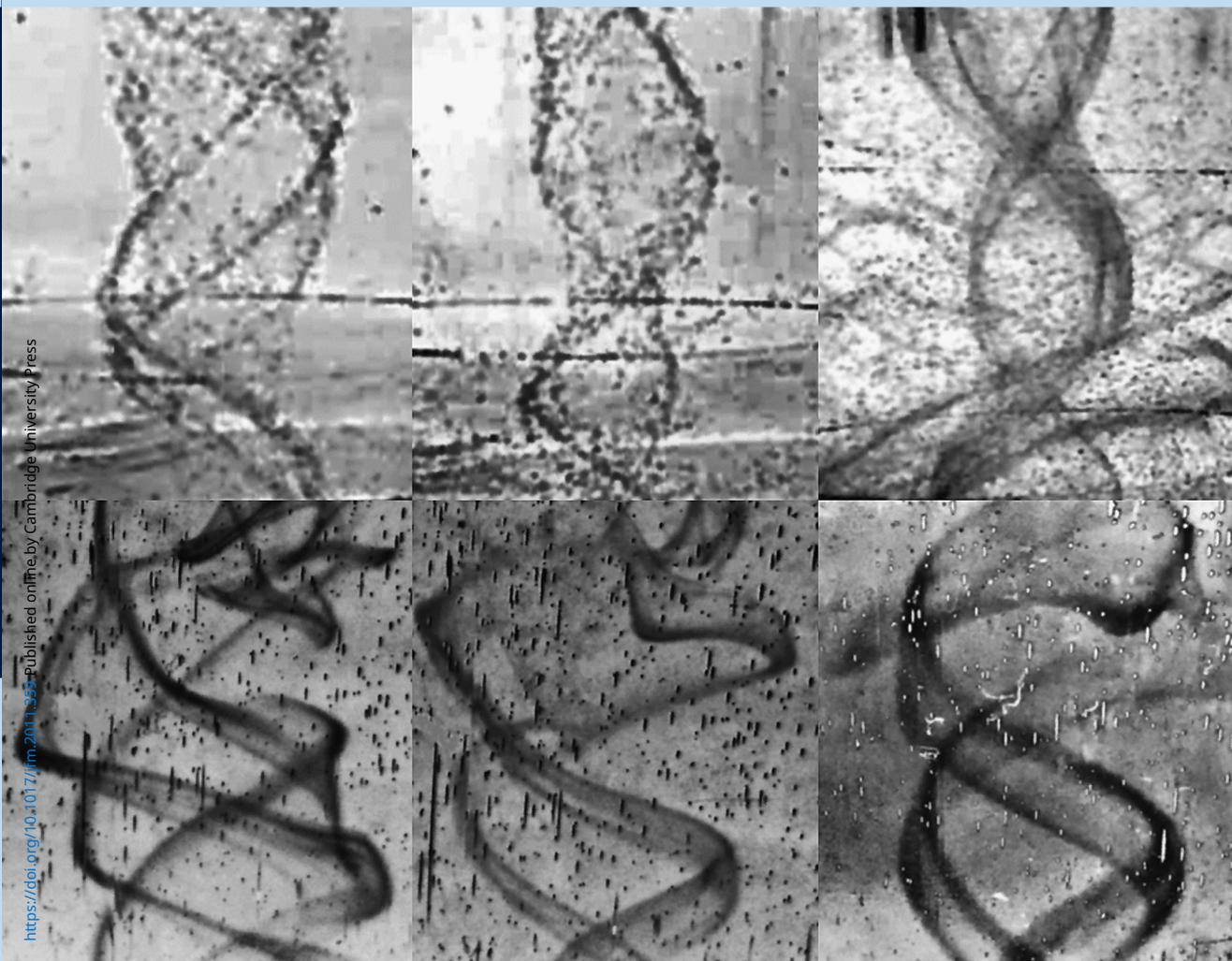


CAMBRIDGE
UNIVERSITY PRESS

25 September 2011

Journal of Fluid Mechanics

VOLUME 683



SUBSCRIPTIONS

The *Journal of Fluid Mechanics* (ISSN 0022-1120) is published *semimonthly* in 24 volumes each year by Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU, UK/Cambridge University Press, 32 Avenue of the Americas, New York, NY 10013-2473, USA. The subscription price (excluding VAT but including postage) for volumes 666–689, 2011, is £2558 or \$4806 (online and print) and £2300 or \$4104 (online only) for institutions; £730 or \$1377 (online and print) and £714 or \$1263 (online only) for individuals. The print-only price available to institutional subscribers is £2410 (US \$4320 in USA, Canada and Mexico). Single volumes cost £110 (US \$198 in the USA, Canada and Mexico) plus postage. Orders, which must be accompanied by payment, should be sent to any bookseller or subscription agent, or direct to the publisher: Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU. Subscriptions in the USA, Canada and Mexico should be sent to Cambridge University Press, Journals Fulfillment Department, 100 Brook Hill Drive, West Nyack, NY 10994-2133. EU subscribers (outside the UK) who are not registered for VAT should add VAT at their country's rate. VAT registered subscribers should provide their VAT registration number. Japanese prices for institutions are available from Kinokuniya Company Ltd, PO Box 55, Chitose, Tokyo 156, Japan. Prices include delivery by air. Copies of the *Journal* for subscribers in the USA, Canada and Mexico are sent by air to New York. Periodicals postage is paid at New York, NY, and at additional mailing offices. POSTMASTER: send address changes in USA, Canada and Mexico to *Journal of Fluid Mechanics*, Cambridge University Press, 100 Brook Hill Drive, West Nyack, NY 10994-2133. Claims for missing issues can only be considered if made immediately upon receipt of the subsequent issue. Copies of back numbers are available from Cambridge University Press.

COPYING

The *Journal* is registered with the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923. Organizations in the USA which are also registered with CCC may therefore copy material (beyond the limits permitted by sections 107 and 108 of US copyright law) subject to payment to CCC of the per-copy fee of \$16.00. This consent does not extend to multiple copying for promotional or commercial purposes. Code 0022-1120/2011/\$16.00.

ISI Tear Sheet Service, 3501 Market Street, Philadelphia, PA 19104, USA is authorized to supply single copies of separate articles for private use only.

Organizations authorized by the Copyright Licensing Agency may also copy material subject to the usual conditions.

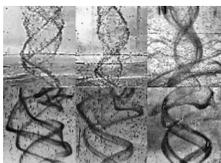
For all other use of material from the *Journal* permission should be sought from Cambridge or the American Branch of Cambridge University Press.

Information on *Journal of Fluid Mechanics* is available on <http://www.jfm.damtp.cam.ac.uk/> and it is included in the Cambridge Journals Online service which can be found at journals.cambridge.org/. For further information on other Press titles access cambridge.org/.

Readers should note that where reference is made to a Web site for additional material relating to an article published in *Journal of Fluid Mechanics* this material has not been refereed and the Editors and Cambridge University Press have no responsibility for its content.

This journal issue has been printed on FSC-certified paper and cover board. FSC is an independent, non-governmental, not-for-profit organization established to promote the responsible management of the World's forests. Please see www.fsc.org for information.

Printed by the University Press, Cambridge, UK.



The picture on the cover is based on figure 9 of 'Multiple helical modes of vortex breakdown', by J. N. Sørensen, I. V. Naumov & V. L. Okulov.

The JOURNAL OF FLUID MECHANICS exists for the publication of theoretical, computational and experimental investigations of all aspects of the mechanics of fluids.

EDITOR

Prof. M. G. Worster, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. FAX 44 1223 765900; mgw.jfm@damtp.cam.ac.uk

DEPUTY EDITORS

Prof. P. F. Linden, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. FAX 44 1223 765900; p.f.linden@damtp.cam.ac.uk

Prof. C. Meneveau, Department of Mechanical Engineering and Center for Environmental and Applied Fluid Mechanics, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA. FAX 1 410 516 7254; meneveau@jhu.edu

Editorial Office: FAX 44 1223 325802; JFMproduction@cambridge.org

ASSOCIATE EDITORS

Prof. D. Barthès-Biesel, Génie Biologique, Université de Technologie de Compiègne, BP 20529, Compiègne 60205, France. FAX 33 3 44 23 79 42; dbb@utc.fr

Prof. O. Bühler, Courant Institute of Mathematical Sciences, New York University, 251 Mercer Street, New York, NY 10012-1185, USA. FAX 1 212 995 4121; obuhler@cims.nyu.edu

Dr C. P. Caulfield‡, DAMTP, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. FAX 44 1223 765900; c.p.caulfield@damtp.cam.ac.uk

Prof. P. A. Davidson, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK. FAX 44 1223 332662; pad3@eng.cam.ac.uk

Prof. J. Duncan, Department of Mechanical Engineering, University of Maryland, College Park, Maryland 20742, USA. FAX 1 301 314 9477; duncan@umd.edu

Prof. M. D. Graham, Department of Chemical and Biological Engineering, University of Wisconsin-Madison, 1415 Engineering Drive, Madison, WI 53706-1691, USA. FAX 1 608 262 5434; graham@enr.wisc.edu

Prof. R. W. Griffiths, Research School of Earth Sciences, Australian National University, Building 61, Canberra, ACT 0200, Australia. FAX 61 2 6257 2737; Ross.Griffiths@anu.edu.au

Prof. É. Guazzelli†, IUSTI CNRS - Aix Marseille University, 5 rue Enrico Fermi, 13453 Marseille CEDEX 13, France. FAX 33 4 91 10 69 69; guazzelli.jfm@polytech.univ-mrs.fr

Prof. D. S. Henningson, KTH Mechanics, SE-10044 Stockholm, Sweden. FAX 46 8 205131; jfm@mech.kth.se

Prof. O. E. Jensen, School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK. FAX 44 115 951 3837; oliver.jensen@nottingham.ac.uk

Prof. Y. Kaneda, Department of Computational Science and Engineering, Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8603, Japan. FAX 81 52 789 4546; kaneda@cse.nagoya-u.ac.jp

Prof. D. Lohse, Physics of Fluids Group, Department of Applied Physics, Faculty of Science, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands. FAX 31 53 489 8068; lohse.jfm@tnw.utwente.nl

Prof. J. Magnaudet, Institut de Mécanique des Fluides de Toulouse, Allée Camille Soula, 31400 Toulouse, France. FAX 33 534 322 899; magnau.jfm@imft.fr

Prof. I. Marusic, Department of Mechanical Engineering, University of Melbourne, VIC 3010, Australia. FAX 61 3 9347 8784; imarusic@unimelb.edu.au

Prof. M. Matalon, Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, 1206 West Green Street, Urbana, IL 61801, USA. FAX 1 217 244 6534; matalon@illinois.edu

Prof. N. Peake†, DAMTP, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. FAX 44 1223 765900; N.Peake@damtp.cam.ac.uk

Prof. O. Pouliquen, IUSTI, CNRS - Aix Marseille University, 5 rue Enrico Fermi, 13453 Marseille CEDEX 13, France. FAX 33 4 91 10 69 69; pouliquen.jfm@polytech.univ-mrs.fr

Prof. J. J. Riley, Department of Mechanical Engineering, Box 352600, University of Washington, Seattle, WA 98195, USA. FAX 1 206 685 8047; rileyj@u.washington.edu

Prof. P. H. Steen, School of Chemical Engineering, Cornell University, Olin Hall, Ithaca, NY 14853-5201, USA. FAX 1 607 255 9166; phs7@cornell.edu

Prof. J. S. Wettlaufer†, Department of Geology and Geophysics, and Department of Physics, Yale University, 210 Whitney Avenue, PO Box 208109, New Haven, CT 06520, USA. FAX 1 203 432 3134; jfm@yale.edu

† Editor handling fast-track papers. ‡ Book Review and Focus on Fluids Editor.

SUMMARY OF INSTRUCTIONS FOR AUTHORS

Full instructions are available on the JFM web page at <http://www.jfm.damtp.cam.ac.uk>

Submission

Authors wishing to have papers published in the *Journal* should submit them via the online submission and refereeing system, Manuscript Central, at <http://mc.manuscriptcentral.com/cup/jfm>. Papers may be submitted to any editor or associate editor but fast track papers (10 printed pages or fewer) must be submitted to Professors Guazzelli, Peake or Wettlaufer who should be consulted in advance. Submission of a paper implies a declaration by the author that the work is not being considered for publication elsewhere and that it has not already been considered by a different editor of the *Journal*. Conference Reports must be submitted within three months of the meeting.

Preparation of papers

Authors are encouraged to write their papers clearly, concisely and attractively, so that their work will be readily understood. A brief summary of editorial requirements for notation, English and presentation is available on the JFM web page (address above). Authors are urged to use the JFM latex style macros. The [referee] option should be used for initial submission. The style file, together with a guide to its use, sample pages and details of editorial style and notation, is available via anonymous ftp from the Cambridge University Press at <ftp.cup.cam.ac.uk> in the directory `/pub/texarchive/journals/latex/jfm-cls` or `/pub/texarchive/journals/latex/jfm-sty`; or from the JFM Editorial Office. These files will be updated periodically; please make sure that you have the latest version. While use of the JFM latex style file is preferred, ordinary latex or plain tex files can also be accepted. Other software, such as Word, will be converted to latex by the Press or retyped. Manuscripts not prepared using the JFM latex style file should be typed in double spacing, with references listed at the end in alphabetical order of authors and with a separate list of figure captions.

Extensive detailed mathematical relations, tables or figures likely to be useful only to a few specialists will not be printed, but will be available as an electronic supplement to the online version or from the JFM Editorial Office.

Movies

Refereed movies that are integral to a paper can be linked to the online version.

Accepted papers

Once a paper is accepted, final production files (e.g. the LaTeX source) must be uploaded to the Manuscript Central site and any material not available electronically should be sent to the JFM Editorial Office, labelled with the paper's ID number. Full details are given on the JFM web page. Do not email files to the JFM Editorial Office unless requested to do so.

Charges

There is no charge for publication, but the cost of any colour figures must be borne by authors. Authors will receive a PDF file of their published article via email. Printed offprints can be purchased if ordered when the proofs are returned.

Address questions or comments to Mrs Amanda Johns (Editorial Assistant) or Mrs Alison James (Production Editor) at the Journals Department, Cambridge University Press, Shaftesbury Road, Cambridge CB2 8RU, UK; tel: 44 (0)1223 347922; fax: 44 (0)1223 325802; e-mail: JFMproduction@cambridge.org.