MATHEMATICAL REFORMULATION OF THE KOLMOGOROV-RICHARDSON ENERGY CASCADE IN TERMS OF VORTEX STRETCHING

TSUYOSHI YONEDA, SUSUMU GOTO, AND TOMONORI TSURUHASHI

ABSTRACT. In this paper, with the aid of direct numerical simulations (DNS) of forced turbulence in a periodic domain, we mathematically reformulate the Kolmogorov-Richardson energy cascade in terms of vortex stretching. By using the description, we prove that if the Navier-Stokes flow satisfies a new blowup criterion in terms of the enstrophy production rate, then the flow does not blow up. Our DNS results seem to support this blowup criterion. Next, we mathematically construct the hierarchy of tubular vortices, which is statistically self-similar in the inertial range. Under the assumptions of the scale-locality of the vortex stretching/compressing (i.e. energy cascade) process and the statistical independence between vortices that are not directly stretched or compressed, we can derive the −5/3 power law of the energy spectrum of statistically stationary turbulence without directly using the Kolmogorov hypotheses.

1. INTRODUCTION

Since the seminal study by Orszag and Patterson (1972) [21], the numerical integration (i.e. the direct numerical simulations, DNS) of the Navier-Stokes equation without any turbulence model has been playing important roles in turbulence researches; see Ref. [12] for a review of DNS of turbulence. One of the most important features unveiled by DNS of turbulence is that turbulence is not random but composed of coherent motions. In particular, recent DNS [7, 9, 18, 19] of turbulence at sufficiently high Reynolds numbers have revealed that there exists a hierarchy of coherent vortices in developed turbulence.

In the present study, we investigate the energy cascade picture [23, 5] in turbulence of an incompressible fluid with uniform density and kinematic viscosity ν under periodic boundary conditions in three orthogonal directions; and, on the basis of the picture, we develop arguments on the global-in-time smooth solution of the Navier-Stokes equation. Since we need external force to drive flow in a periodic cube, we impose body force f which injects the kinetic energy at a large scale $\mathcal{L}$. Here, we define the Reynolds number by

(1.1) $$Re = U\mathcal{L}/\nu$$

with U being the characteristic velocity directly driven by f. When Re is sufficiently high (more concretely, higher than $O(10^4)$ [4]), turbulence is composed of vortices with various length scales. We reemphasize that these vortices are coherent

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Marco Cascella

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   Foundations of Computational Intelligence Volume 3 Ajith Abraham,Aboul-Ella Hassanien,Patrick Siarry,Andries Engelbrecht,2009-04-27 Global optimization is a branch of applied mathematics and numerical analysis that deals with the task of finding the absolutely best set of admissible conditions to satisfy certain criteria objective function s formulated in mathematical terms Global optimization includes nonlinear stochastic and combinatorial programming multiobjective programming control games geometry approximation algorithms for parallel architectures and so on Due to its wide usage and applications it has gained the attention of researchers and practitioners from a plethora of scientific domains Typical practical examples of global optimization applications include Traveling salesman problem and electrical circuit design minimize the path length safety engineering building and mechanical structures mathematical problems Kepler conjecture Protein structure prediction minimize the energy function etc Global Optimization algorithms may be categorized into several types Deterministic example branch and bound methods Stochastic optimization example simulated annealing Heuristics and meta heuristics example evolutionary algorithms etc Recently there has been a growing interest in combining global and local search strategies to solve more complicated optimization problems This edited volume comprises 17 chapters including several overview Chapters which provides an up to date and state of the art research covering the theory and algorithms of global optimization Besides research articles and expository papers on theory and algorithms of global optimization papers on numerical experiments and on real world applications were also encouraged The book is divided into 2 main parts   A History of Economic Theory T. Negishi,1989   The Origins of International Economics: General equilibrium in international trade Robert William Dimand,2004 A collection of materials reprinted from various sources   The Expanding Worlds of General Relativity Hubert Goenner,Jürgen Renn,Jim Ritter,Tilman Sauer,1998-12-01 The past decade has seen a considerable surge of interest in historical and philo sophical studies of gravitation and relativity due not only to the tremendous amount of world wide research in general relativity and its theoretical and observational consequences but also to an increasing awareness that a collaboration between working scientists historians and philosophers of science is in this field partic ularly promising for all participants The expanding activity in this field is well documented by recent volumes in this Einstein Studies series on the History of General Relativity as well as by a series of international conferences on this topic at Osgood Hill 1986 Luminy 1988 and Pittsburgh 1991 The fourth of these conferences hosted by the Max Planck Institute for the History of Science was held in Berlin from 31 July to 3 August 1995 with a record attendance of some 80 historians and philosophers of science physicists mathematicians and as tronomers Based on presentations at the Berlin conference this volume provides an overview of the present state of research in this field documenting not only the increasing scope of recent investigations in the history of relativity and gravitation but also the emergence of several key issues that will probably remain at the focus of debate in the near future RELATIVITY IN THE MAKING The papers of this section deal with

the origins and genesis of relativity theory **The Collected Scientific Papers of Paul A. Samuelson** Paul Anthony Samuelson,1972 The col scient pap P A Samuelson Ed R C Merton v 3 *Foundations Of The Theory Of General Equilibrium (Second Edition)* Yves Balasko,2016-05-11 The economic theory of general equilibrium underpins the most important models used in economic theory in general and in its more specialized areas such as macroeconomics international trade environmental economics growth theory and developmental economics In Foundations of the Theory of General Equilibrium leading academic scholar Yves Balasko offers a good introduction to the economic theory of general equilibrium and makes use of various mathematical tools as intuitive and easy as possible The second half of the book addresses properties of the general equilibrium model that are still at the frontier of current research These properties deal with the characterization of economies with a unique equilibrium and more generally with the relationships between the number of equilibria and the fundamentals of an economy **Reformulation: Nonsmooth, Piecewise Smooth, Semismooth and Smoothing Methods** Masao Fukushima,Liqun Qi,2013-04-17 The concept of reformulation has long been playing an important role in mathematical programming A classical example is the penalization technique in constrained optimization that transforms the constraints into the objective function via a penalty function thereby reformulating a constrained problem as an equivalent or approximately equivalent unconstrained problem More recent trends consist of the reformulation of various mathematical programming prob lems including variational inequalities and complementarity problems into equivalent systems of possibly nonsmooth piecewise smooth or semismooth nonlinear equations or equivalent unconstrained optimization problems that are usually differentiable but in general not twice differentiable Because of the recent advent of various tools in nonsmooth analysis the reformulation approach has become increasingly profound and diversified In view of growing interests in this active field we planned to organize a cluster of sessions entitled Reformulation Nonsmooth Piecewise Smooth Semismooth and Smoothing Methods in the 16th International Symposium on Mathematical Programming ismp97 held at Lausanne EPFL Switzerland on August 24 29 1997 Responding to our invitation thirty eight people agreed to give a talk within the cluster which enabled us to organize thirteen sessions in total We think that it was one of the largest and most exciting clusters in the symposium Thanks to the earnest support by the speakers and the chairpersons the sessions attracted much attention of the participants and were filled with great enthusiasm of the audience **Gravitation and Spacetime** Hans C. Ohanian,Remo Ruffini,2013-04-08 The third edition of this classic textbook is a quantitative introduction for advanced undergraduates and graduate students It gently guides students from Newton s gravitational theory to special relativity and then to the relativistic theory of gravitation General relativity is approached from several perspectives as a theory constructed by analogy with Maxwell s electrodynamics as a relativistic generalization of Newton s theory and as a theory of curved spacetime The authors provide a concise overview of the important concepts and formulas coupled with the experimental results underpinning the latest research in the field Numerous exercises in Newtonian gravitational theory and

Maxwell s equations help students master essential concepts for advanced work in general relativity while detailed spacetime diagrams encourage them to think in terms of four dimensional geometry Featuring comprehensive reviews of recent experimental and observational data the text concludes with chapters on cosmology and the physics of the Big Bang and inflation **EPSA Philosophical Issues in the Sciences** Mauricio Suárez,Mauro Dorato,Miklós Rédei,2010-07-17 This volume collects papers presented at the Founding Conference of the European Philosophy of Science Association meeting held November 2007 It provides an excellent overview of the state of the art in philosophy of science in different European countries General Relativity Conflict and Rivalries Galina Weinstein,2016-01-14 This book focuses on Albert Einstein and his interactions with and responses to various scientists both famous and lesser known It takes as its starting point that the discussions between Einstein and other scientists all represented a contribution to the edifice of general relativity and relativistic cosmology These scientists with whom Einstein implicitly or explicitly interacted form a complicated web of collaboration which this study explores focusing on their implicit and explicit responses to Einstein s work This analysis uncovers latent undercurrents indiscernible to other approaches to tracking the intellectual pathway of Einstein to his general theory of relativity The interconnections and interactions presented here reveal the central figures who influenced Einstein during this intellectual period Despite current approaches to history presupposing that the efforts of scientists such as Max Abraham and Gunnar Nordstr m which differed from Einstein s own views be relegated to the background this book shows that they all had an impact on the development of Einstein s theories stressing the limits of approaches focusing solely on Einstein As such General Relativity Conflict and Rivalries proves that the general theory of relativity was not developed as a single coherent construction by an isolated brooding individual but rather that it came to fruition through Einstein s conflicts and interactions with other scientists and was consolidated by his creative processes during these exchanges **Optimization and Control for Systems in the Big-Data Era** Tsan-Ming Choi,Jianjun Gao,James H. Lambert,Chi-Kong Ng,Jun Wang,2017-05-04 This book focuses on optimal control and systems engineering in the big data era It examines the scientific innovations in optimization control and resilience management that can be applied to further success In both business operations and engineering applications there are huge amounts of data that can overwhelm computing resources of large scale systems This big data provides new opportunities to improve decision making and addresses risk for individuals as well in organizations While utilizing data smartly can enhance decision making how to use and incorporate data into the decision making framework remains a challenging topic Ultimately the chapters in this book present new models and frameworks to help overcome this obstacle Optimization and Control for Systems in the Big Data Era Theory and Applications is divided into five parts Part I offers reviews on optimization and control theories and Part II examines the optimization and control applications Part III provides novel insights and new findings in the area of financial optimization analysis The chapters in Part IV deal with operations analysis covering flow shop operations and quick response systems The book

concludes with final remarks and a look to the future of big data related optimization and control problems **The Palgrave Companion to Chicago Economics** Robert A. Cord,2023-01-01 The University of Chicago has been and continues to be one of the most important global centres for economics With six chapters on themes in Chicago economics and 33 chapters on the lives and work of Chicago economists this volume shows how economics became established at the University how it produced some of the world s best known economists including Frank Knight Milton Friedman and Robert Lucas and how it remains a global force for the very best in teaching and research in economics With original contributions from a stellar cast this volume provides economists especially those interested in macroeconomics and the history of economic thought with an in depth analysis of Chicago economics *Economic Thought Since Keynes* Michel Beaud,Gilles Dostaler,2005-09-27 Economic Thought Since Keynes provides a concise overview of changing economic thought in the latter part of the twentieth century Part 1 gives an analysis of topics including Keynes and the General Theory the triumph of interventionism the neoclassical synthesis the resurgence of liberalism Part 11 gives a concise biography of the 150 most influential economists since Keynes This invaluable book will be a useful reference tool for anyone teaching or studying economics **Collected Papers** Lloyd Appleton Metzler,1973 A pioneer in bringing mathematical methods into everyday use in economics Lloyd A Metzler is well known for his adroit use of formal tools and exceptionally readable prose style which have provided a generation of economists with clear solutions to difficult analytical problems The papers collected in this volume including four previously unpublished retain a freshness and clarity that is readily recognized by today s students of economics Over the years Mr Metzler s contributions to economic theory have ranged widely over the fields of international economics macroeconomic theory business fluctuations and the mathematical theory of general equilibrium Most notably he carries Lord Keynes s theories further working out the essential properties of the foreign trade multiplier His discussions of tariff repercussions capital transfers and stability conditions in the foreign exchange market are of vital importance to today s dramatic efforts to achieve economic stability throughout the world Collected Papers enhanced by many tables and figures and clearly indicative of the author s far reaching economic mind is organized into four sections The Theory of International Trade Money Interest and Prices Business Cycles and Economic Fluctuations and Mathematical Economics and Statistics Two of the articles in this volume were part of the author s doctoral thesis which was awarded the David A Wells Prize at Harvard University **Man and the Social Sciences (Routledge Revivals)** William Alexander Robson,2014-02-04 One of the most significant movements in the world of learning in the twentieth century was the rise and development of the social sciences However few attempts have been made to see how far social scientists have travelled on the road to studying and understanding human society First published in 1972 the lectures reprinted in this book aim to trace the development of the social sciences during the twentieth century and to show the role of the London School of Economics and Political Science in this development since it was founded in 1895 Each of the very distinguished lecturers was asked to take the larger view to

be critical where necessary to treat his subject in the context of the world of learning The result is a survey of exceptional interest in which the growth of the social sciences is analysed from a number of contrasting viewpoints each of which ranges widely and often with provocative brilliance over themes that are of general concern The introduction by Professor W A Robson which was not part of the original lecture series is in itself a critical assessment of the field that will be read with close attention *The Formative Years of Relativity* Hanoch Gutfreund,Jürgen Renn,2017-09-08 First published in 1922 and based on lectures delivered in May 1921 Albert Einstein s The Meaning of Relativity offered an overview and explanation of the then new and controversial theory of relativity The work would go on to become a monumental classic printed in numerous editions and translations worldwide Now The Formative Years of Relativity introduces Einstein s masterpiece to new audiences This beautiful volume contains Einstein s insightful text accompanied by important historical materials and commentary looking at the origins and development of general relativity Hanoch Gutfreund and J rgen Renn provide fresh original perspectives placing Einstein s achievements into a broader context for all readers In this book Gutfreund and Renn tell the rich story behind the early reception spread and consequences of Einstein s ideas during the formative years of general relativity in the late 1910s and 1920s They show that relativity s meaning changed radically throughout the nascent years of its development and they describe in detail the transformation of Einstein s work from the esoteric pursuit of one individual communicating with a handful of colleagues into the preoccupation of a growing community of physicists astronomers mathematicians and philosophers This handsome edition quotes extensively from Einstein s correspondence and reproduces historical documents such as newspaper articles and letters Inserts are featured in the main text giving concise explanations of basic concepts and short biographical notes and photographs of some of Einstein s contemporaries are included The first ever English translations of two of Einstein s popular Princeton lectures are featured at the book s end

Studies in the Theory of International Trade Jacob Viner,2016-11-03 In this book originally published in 1937 Jacob Viner traces in a series of studies of contemporary source material the evolution of the modern orthodox theory of international trade from its beginnings in the revolt against English mercantilism in the 17th and 18th centuries through the English currency and tariff controversies of the 19th century to the late 20th century The author offers a detailed examination of controversies in the technical literature centering on important propositions of the classical and neo classical economists relating to the theory of the mechanism of international trade and the theory of gain from trade **Learning and Intelligent Optimization** Carlos A. Coello-Coello,2011-12-15 This book constitutes the thoroughly refereed post conference proceedings of the 5th International Conference on Learning and Intelligent Optimization LION 5 held in Rome Italy in January 2011 The 32 revised regular and 3 revised short papers were carefully reviewed and selected from a total of 99 submissions In addition to the contributions to the general track there are 11 full papers and 3 short papers presented at the following four special sessions IMON Intelligent Multiobjective OptimizatioN LION PP Performance Prediction Self EAs Self

tuning self configuring and self generating evolutionary algorithms LION SWAP Software and Applications **Essays on and in the Chicago Tradition** Don Patinkin,1981 *Historical Roots of Spontaneous Symmetry Breaking* Rocco Gaudenzi,2022-04-28 What are the thinking processes and knowledge resources involved in a complex discovery How can the physics of solids the physics of nuclei and elementary particle physics cross fertilise in spite of the widely differing domains and energy scales they deal with This book addresses the questions by reconstructing and examining from the historical epistemological perspective the fascinating heuristic path to the concept of spontaneous symmetry breaking This analysis especially brings to light the role that analogical reasoning and mathematical reformulations played in the discovery process as well as the influence of the Japanese milieu and approach to physical problems

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