

Review

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Review

Seventy Years of Compressible-Flow Physics at Moscow University: A Scientific Retrospective on the Research of Professor Fedor Vasilievich Shugaev

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Abstract

This article reviews the research of Fedor Vasilievich Shugaev, Doctor of Physical and Mathematical Sciences and Professor at the Faculty of Physics of M. V. Lomonosov Moscow State University. Over a career at MSU spanning more than six decades, Professor Shugaev has published 146 journal articles, 4 monographs, 46 conference papers and 83 invited talks, and supervised twelve Candidate-of-Sciences dissertations and twenty diploma theses. The main research lines covered below are the propagation and reflection of shock waves; shock-wave interaction with vortices, acoustic disturbances and turbulent fluctuations; shock-wave dynamics in low-temperature and discharge plasmas; the geometry and stability of magnetised and astrophysical bow shocks; Navier–Stokes-based methods for vortex acoustics; laser-beam propagation through the turbulent atmosphere; and a recent cycle of work in theoretical astrophysics.

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1. Introduction

Professor Fedor Vasilievich Shugaev (born 19 October 1932 in Moscow) graduated from the Faculty of Physics of M. V. Lomonosov Moscow State University in 1955 [1]. He defended his Candidate-of-Sciences dissertation, *Interaction of a Supersonic Flow with a Blunt Body*, in 1965, and his Doctor-of-Sciences dissertation, *Dynamic Compatibility Conditions and Their Application to the Propagation of Shock Waves*, in 1985; he became Docent in 1972 and Professor in 2012. Between 1982 and 1986 he was acting head of the Department of Molecular Physics and Physical Measurements of the Faculty of Physics [1]. He is currently Professor at the Department of Molecular Processes and Extreme States of Matter of the same Faculty [2]. His research has stayed within a single broad subject: the behaviour of compressible gases in regimes that combine strong non-linearity, dissipation and non-equilibrium effects, treated through the Navier–Stokes equations.

According to the ISTINA database [2], Professor Shugaev has authored or co-authored 146 journal articles, 4 books, 46 conference papers and 83 invited talks. He has supervised 12 Candidate-of-Sciences dissertations and 20 diploma theses, and holds one patent; Scopus lists 135 citations to his work, Web of Science 129. The present article does not enumerate this record. Instead, it follows the principal lines of research in roughly chronological order, picking from each the publications that shaped the subsequent work.

2. Propagation and Reflection of Shock Waves—The Founding Programme

Professor Shugaev's first line of work, already present in his 1965 Candidate dissertation on the interaction of a supersonic flow with a blunt body, deals with the propagation of three-dimensional shock waves and their reflection from curved and grooved bodies. The 1976 paper 'On the motion of shock waves in a gas with variable parameters' in the *USSR Journal of Computational Mathematics and*

Mathematical Physics [3] introduces a ray method for weak and moderate shocks in media with smooth inhomogeneities. This method underlies most of his work over the next two decades and provided the framework for his 1985 Doctor-of-Sciences dissertation, *Dynamic Compatibility Conditions and Their Application to the Propagation of Shock Waves*.

Three sub-themes grew out of this programme. The unsteady reflection of a shock from spherical and cylindrical bodies was studied with N. N. Sysoev, M. V. Piskaryova, V. G. Markin and A. P. Ryazin in 1977–1979 [4–7]. The reflection from bodies with grooves, slots and cavities, geometries relevant to supersonic intakes and shock-tube diagnostics, was treated with I. A. Znamenskaya, M. A. Ibragim, V. G. Grudnitsky, E. M. Kudryavtsev, V. N. Podobryaev, A. O. Serov and L. S. Shtemenko in *Izvestiya AN SSSR. Mekhanika Zhidkosti i Gaza, Doklady AN SSSR, Akusticheskii Zhurnal, Uchenye Zapiski TsAGI* and their English translations (*Fluid Dynamics, Fluid Mechanics – Soviet Research*) between 1980 and 1987 [8–14]. The propagation of shocks through media with localised thermal or compositional inhomogeneities, including the growth of density gradients in heated regions, was treated in [15,16].

The synthesis of this work is the 1998 World Scientific monograph *Propagation and Reflection of Shock Waves*, written with L. S. Shtemenko as volume 49 of the *Series on Advances in Mathematics for Applied Sciences* [17]. The book combines the ray method of the 1970s with numerical and experimental treatments of shock focusing on concave bodies, the formation of jets and vortices behind reflected shocks, the appearance of disturbances on the shock front, and shock propagation through weakly ionised plasmas. Its main experimental result, observed jointly with H. Kishige and M. Nishida of Kyushu University, was published the same year in *Shock Waves* [18].

3. Shock–Vortex, Shock–Acoustic and Shock–Turbulence Interactions

In 1978 Professor Shugaev opened a second line of work: the interaction of shock waves with organised vorticity and with acoustic and turbulent fluctuations. With M. A. Ibragim and A. I. Klimov he published three back-to-back papers: *Interaction of a vortex ring with a shock wave* [19], an experimental study of the same problem [20], and a theoretical treatment of sound-wave interaction with a shock front [21]. In the early 1980s the same group, joined by I. A. Znamenskaya, studied the oscillations of a shock front during reflection from a resonator [22].

In the 1990s the programme grew to include the statistics of turbulent fluctuations downstream of a shock. With O. A. Azarova, E. A. Bratinkova, A. V. Samsonov, V. E. Yanitsky and L. S. Shtemenko, the papers of 1995–1999 in *Vestnik Moskovskogo Universiteta* developed the theory of shock-induced amplification of density and pressure fluctuations [23–26]. The numerical treatment was set out in 2003 with O. A. Azarova and L. S. Shtemenko in the *Computational Fluid Dynamics Journal* [27]. The stability of the shock front in non-uniform and magnetised media was treated with A. P. Kalinchenko in two papers on corrugation instability: in inhomogeneous gases (2001) and in plane MHD shocks (2003) [28,29].

This turbulence–shock programme matured into the cycle of papers with O. I. Dokukina, E. N. Terentiev and L. S. Shtemenko: *Pressure Fluctuations within a Turbulent Gas Flow and Their Interaction with a Shock Wave* (Moscow University Physics Bulletin, 2013) [30], *Grid Turbulence and its Interaction with a Shock Wave* (Doklady Physics, 2017) [31], and the binary-mixture extension *Density and Pressure Fluctuations in a Turbulent Flow of Air and Argon and Their Interaction with a Shock Wave* (2019) [32]. A 2018 paper with D. Yu. Cherkasov on the evolution of acoustic radiation by an ensemble of vortex rings in air [33] returns to the 1978 vortex-ring problem in a three-dimensional setting.

4. Shock Waves in Low-Temperature and Discharge Plasmas

A third direction concerns shock waves in weakly ionised media. From the mid-1980s to the late 1990s Professor Shugaev led an experimental and theoretical programme on shock dynamics in carbon-torch plasmas (with A. M. Galkin, S. A. Dvinin, A. P. Ershov and N. N. Sysoev, 1985, 1988) [34–36], in high-frequency discharge plasmas (with S. A. Bystrov, I. S. Zaslono, Yu. K. Mukoseev

and others, 1990–1993) [37–40], and in non-self-sustained CO₂ discharges (with I. V. Kochetov, D. A. Mazalov, A. P. Napartovich, A. F. Pal, V. V. Pichugin and A. V. Filippov, 1995) [41,42]. The cycle closed with the 1998 *Plasma Physics Reports* paper on the dynamics of shock waves during optical breakdown in a non-self-maintained discharge plasma [43].

An experimental sub-line produced three papers in the 1993 inaugural volumes of the *Journal of Flow Visualization and Image Processing* [44–46]. They introduced a laser-schlieren technique for reconstructing density profiles from the diffraction of acoustic waves. The technique was refined with H. Honma, V. I. Ivanov, J. Koreeda, K. Maeno and H. Yanagisawa of Chiba University and published in *Shock Waves* in 1998 [47]. Twenty years later, the plasma–flow theme reappeared in the 2018 *Journal of Physics: Conference Series* paper on dusty waves and vortices in rf magnetron discharge plasma, with A. V. Filippov, A. F. Pal, A. N. Ryabinkin and A. O. Serov [48].

5. Magnetospheric Bow Shocks: An International Collaboration

In 2001 Professor Shugaev's interest in shock geometry moved into space physics. Two papers, published the same year in *Advances in Space Research* [49] and *Earth, Planets and Space* [50], reconstruct the three-dimensional shape and motion of the terrestrial bow shock from observations by the *Interball*, *Magion 4* and *Wind* spacecraft. The co-authors are T. Gombosi, K. Kabin, A. P. Kalinchenko, M. Kessel, G. Kotova, Z. Nemecek, J. Safrankova, J. Slavin, A. Szabo and M. Verigin. Both papers are still cited in the literature on empirical bow-shock geometry.

6.. Navier–Stokes methods for vortex acoustics

From the late 1980s onwards Professor Shugaev developed a procedure for solving the unsteady, three-dimensional Navier–Stokes system by expanding the solution in powers of a small parameter (for compressible flow, the initial vorticity) and applying the fundamental solution matrix of the linear parabolic system associated with the linearised operator. The method places no restriction on the Reynolds number or on the amplitude of the turbulent fluctuations. The derivation appeared in the 2009 WDS proceedings of Charles University [51] and in a 2015 chapter of the *International Journal of Fluid Mechanics Research* [52].

Applied to the spontaneous sound radiation of an isolated cylindrical vortex in a viscous heat-conducting gas, the method produced a small cycle of papers published between 2012 and 2016: an analysis of the oscillations of flow parameters in the vortex vicinity (Moscow University Physics Bulletin, 2012) [53], the calculation of the dominant acoustic radiation frequency (2015) [54], and the complete acoustic spectrum, including viscous and thermal-conduction contributions, in *Computation* 4(3) (2016) [55]. A longer Russian-language version of the intermediate calculations appeared the same year in *Nanostructures: Mathematical Physics and Modelling*. The three-dimensional generalisation, *Acoustic Radiation by 3D Vortex Rings in Air*, appeared in 2015 in *Aerospace* with D. Cherkasov and O. Solenaya [56].

7. Laser-Beam Propagation Through the Turbulent Atmosphere

From the mid-2000s Professor Shugaev's group, with E. N. Terentiev, L. S. Shtemenko, O. I. Dokukina, O. A. Nikolaeva, T. I. Arsenyan, N. A. Sukhareva and A. P. Sukhorukov, worked on the propagation of laser beams through atmospheric turbulence. The first paper appeared in 2005 in *Izvestiya RAN, Seriya Fizicheskaya* [57]. A series of *Proceedings of SPIE* papers in *Optics in Atmospheric Propagation and Adaptive Systems* followed: the strong-turbulence regime and beam focusing in 2008 [58], the general characterisation of beam propagation in 2009 [59], specific beam-propagation problems in 2010 [60], and the statistical properties of atmospheric density fluctuations in 2011 [61].

The analytical strand of the programme produced the 2014 *Doklady Akademii Nauk* paper with O. A. Nikolaeva on an analytical solution describing Gaussian-beam propagation in an inhomogeneous gas [62], and a 2014 SPIE paper on modelling laser-beam propagation through turbulence [63]. The non-paraxial Gaussian beam in a non-uniform atmosphere was the subject of

SPIE papers in 2017, 2018, 2019 and 2021, with O. A. Nikolaeva, N. A. Sukhareva and E. N. Terentiev [64–67]. A 2021 paper in *Protsessy v geosredakh* with D. M. Volkova addresses the detection of point objects in measurement devices with unknown instrument function [68].

8. Recent Work: Theoretical Astrophysics

Between 2022 and 2023 Professor Shugaev, with E. N. Terentiev and N. E. Shilin-Terentyev, published three papers that open a new direction in theoretical astrophysics: *The Analysis of Action Mechanisms of Black Holes* in the *Journal of Applied Mathematics and Computation* [69], the companion paper *Objects of Civilization of the Second and Third Types* [70], and the Russian-language paper on the vicinity of black holes and protoplanetary discs in *Mnogofaznye Sistemy* [71]. The papers extend the fundamental-solution-matrix approach to regimes of strong gravity and accretion physics.

9. Pedagogy and Scientific School

Professor Shugaev has supervised 12 Candidate-of-Sciences dissertations and 20 diploma theses. He has designed and delivered lecture courses at the Faculty of Physics, including *Introduction to the Theory of Nonlinear Waves* and *Hydrodynamics of Superfluids* [1]. The 1987 monograph *Shock Waves in Gases and Condensed Media* (MSU Press, co-authored) [72] preceded the World Scientific book of 1998 [17]; the textbook *Introduction to the Theory of Nonlinear Waves* (MSU Press, 2011) [73] collects the lecture material. He holds one patent [2]. His long-term co-authors include L. S. Shtemenko (World Scientific monograph), A. O. Serov (shock-reflection programme of the 1980s and 1990s), I. A. Znamenskaya (resonator and groove studies), N. N. Sysoev and A. M. Galkin (carbon-torch experiments), A. V. Filippov and A. F. Pal (plasma gas dynamics), O. A. Azarova, V. E. Yanitsky and E. A. Bratinkova (turbulence–shock cycle), A. P. Kalinchenko (shock stability), E. N. Terentiev, O. I. Dokukina, O. A. Nikolaeva and N. A. Sukhareva (atmospheric optics), and, more recently, D. Yu. Cherkasov and N. E. Shilin-Terentyev. The ISTINA profile lists more than fifty co-authors in total [2].

10. Concluding Remarks

Professor Shugaev's work returns repeatedly to the same set of questions. The propagation of shocks in a non-uniform compressible medium, posed in his 1976 paper [3], reappears in the 2019 study of air–argon mixtures [32]. The 1978 vortex-ring/shock-wave interaction [19] returns in the 2018 ensemble-of-vortex-rings paper [33]. The jets and vortices behind a reflected shock that occupy much of the 1998 monograph [17,18] reappear in the 2015–2016 cylindrical-vortex acoustics cycle [54,55]. The recent astrophysical papers [69–71] continue the same line of interest in strong compressions, vortical structure and the statistical state of matter far from equilibrium.

Professor Shugaev remains an active member of the Faculty of Physics of Moscow State University.

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