A.A. Andronov and the Development of Soviet Control Engineering

Chris Bissell

Control engineering saw rapid development in many countries in the period immediately following World War II. Engineers and scientists concerned with control problems formed new professional groupings; university courses in the subject began to be offered; and research groups were set up in industrial, academic, and government laboratories. Hitherto secret wartime work was widely disseminated, and new military, industrial, and other applications of the emerging discipline were identified.

Aleksandr Aleksandrovich Andronov (1901-1952) was a key figure in the development of control engineering in the former Soviet Union during this period, yet his name and his contributions to control theory and nonlinear dynamics are much less well known in the West than they deserve. The aim of this article is to give a brief introduction to Andronov's work, concentrating on his background in nonlinear dynamics, and his subsequent role in stimulating Soviet research into control engineering—most significantly in the wake of the founding of his Moscow "seminar" on the topic in 1944.

The Mandelstam-Andronov School of Nonlinear Dynamics

An important center for the study of nonlinear dynamics in Russia from the 1920s onward was the group that formed in Moscow around L.I. Mandelstam and N.D. Papalexi. Research by this group led, among other things, to the development of the theory of multivibrators and the creation of the discipline of radio-geodesy.

Andronov was one of a number of young physicists who began their academic careers studying nonlinear dynamics as research students under Mandelstam. Mandelstam was renowned as a gifted lecturer and teacher, and his group was characterized by a collaborative intellectual environment in which any artificial separation of theoretical and practical physics, or of teaching and research, was rejected (see sidebar). Andronov, like many of his fellow students, was strongly influenced by Mandelstam's style; and the best features of Mandelstam's group were to form the basis of Andronov's own teaching and research in later life. Indeed, Andronov maintained close contact with his former teacher until Mandelstam's death in 1944. Mandelstam acted as formal proposer for most, if not all, of Andronov's papers that appeared in the publications of the Soviet Academy of Sciences up to that year.

One of Andronov's first great achievements was to demonstrate, in the late 1920s, the connection between Poincaré's limit cycles and a whole range of practical oscillatory processes [1]. Oscillatory phenomena in chemistry, biology, and engineering, Andronov predicted, would be amenable to the phase-plane techniques developed initially in quite another context. This work was the start of an enormously fruitful period. As Minorsky was to put it 30 years later, Andronov and his colleagues made the fundamental link between singular points and positions of equilibria; between limit cycles and stationary motion; and between self-excitations and bifurcations [2]. In a series of publications, Andronov and others (particularly L.S. Pontryagin and A.A. Vitt) developed a rigorous approach to nonlinear systems, taking as their starting point the work of Poincaré and Lyapunov in the 19th century, but going much further. One strand of this work culminated in the 1937 classic "Theory of Oscillations" [3], jointly authored by Andronov with S.E. Khaikin and A.A. Vitt. (Vitt's name never appeared in the first edition of this work; he was arrested in 1937 and died the next year in a Siberian labor camp [4].) To gain an impression of this scientific classic, readers without a knowledge of Russian are referred either to the English adaptation of the first edition by Lefshetz [5] or to the full translation of the

Fig. 1. Aleksandr Aleksandrovich Andronov.

The author is with The Open University, Milton Keynes, United Kingdom, GB-MK7 6AA; c.c.bissell@open.ac.uk.

Russian second edition [6]. Neither is an ideal reflection of the original, however. Lefshetz omitted and modified much of the text of the first edition; while the second edition, although much more detailed and (unlike the first) dealing with specific control applications, is a version which appeared well after Andronov's death, greatly expanded and partially rewritten by other contributors.

Leonid Isaakovich Mandelstam

Leonid Isaakovich Mandelstam (1879-1944) was one of the most distinguished Soviet physicists of the first half of the 20th century. Expelled from Odessa University after student riots in 1899, he continued his undergraduate and postgraduate studies in Strasbourg, returning to Russia in 1914. A variety of scientific and academic posts followed, culminating in the chair of Theoretical Physics at Moscow State University in 1925 and full membership of the Soviet Academy of Sciences in 1929.

Mandelstam's research centered on optics and radiophysics. In 1918 he suggested that Rayleigh lines should possess a fine structure (due to what was to become known as the Brillouin effect). Together with G.S. Landsberg he discovered Raman scattering in crystals, independently of Raman and Krishnan's work on liquids. Collaboration with Papaleksi and others on nonlinear systems, and on linear systems with time-varying parameters, led to a number of important results in electrotechnology, including the theory of multivibrators and the construction of the first parametric oscillator with periodically varying inductance. One of Mandelstam and Papaleksi's most significant achievements was the radio interference method of measurement, leading to the new discipline of radiogeodesy. Mandelstam also conducted basic theoretical research into quantum mechanics.

In 1931 Andronov moved to Gorkii (Nizhnii-Novgorod), although he appears to have retained a part-time paid position in Moscow until 1937. The reasons for the move are not entirely clear, but they appear to have been linked with unfounded political attacks on Mandelstam (due to his Jewish ethnic origin and his close academic links to Germany), and a resulting dispute between Andronov and a senior Moscow scientist. Whatever the precise reasons, Andronov soon built up an extremely successful research group in Gorkii, complementing ongoing work in the capital. He continued to collaborate closely with researchers in Moscow, publishing jointly and visiting Moscow regularly. The general approach to the study of nonlinear dynamics established at these centers during this period is still referred

Table 1. Some Key Events in Andronov's Life

1901	Born, Moscow, 11 April
1919-20	Military service in the Red Army
1920	Registered as student at Moscow Higher Technical Institute; soon also began to follow lectures at Moscow State University (MSU)
1923	Transferred to MSU physics faculty
1925	Began postgraduate work with Mandelstam
1926	Married E.A. Leontovich, a mathematician by training, and a subsequent coauthor with him of a number of scientific publications
1928	Presented fundamental paper on limit cycles at the Sixth Conference of Soviet Physicists
1929	"Kandidat" degree awarded (≈ Ph.D.)
1931	Moved to Gorkii University
1934	Became full professor
1935	Awarded doctor of science degree (the highest Russian academic degree)
1937	Published "Theory of Oscillations" (with Khaikin and Vitt)
1944	Set up "seminar" in Institute of Automation and Remote Control, while retaining post in Gorkii; published seminal paper on nonlinearities in control loops
1946	Elected full member of the Soviet Academy of Sciences
1947	Became member of Russian Supreme Soviet
1949	Published historical account of early control engineering work by Maxwell, Vyshnegradskii and Stodola (with Voznesenskii)
1950	Became deputy to Supreme Soviet of USSR

to in the Russian scientific literature as the *Mandelstam-Andronov school.* Major stages in Andronov's academic career, as well as some other key events in his life, are listed in Table 1.

The Emergence of the Discipline of Automatic Control in the Soviet Union

In common with a number of other European countries, the Soviet Union saw a significant increase in interest in control engineering in the 1930s. A Special Commission on Automation and Remote Control was set up by the Soviet Academy of Sciences in 1934—somewhat earlier than the establishment of the Industrial Instruments and Regulators Committee of the American Society of Mechanical Engineers (1936) or the control committee of the Verein Deutscher Ingenieure in Germany (1939). The commission held a conference on the subject in May 1935, and the journal *Automation and Remote Control* was established the following year. If anything, then, the push to modernize Soviet industry meant that automation and control, particularly in its process control aspects, was treated with urgency earlier than in many other countries. The Institute of Automation and Remote Control was set up in June 1939, and the first All-Union Conference on the Theory of Automatic Control was sponsored by the Institute in December 1940. The new Institute recruited not only engineers already familiar with aspects of control engineering but also theoreticians, and soon after its inception the first postgraduate students began their research and the first research seminars were held.

At the time of the establishment of the Institute of Automation and Remote Control in Moscow, Andronov and some of his Gorkii colleagues already were beginning to take a specific interest in control theory. He and another Gorkii researcher, A.G. Maier, were first drawn to the subject in the late 1930s by the problem of modeling the effect of static friction in control systems and the connection between this particular nonlinear problem and other areas of interest to them [7, 8]. Andronov and Maier were able to meet a key figure in contemporary Soviet control engineering, I.N. Voznesenskii, from the Leningrad Central Boiler and Turbine Institute, in 1940, and in the same year they all attended the first All-Union Conference on the Theory of Automatic Control, where they made the acquaintance of like-minded colleagues and gathered further information on the emerging discipline.

From Nonlinear Dynamics to Automatic Control

Andronov's first major piece of research into nonlinear dynamics concerned what is known in Russian as the *metod pripasovyvaniya*, the technique in which separate solutions for the various linear regimes of a piecewise linear problem are joined to form a complete solution—they are "stitched together," as the graphic alternative Russian term *metod sshivaniya* puts it. This method already had been used by Papaleksi, Sommerfeld, and others, but in 1927 Mandelstam charged Andronov with putting it on a proper mathematical basis. This aim was not fully achieved at the time, but the research turned out to have a close link with Andronov's later work on automatic control.

The late 1920s and the 1930s saw a period of rapid progress by Andronov and colleagues in the theory of nonlinear dynamics, in particular by extending earlier seminal results of Poincaré, Lyapunov, Birkhoff, Van der Pol, and others. Topics investigated in detail included limit cycles, the small parameter method (both of these drawing on Poincaré's original work), and stability analysis (using Lyapunov methods). The outcome was the creation of a comprehensive theoretical framework for nonlinear dynamics, much of which was set out in the 1937 text "Theory of Oscillations" [3].

By the mid-1940s Andronov was investigating the higher-order nonlinear systems associated with control engineering, beginning with third-order systems which are linear except for one nonlinearity caused by a relay or by Coulomb friction. His "point transformation" method, first published in 1944 [12], is of particular interest. Andronov and colleagues made a rigorous study of stability of such systems by searching for fixed points of transformations of the switching plane (Fig. 2). The technique as developed by Andronov and colleagues in the 1940s is a direct descendent of Andronov's own late 1920s work on limit cycles, and was gradually extended to higher-dimension state spaces.

The conference was held at a time of intense scientific and political criticism of the work being carried out at the new Institute of Automation and Remote Control, the precise circumstances of which are currently the subject of further research by the present author. Nevertheless, one important result of the conference was the forging of stronger links between at least some researchers at

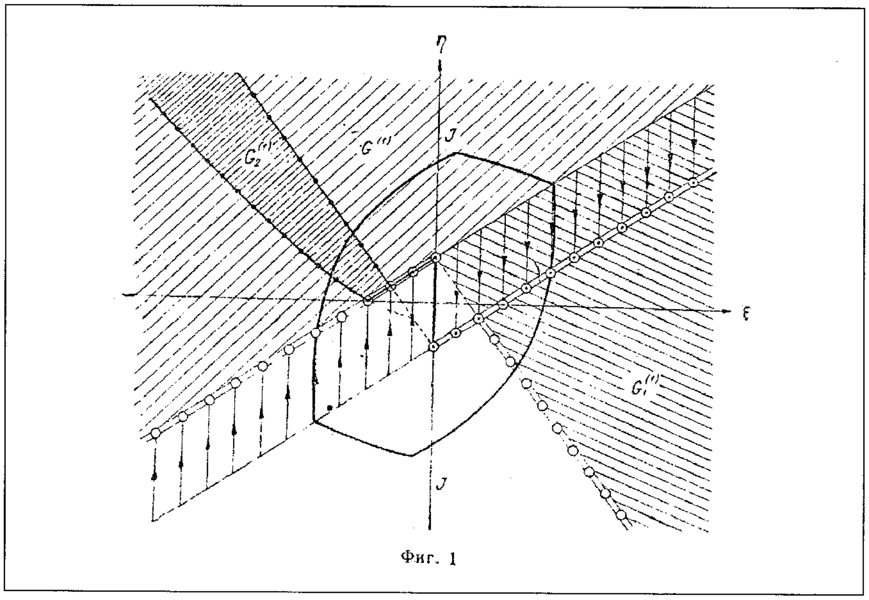

Fig. 2. Regions of the switching plane for a nonlinear system (Andronov and Maier [12]).

Table 2. *Doktor nauk* dissertations by members of Andronov's Moscow group 1946-1950

Approximate Date	Name	Topic Area
1946	Aizerman	Stability of a class of nonlinear automatic control systems
1947	Tsypkin	Stability and dynamics of systems with delay
1948	Meerov	Automatic control systems which are stable for arbitrarily small static and dynamic errors.
1949	Feldbaum, Solodovnikov	Topics in the "quality of control" of automatic control systems: i.e., time- and frequency-domain measures of the "goodness" of transient response
1950	Goldfarb	The "harmonic balance" approach to nonlinear control systems

the Institute in Moscow, Voznesenskii and colleagues in Leningrad, and Andronov's group in Gorkii. It should be noted, however, that these were not the only centers of expertise. By 1940, when the notion of control engineering as a separate discipline was just beginning to take root in the Soviet Union, work on control topics and nonlinear dynamics was already being carried out in various scientific, academic, and industrial establishments. In addition to the above-mentioned, it is also worth singling out the following major centers:

- Kazan, where N.G. Chetaev and others had been applying Lyapunov methods to engineering problems;
- Kiev, where N.M. Krylov and N.N. Bogolyubov had been making detailed investigations into the harmonic linearization approach to nonlinear systems;
- The All-Union Electrotechnical Institute, where A.V. Mikhailov applied the Nyquist criterion to problems of electrical regulation, in seminal work first published in 1938.

This is not an exhaustive list, and important work was carried out in other places, too. M.V. Meerov, for example, working at the Kharkov Electrotechnical Institute, derived a criterion for aperiodic stability in 1942—although it was not published until 1945 [9].

The study of control topics soon became a major feature of Andronov's group in Gorkii, and in March 1941 Andronov was invited to speak to the Physics and Mathematics Section of the Academy of Sciences in Moscow. In a letter [10] to M.A. Aizerman at the Institute of Automation and Remote Control, dated 19 March that year, Andronov sketched out his talk, which was to include:

- The physics of oscillations and the theory of automatic control
- Self-oscillations in control systems
- Classical theory of control: stability and the Routh-Hurwitz criterion
- Recent developments in control theory, includingthermal processes (Synge), servomechanisms (Hazen), friction and stability (Aizerman), linear theory (Hartree et al.), current nonlinear research at Gorkii, and autopilots and delay.

One of the interesting features of this lecture was that it included a review of some of the most important work in the United Kingdom and the United States of the 1930s: Hazen's analysis of high-performance servomechanisms, which had appeared in the U.S. in 1934, and work by Hartree and Porter on the application of Fourier methods to thermal processes, which had been published in the U.K. in 1936-7 [11]. Clearly, Andronov was already *au fait* with the international state of the art.

Over the next few years Andronov's interest in nonlinear control problems led him to perfect an important new technique: a way to solve piecewise linear problems by means of so-called "point transformations." The first application of this technique to a control problem is generally attributed in the Russian literature to a 1944 paper by Andronov and Maier on the effect of static friction on the behaviour of a direct-acting governor [12]. The method was used by Andronov and others to address a range of nonlinear problems in control engineering during the period 1944-1950 (see sidebar).

The Andronov Seminar at the Institute of Automation and Remote Control

In 1944, Andronov established a research seminar at the Moscow Institute, drawing on his experience studying under Mandelstam, and on his personal approach to teaching and research developed in Gorkii. A group of young researchers formed the core in Moscow, while Andronov periodically made the trip from Gorkii to the capital. The seminar immediately became an force to be reckoned with. M.V. Meerov, then one of the younger "core" of the seminar, recalls:

> *The work of the seminar was inaugurated with a lecture by A.A. Andronov on nonlinear friction in the theory of the direct-acting governor, and the theory of the point transformation of surfaces. This meeting was no mere "seminar session"—it was a major scientific event, attended by a number of full Academicians and Corresponding Members of the Academy, as well as by various other professors and engineers. After the lecture there was no need to worry about attendance at the seminar, it had a momentum of its own [13].*

The weekly seminar meetings regularly drew 40-60 participants—from the Institute of Automation and Remote Control itself, from other Moscow educational and research institutions, and even from institutions outside the capital. Discussions ranged over the whole of contemporary control engineering, with major topics in the first few years being (naturally) nonlinear techniques (including the application of Lyapunov's second method); frequency response methods (building on both Mikhailov's work and the results emerging from Western wartime work); and D-partition (a technique for assessing stability which was elaborated fully by Yu. I. Neimark, one of Andronov's researchers in Gorkii, following related work by A.A. Sokolov and M.V. Meerov).

Andronov was a charismatic figure and an inspiring teacher, as other former students and colleagues have testified on many occasions. Two citations from seminar participants will suffice here:

> *I must say something of the extraordinary atmosphere which characterized [the group]. The youth and enthusiasm of the participants (they were all of a very similar age, survivors of the dreadful war years); the novelty and unusual nature of the ideas that emerged; the fiery talent of Andronov himself—he was able to enthuse people and spark off ideas for subsequent discussions even though he was not often present in the Institute; the high scientific expectations of the group (which occasionally led to sharp words!); the spirit of openness and high-mindedness: all this gave the seminar a romantic, animated feeling of creative enthusiasm, of collective endeavour, such as is rarely found in scientific groups and which, unfortunately, is not usually sustained for very long [Aizerman, 14].*

> *The figure of Aleksandr Aleksandrovich Andronov made an indelible impression on the memory of a great many people, and in particular on people of my generation who knew him personally, attended his lectures, or saw him in action during discussion at scientific meetings or when solving both scientific problems and questions relating purely to everyday matters. It is difficult to find the words to describe completely this remarkable man, a great scientist and outstanding teacher, with a profound knowledge of the history of science, and possessed of a rare bibliographic memory. In his personality were combined such traits as firmness and kindness, uncompromising integrity and sympathy, a great inner force, and enormous charm. He made a great impression on everyone around him [Tsypkin, 15].*

The Vyshnegradskii Approach

In modeling a steam engine with a centrifugal governor, Vyshnegradskii neglected Coulomb friction and linearized the system about an operating point. Treating the engine as an integrator and the governor as a second-order system, he made an ingenious change of variables in order to transform the resulting third-order characteristic equation into the form

$$\phi^3 + x\phi^2 + y\phi + 1 = 0$$

the nature of whose roots determines the general form of the system transient response.

The parameters x and y, which depend on such system characteristics as governor restoring-force constant, moment of inertia, and so on, became known in the Russian and German literature as the Vyshnegradskii parameters. The transformed equation lent itself perfectly to a graphical technique of stability analysis, summarized in Fig. 3. This figure is derived from Vyshnegradskii's own paper, but to it have been added sample pole positions to indicate the nature of the roots, and hence the transient response (as correctly identified by Vyshnegradskii), in the various regions of the plane. Vyshnegradskii's work was known to some workers on control topics in the Soviet Union in the 1930s, in particular to Voznesenskii's group in Leningrad. But following Andronov and Voznesenskii's detailed historical exposition, many post-war Russian control engineering texts featured diagrams of this type, and Vyshnegradskii's approach was also related explicitly to more recent techniques of analyzing higher-order systems. And once Neimark had fully developed the D-partition approach, it was possible to demonstrate a clear theoretical link between Vyshnegradskii's method and later techniques in stability assessment.

An indication of the quality of the work nurtured in the environment created by Andronov can be gained from a brief look at some of the Doctor of Science degrees awarded to members of the Moscow seminar under his tutelage (Table 2) [16]. A note on the Soviet system of higher degrees is in order here, since it differed significantly from that of the West. (The system is currently in a state of flux, being influenced, like much else in contemporary Russia, by Western norms.) In the past, at least, graduates pursuing a research career would first aspire to the higher degree of *kandidat*, a qualification approximately, but not entirely, equivalent to a western Ph.D. The much more prestigious *doktor nauk* ("doctor of science") degree was awarded only on completion of a more substantial body of research—normally when the researcher was well-established in a particular area, and often not until middle age. The fact that Andronov, for example, obtained a full professorship before his *doktor nauk* was not unusual.

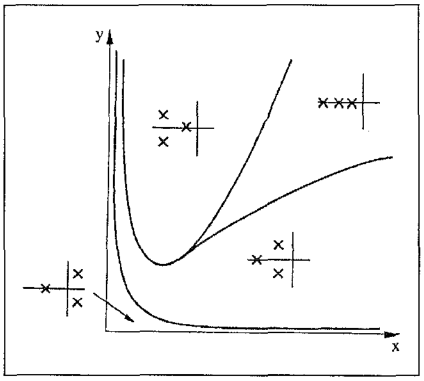

Fig. 3. Vyshnegradskii's stability diagram (with modern pole-zero plots).

The work outlined in the accompanying table is indicative, therefore, of an enormous research enterprise, which was to color much Soviet activity in control theory for the next decade or more. All the researchers listed were to become preeminent in the Soviet Union, and several of them acquired an international reputation. As examples of the latter, one might point to the extremely fruitful consequences of the "Aizerman conjecture" concerning the behavior of nonlinear control systems delineated by boundary values of gain; or to Tsypkin's theories first of sampled-data systems (the Soviet counterpoint to the work of Jury in the U.S.), and then of relay control systems. Similarly, Meerov went on to produce an enormous body of work on control system structure, particularly in the context of multivariable systems (some of his later results are still little known outside Russia [17]); while Goldfarb's describing function approach, based on earlier work by Krylov and Bogolyubov [18] on harmonic linearization, became the standard approach in the Soviet Union (paralleling Western work by Kochenberger in the U.S., and the less well known work of Tustin in the U.K., Oppelt in Germany, and Dutilh in France) [19].

Not only did Andronov set up an exciting and productive intellectual environment in the Moscow seminar, he also encouraged close links with researchers elsewhere. The relationship between Moscow and Gorkii was particularly close, as might be expected, with a number of other Gorkii academics besides Andronov giving papers in Moscow, but there were also links with other centers—with Leningrad, for example. Indeed, a seminar modeled on the Moscow one was soon established in Leningrad, where A.I. Lure and a number of other outstanding control theorists were active in the post-war period.

The History Connection

No discussion of Andronov's work on control engineering would be complete without some mention of his interest in the history of the discipline. It has already been noted that Andronov's initial attraction to control engineering was prompted by the problems caused by nonlinearities such as Coulomb friction in a control loop. One of these problems, sometimes referred to in the Russian literature as the "Vyshnegradskii problem," goes back to attempts in the late 19th century to model the behavior of a steam engine provided with a Watt governor, and to explain the onset of hunting and instability.

Vyshnegradskii's original approach was highly influential outside Russia, and was recognised by a number of other European workers in the field around the turn of the century (see sidebar). However, there was some controversy about the validity of Vyshnegradskii's work (because he chose to neglect static friction in his model), and a number of Russian and foreign writers accused him of serious error. Prompted initially by the still unresolved technical problem of static friction in control loops, Andronov's interest in Vyshnegradskii and other 19th century precursors of control engineering soon became much deeper and broader.

Andronov had a longstanding interest in the history of science. Together with his wife, E.A. Leontovich, he published a short book on Laplace as early as 1930; he carried out research for a biography of Lobachevskii (the Russian pioneer of non-Euclidean geometry) during the 1940s; and it seems likely that he knew of the historical background to control engineering in Russia even before he took an active research interest in the history of the subject [10]. Indeed, throughout his career he emphasized the importance to all researchers of a detailed knowledge of the history of their specialism, believing with Ehrenfest that a thorough understanding of the old is vital for the development of the new. I.N. Voznesenskii, the Leningrad colleague Andronov had met in 1940, turned out to share this deep historical interest. They began to collaborate in earnest sometime during 1943 to 1944, when Andronov proposed an ambitious historical project. Initially Andronov envisaged four volumes of "control classics": three volumes covering linear control, nonlinear control, and pulsed control systems (sampled data systems), together with a fourth, more general compilation. In the end, only one of these was written, and it did not appear until 1949, after Voznesenskii's death [20]. Part of the proposed project, a translation by M.V. Meerov of E.J. Routh's classic 1877 monograph "A Treatise on the Stability of a Given State of Motion," fell afoul of the worsening political climate and never appeared: as the Cold War became more intense, it became impossible openly to celebrate the pioneering achievement of a non-Russian scholar in the way proposed [21].

Nevertheless, the single volume that did appear was an impressive piece of scholarship, consisting of more than 400 pages of translations and critical analyses of seminal works by Maxwell, Vyshnegradskii, and Stodola (who had applied Vyshnegradskii's work to turbine control in Switzerland toward the end of the 19th century, and who was responsible for prompting Hurwitz to study the problem of dynamic stability [22]). The book became well known in control circles in the Soviet Union, and the post-war generation of Russian control engineering textbooks tended to include the Vyshnegradskii technique, with its famous diagram, alongside other, later, methods for assessing stability. And if, as noted in an earlier article [23] in this journal, an ideological subtext to the work can be discerned (in common with post-war "technical" publications in many other countries), this does not prevent it from being the first substantive investigation of the intellectual history of control theory, and an account that is still of interest today. Indeed, given the political climate of the late 1940s in the Soviet Union, it is greatly to Andronov's credit that he was able to produce such a scholarly analysis.

Conclusion

The memory of Aleksandr Aleksandrovich Andronov was honored in the Soviet Union by the establishment of a prize bearing his name; recipients have included Butkovskii, Meerov, Neimark, Petrov, and Tsypkin & Polyak. Andronov's collected works appeared in 1956 [24]. The comparatively low-level of awareness in the West of Andronov's contributions both to nonlinear dynamics and to control theory can be attributed to a combination of factors. First, many of Andronov's original papers (including [12]) were very terse, and often omitted full proofs. More extensive treatments did not appear even in Russian until after his death, and even these were inaccessible to many control engineers. Second, relatively little of Andronov's work appeared in English during his lifetime, the "Theory of Oscillations" being an important exception. Most of the translations that did appear were published after his death, once Western interest had been aroused, and in a later, substantially revised, form. As with many of his Russian contemporaries, when Andronov did publish new research results in a foreign language it was in French or German, still major international languages for physics and many other sciences in the first half of the 20th century. Furthermore, after the mid-1930s, foreign publications were increasingly frowned upon in the Soviet Union, unless they were expressly designed to promulgate Soviet work abroad. Finally, Andronov died in 1952 at the early age of 51, well before so-called "modern" control theory had become widely known to non-Russian speakers, and before many of the lines of research that he initiated and supported were fully worked out. Although a few Western scientists and engineers soon became aware of what had been going on in the Soviet Union, knowledge of these techniques became wide-

Chris Bissell is currently Head of the Department of Telematics at the British Open University, an institution he joined in 1980. He has produced distance teaching material and undergraduate textbooks in signal processing, telecommunications, and control engineering. His major research interest is the history of technology, in particular a comparative study of the development of control engineering in Western Europe, the United States, and the former Soviet Union.

spread in the West only much later, when high-performance systems for missile and space vehicle control had become a major issue in the Cold War [25]. The cover-to-cover translation of a number of Russian scientific journals was a great help to technology transfer to the West in the late 1950s and 1960s [26]. As a result of all this, the names of Andronov's colleagues and former students, such as Aizerman, Pontryagin, and Tsypkin, to name but three, are much better known outside Russia than is his own.

Although Andronov was a distinguished physicist and control theorist in his own right, perhaps his greatest achievement was the manner in which he furthered the discipline of control engineering as a whole by virtue of his institutional and pedagogical activities. In particular, the way he motivated and enthused his students and colleagues in the two groups in Gorkii and Moscow, creating an intellectual environment in the post-war Soviet Union in which the new discipline could flower, assures him a pre-eminent place in the history of control engineering in the mid-20th century.

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[16] Interview with Meerov, November 1996. These dates are believed to be accurate to within a year. (As with higher degrees in other countries, the submission of the *doktor nauk* dissertation and the granting of the degree might well take place in successive years.) Note that Andronov also supervised other postgraduate and postdoctoral students in Gorky, of whom Yu.I. Neimark is perhaps the best known.

[17] M.V. Meerov, "Issledovanie i optimizatsiya mnogosvyaznykh sistem upravleniya," Nauka, 1986.

[18] N.M. Krylov and N.N. Bogolyubov, "Vvedenie v nelineinuyu Mekhaniku," Izd-vo Ak. Nauk Ukr.SSR, Kiev, 1937. Free translation: S. Lefschetz, "Introduction to Nonlinear Mechanics," Princeton University Press, Princeton, 1943.

[19] For further references and brief technical descriptions of some of the work mentioned here in the general Soviet context, see C.C. Bissell, "Russian and Soviet Contributions to the Development of Control Engineering: A Celebration of the Lyapunov Centenary," *Trans. Inst. Measurement and Control*, vol. 14, no. 4, 1992, pp. 170-178. A more technical treatment of some of the ideas can be found in: A.G.J. MacFarlane, ed., "Frequency-Response Methods in Control Systems," IEEE Press, New York, 1979.

[20] A.A. Andronov and I.N. Voznesenskii, "J.C. Maxwell, I.A. Vyshnegradskii, A. Stodola. Teoriya Avtomaticheskogo Regulirovaniya," Izdat. Ak. Nauk. SSSR, Moscow, 1949.

[21] Personal communication from Meerov, June 1996, and interview, November 1996. The history of science in the former Soviet Union became highly politicized in the late 1940s; the ideological context of Andronov's historical and scientific work at this time is currently the subject of further study by the author. Andronov's personal papers, held in the archives of the Russian Academy of Sciences, contain a number of documents that reflect the hardening of political attitudes at this time.

[22] C.C. Bissell, "Stodola, Hurwitz and the Genesis of the Stability Criterion," *Int. J. Control*, vol. 50, 1989, pp. 2313-2332.

[23] C.C. Bissell, "Textbooks and Subtexts," *IEEE Control Systems Magazine*, vol. 16, no. 2, 1996, pp. 71-78.

[24] A.A. Andronov, "Sobranie Trudov," Izdat. AN SSSR, 1956.

[25] Major figures in the early promulgation of this work in the English-speaking world included S. Lefschetz [e.g. in 5, 18] and N. Minorsky. The latter performed an invaluable service by reporting the Soviet state of the art in a set of (at first classified) U.S. government reports, which formed the basis of later published texts. See: "Introduction to Nonlinear Mechanics: Reports 534, 546, 558, 564," David W Taylor Model Basin, U.S. Navy, 1944-6. A later compendium of work by Andronov and colleagues that did appear in English is: A.A. Andronov, et al., "Theory of Bifurcations of Dynamic Systems on a Plane," Israel Programme for Scientific Translations, Jerusalem 1971.

[26] For example, *Automation and Remote Control* from 1957 onward. Individual papers of significance were also translated by Western military research organizations from the mid-1950s. It is interesting to contrast this late and sporadic transfer of information to the West with the efforts made in Russia to keep abreast of Western developments. During the 1930s, for instance, the Commission on Automation and Remote Control made a concerted effort both to review technical and academic literature, in both Europe and the United States, and to contact manufacturers in the control and instrumentation field (Archives of the Russian Academy of Sciences).