

Absolute Stability of Nonlinear Systems of Automatic Control

V. M. POPOV

A CENTRAL specification imposed on a control mechanism is invariably its stability. Maxwell's paper "On Governors" [10], settled the problem of stability of systems described by third order linear differential equations in terms of the coefficients of the associated characteristic polynomial. Subsequent to this paper, the problem of stability of systems described by linear differential equations in terms of the coefficients of the characteristic polynomial was solved by Routh and Hurwitz. It is worth noting that the mathematical problem of determining when the roots of a polynomial lie in the left half of the complex plane had actually been effectively solved by Hermite [5] a decade before Maxwell posed the stability problem as a question in control.

In his thesis in 1895, Lyapunov put forward a method, now called "the second method of Lyapunov", for determining the stability of an equilibrium of a system described by nonlinear differential equations. While Lyapunov was primarily interested in applications to mechanics, his method and stability concepts became very influential and widely applied in control. His ideas were especially popular in the Eastern European control literature, since it was customary in these countries to use differential equations as models for control mechanisms.

By contrast, in the Western literature, stability analysis in control had been centered on frequency-domain methods, propelled by the beauty, practicality, and generality (for linear systems) of the Nyquist criterion [11].

Each of these approaches has its advantages. Frequency-domain methods use very compact model specifications and are able to address robustness through gain and phase margins. However, the generalization to nonlinear systems of frequency-domain methods proved awkward. Differential equation models by and large proved a much better way of addressing nonlinearities.

Through the problem of determining conditions for the stability of systems with one nonlinear element, control witnessed a symbiosis between stability theory of Lyapunov methods and frequency-domain techniques. A key result that was the catalyst in this development was Popov's stability criterion, the subject of the paper that follows.

The history of the problem is as follows (see [2] for more details). In 1944, Lur'e and Postnikov [7] formulated the problem of stability in the large of a finite dimensional system with one nonlinear element $f: \mathbb{R} \rightarrow \mathbb{R}$ satisfying $\sigma f(\sigma) \geq 0$ for all $\sigma \in \mathbb{R}$. In subsequent publications, Lur'e obtained, using Lyapunov methods, a set of "resolving equations" that allowed to conclude stability. These ideas were further developed in [9], [16], [8], but the resulting conditions remained difficult to verify and to interpret.

This problem of stability of a system with one nonlinear element led also to the Aizerman conjecture [1]. This states that if there exist k_1, k_2 such that $k_1 < \frac{\sigma f(\sigma)}{\sigma^2} < k_2$ for all $\sigma \in \mathbb{R}$, and if the linear system obtained by replacing the nonlinear element by a linear one with gain k , is asymptotically stable for all $k \in [k_1, k_2]$, then the nonlinear system is also asymptotically stable in the large. Aizerman's conjecture is valid for second order systems, but was proven to be false for third and higher order systems [12] (see also [14], [15]).

By introducing the frequency response of a system, Popov obtained a sufficient condition for the stability of such systems. This criterion can be formulated as follows. Consider the feedback system described by (see Figure 3 in Popov's article):

$$\frac{d}{dt}x = Ax + bu; \quad y = c^T x; \quad u = -f(y)$$

with $A \in \mathbb{R}^{n \times n}$, $b, c \in \mathbb{R}^n$, and $f: \mathbb{R} \rightarrow \mathbb{R}$ a continuous nonlinearity with $f(0) = 0$. Denote by G the transfer function of the linear part, i.e., $G(s) := c^T (sI - A)^{-1} b$. Assume furthermore that A is a stability matrix (meaning that $t \in \mathbb{R} \mapsto \exp(At) \in \mathbb{R}^{n \times n}$ is bounded on $[0, \infty)$). The matrix A need not have all its eigenvalues in the open left half of the complex plane. In fact, Popov assumes that A has all its eigenvalues in the open left half of the complex plane, except, possibly, one eigenvalue at the origin. The assumption that A need not be Hurwitz in fact complicates his analysis considerably.

Popov proves that the equilibrium trajectory $x = 0$ is globally asymptotically stable if the following conditions are satisfied:

1. $\sigma f(\sigma) > 0$ for all $0 \neq \sigma \in \mathbb{R}$.

Absolute Stability Of Nonlinear Control Systems

SJ Ball



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