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*Transient performance:* On a lineal change. Two-capacity plant. Different effects of changes of demand and supply. Hunting. Main components of the normal controller: corresponding, or proportional, control; floating, or non-corresponding, control; and rate component. Intermittent control. Two-position control. Gouy regulation. Dead-zone. Rate component of meter or of controller. Kickers. Anticipatory control. Applications of rate components. Exact control.

*Steady hunting performance:* Energy.  $360^\circ$  requirement for steady hunting. Phase lags due to plant or process. Lag diagrams for the three normal-regulator components. Transportation lag. Attenuation in temperature control. Fixed and flexible lags. Chemical-reaction time requirements. Dead-time lags. Comparison with transient performance: instantaneous and accumulated errors. Damping for optimum performance. Self-regulation.

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Control valves; in series and parallel, lineal and equal-percentage valves. Control of level, flow, and temperature. Lags and damping. Typical plants. Servo-positioning of heavy masses.

Examples of typical air-operated instruments: on-and-off, high-sensitivity throttling, full-range throttling—alone or with automatic reset and/or rate component. Rate-time.

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QUANTITATIVE ANALYSIS OF CONTROL . . . . . 57

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*Meters:* Proportionally biased, null-type, damped-spring-mass analogue, real and negative-mass (76), milliammeters and potentiometers.

*Regulators:* Proportional, floating, damped proportional, follow-up servo-regulators. Rate component. Higher-derivative components. Stabilizing interruptions. Trend detectors. Spring-equivalents in regulators. *Plants:* Number of capacities *v.* degrees of freedom. Step and lineal changes for one- and two-capacity plants.

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*Regulated systems:* Zero- to three-capacity systems. Response to changes of position, velocity, acceleration and corresponding forces. Stability for three-capacity systems. Single-capacity systems analyzed as to stabilizing effect of self-regulation upon floating control, rate-component regulator. Two-capacity plant with inertia regulated by different components. Convenient comparison system: mass-damping-spring (*MNB*) plant with rate-proportional-floating (*RPF*) regulator. Distributed capacity-and-resistance plants.

*Elements of meters and regulators:* Functions required, including differentiation and integration. Mechanical, thermal and electrical analogues. Hydraulic and pneumatic element responses to step-forces. Kinetic differentiating and integrating means. Interrupted systems. Telemeters and telecontrollers. Continuous *v.* cyclical means. The powerful method of differences.

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Controllability and liveliness.

Applications of regulators to usual plants. Synthesis of regulators for special plants.

The patent literature.

*Conclusion:* Future problems of electric and cyclically-operating regulators. Specification. Application tests, fitting regulators to plants.

Trend toward telemeters. Memory-type component regulators. Unity of the subject of control.

## APPENDIX A

TABLES COMMONLY USED IN CONTROL ENGINEERING. . . . . 159

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*Electricity*: (194). Hydraulic-electric analogues. Magnetic circuits. Hysteresis. Electrical generator. Inductance. d.c. and a.c. impedances. The practical system of units.

*Electronics*: Including light-sensitive cells, amplifiers, and photoelectric relay circuits.

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*Asymptotic relation—first-order differential equation*: Derivatives and differentiation. Integration as the inverse of differentiation and as quadrature, constants of integration. Integration of  $x^n$  and the exception  $1/x$ . Logarithms. Series for  $e$ , Maclaurin's and Taylor's series, convergence.

*Oscillations* (trigonometry): Series for  $\sin \omega t$  and  $\cos \omega t$ ,  $j$ .

The complex plane (228).  $e^{i\theta}$ , Vector addition. Polar coordinates.  $\sin$  and  $\cos$  in terms of  $e^{i\theta}$  and  $j$ , de Moivre's theorem, hyperbolic functions.

*Second-order differential equations*: Undamped oscillations, overdamping, and damped oscillations.

*Third-order differential equations*: critical damping, solutions of cubics.

*Methods of obtaining roots*: Synthetic division and graphing remainders, Newton's method, iteration method, Graeffe's method (squaring roots), determinants; numerical step methods with graphical, prediction, and interpolation methods.

## APPENDIX D

ANALYTIC METHODS FOR THE SOLUTION OF DIFFERENTIAL EQUATIONS . . . . . 264

*Preface* including discussion of different methods: numerical-step, classical, heuristic, Heaviside's operational, Laplace transform, and Fourier pairs, also introductory and working references.

*Conventional foundation*. (a) *Differential equations*, definitions and elements; quadratures and integration by parts; homogeneous, exact and partial differential equations; integrating factors. (b) *Solutions*, Different (chameleon-like) forms. Singular, general and complete solutions; Wronskian determinant test for linear independence of solutions.

*Classical method of solution:* One method: by differentiation to obtain particular solution, complementary solution, undetermined coefficients. Complete response of a system to a forcing function: sum of transient (complementary) and steady state (particular) solutions.

*Heuristic method:* R-L a-c circuit example.

*Operational method:* Use of  $p = d/dt$ ,  $e^{-at}$  series, impedances. (a) Use of complex notation, exponents, and algebra, including conjugates, minimum of special cases and close tie-in with the Laplace transform method. (b) Use of algebraizing to avoid complex notation, resonance. (c) Use of partial fractions. (d) References on the solution, by different methods, of a second-order linear differential equation with constant coefficients and a forcing function, use of  $\mathcal{Q}$  for  $1/p$ .

*The usual electrical engineering approach:* Superposition; indicial admittance; Carson's and Duhamel's integrals; "infinite-integral" theorem, series R-C example; shift of operand, poles.

## FUNCTIONS OF A COMPLEX VARIABLE . . . . . 289

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*Differentiation of complex functions:* analytic functions; regular points; Cauchy-Riemann equations; orthogonality; conformal mapping; Laplace's second-order partial differential equation.

*Use of power series to represent analytic functions:* Taylor's and Laurent's series; residues; poles; essential singularities.

*Complex integration:* Meaning; Cauchy's integral theorem; Cauchy-Riemann equations as conditions that real and imaginary parts of integrands are exact differentials; Green's theorem or lemma; residues and four theorems for their calculation; with examples. Deformation of path of integration; the Bromwich path and the inverse Laplace transform. The  $s$ -plane and the  $w$ -plane.

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*Theory: Fundamentals:* Direct and inverse transforms defined; Bromwich path; residues by partial fraction expansion of rational polynomial fractions. Relation of the  $\mathcal{L}$ -transform to the conventional operational method,  $1/s$  difference. Impedance, indicial admittance: response to unit-step function, place of Duhamel's and Carson's integrals. A simple four-step procedure for using  $\mathcal{L}$ -transforms in solving linear differential equations.

*The Fourier analysis:* (a) *The Fourier series* with its coefficients determined in different ways. Odd and even functions. The complex exponential form. (b) *The Fourier integral.* Fourier transforms or pairs and the double Fourier integral. Campbell-Foster tables. Comparison of Laplace transforms, Fourier pairs and C-F mates. (c) The rectangular step wave, sine integrals, and Dirichlet's integral for  $\mathbf{1}(t)$ . The unit step  $\mathbf{1}$ , the Bromwich path, the  $s$ -plane and the  $w$ -plane. (d) Loose ends: error function *erf*, L'Hôpital's and series rules for evaluating indeterminate forms, Bessel's and gamma functions, and elliptic integrals.

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*Transforms* for  $e^{-at}$ ,  $\cos \omega t$ ,  $e^{-at} \cos \omega t$ ,  $f_1(t) + f_2(t)$ ,  $af(t)$ ,  $f_1(t) \times f_2(t)$  or Borel's theorem,  $F_1(s) \times F_2(s)$ , partial fraction series for rational polynomial fractions, derivatives and integrals, tables of time-functions and operations and their transforms.

*Typical examples:* (1)  $R$ - $L$  circuit with  $\sin \omega t$  forcing; (2) same circuit with  $\cos \omega t$  forcing; (3) sprung mass with unit-step force; (4) 'sprung-mass with nonresonant sinusoidal ( $\cos t$ ) forcing; (5) second-order pole case, like-terms case; (6) second-order differential equation system with damped harmonic forcing function.

*Conclusion:* Theoretical limitation, that the  $\mathcal{L}$ -transform method is like a calculating machine that can handle neither inverse nor tangent forcing functions, does not interfere with usefulness for practical cases.

*References,* minimum desk-library, list by subjects, alphabetically arranged bibliography.

APPENDIX E

REFERENCES ON CONTROL . . . . . 339

*Notes on selected references:* Engine-governing, ship-steering, servomechanisms, general control theory, process control (A.S.M.E.'s Process Division, Committee on Industrial Instruments and Regulators, now a Division), performance of instruments in terms of their elements' characteristics and of generalizations, level regulation and the numerical step method, the German approach; hydraulic analogy for temperature control (use of Heaviside's operational calculus *v.* plane trigonometry) incomplete without inertia effects, trend toward emphasis on "applications"; temperature control, sensitivities, steady hunting analyses; rate-component in process control, tests for controllability, and consistency of control in power plants. The German analytical approach, use of time-constants including the *Anlaufzeit*, self-regulation, other foreign literature, A.S.M.E.-I.I.R.D.'s tentative terminology.

*Bibliography:* Index lists, monthly periodicals and reference books on instruments, sections on control in books and also books on related subjects, bibliography (chronological) of papers and articles on industrial instruments.

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