

Analysis and Control of Time-Varying and Perturbed Systems

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Why Study Time-Varying Perturbed Systems?

■ Real-World Imperfections:

- Systems rarely time-invariant
- Parameters drift, components age, environment shifts
- *Ex:* Aircraft dynamics change with fuel, altitude, air density

■ Uncertainty Omnipresent:

- External disturbances (wind gusts, load variations) inherent
- Internal uncertainties (sensor noise, actuator inaccuracies, unmodeled dynamics) ever-present
- *Ex:* Robot arm payload or joint friction varies

■ Performance & Robustness Demands:

- Modern control needs high performance (precision, speed) and robust stability
- Ignoring variations → poor performance, instability, failure

Understanding Perturbation Types

Motivation: Real-world systems exhibit time-dependence, modeling errors, external disturbances

General System Form:

$$\dot{\underline{x}} = f(\underline{x}) + g(\underline{x}, t)$$

Vanishing Perturbation:

- $g(\underline{x}, t) \rightarrow 0$ as $\underline{x} \rightarrow 0$.
- Preserves exponential stability.
- Examples: modeling errors, unmodeled dynamics

Non-Vanishing Perturbation:

- $g(\underline{x}, t) \not\rightarrow 0$ as $\underline{x} \rightarrow 0$.
- Leads to ultimate boundedness.
- Examples: constant disturbances, sensor noise

Lyapunov Theory for Time-Varying Systems

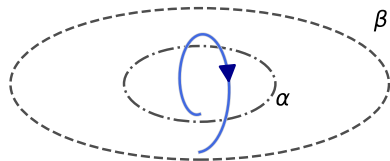
Assumptions:

- Origin $\underline{x} = 0$ is an equilibrium point
- Lyapunov function $V(t, \underline{x})$ is continuously differentiable, positive definite and radially unbounded
- Derivative of Lyapunov function is negative definite

Globally uniformly exponentially stable:

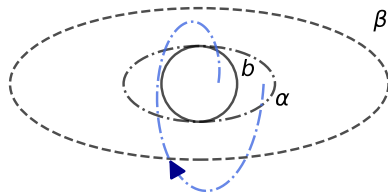
$$\exists c_i, \alpha > 0 : c_1 \|\underline{x}\|^\alpha \leq V(t, \underline{x}) \leq c_2 \|\underline{x}\|^\alpha$$
$$\dot{V}(t, \underline{x}) \leq -c_3 \|\underline{x}\|^\alpha$$

Boundedness and Ultimate Boundedness



Boundedness:

$$\|\underline{x}(t_0)\| \leq \alpha \Rightarrow \|\underline{x}(t)\| \leq \beta, \\ c > 0, \alpha \in (0, c), \beta > 0, \forall t \geq t_0$$



Ultimate Boundedness:

$$\|\underline{x}(t)\| \leq b \\ \forall t \geq t_0 + T$$

Lyapunov Stability for Vanishing Perturbations

Problem: Analyze stability of $\dot{\underline{x}} = f(\underline{x}) + g(\underline{x}, t)$

- Nominal system ($\dot{\underline{x}} = f(\underline{x})$) exponentially stable

Assumptions for Exponential Stability:

- Perturbation $g(\underline{x}, t)$ vanishes (i.e., $g(\underline{x}, t) \rightarrow 0$ as $\underline{x} \rightarrow 0$)
- $V(t, \underline{x})$: continuously differentiable, positive definite, radially unbounded

Condition for Global Uniform Exponential Stability:

$$\frac{\partial V}{\partial t} + \frac{\partial V}{\partial \underline{x}} f(\underline{x}) \leq -c_3 \|\underline{x}\|^2 \text{ and } \left\| \frac{\partial V}{\partial \underline{x}} \right\| \leq c_4 \|\underline{x}\|$$

$$\|g(\underline{x}, t)\| \leq \gamma \|\underline{x}\| \text{ where } 0 \leq \gamma(t) < \frac{c_3}{c_4}$$

Comparison Lemma – Example

Problem: Analyze stability of a scalar perturbed system

$$\dot{x} = -a x(t) + g(t, x), \quad x(0) = 0, \quad a > 0$$

Assumptions/Conditions:

- $x(t) \geq 0 \quad \forall t \geq 0.$
- $g(t, x) \leq b x(t) \quad \forall x \geq 0.$

Integral Condition:

$$\underline{x}(t) \leq \underline{x}_0 + \int_{t_0}^t \gamma(\tau) d\tau = \underline{x}_0 + \int_{t_0}^t [-a \underline{x}(\tau) + b \underline{x}(\tau)] d\tau$$

Bound for Derivative:

$$\dot{\underline{x}}(t) \leq -a \underline{x}(t) + b \underline{x}(t) = -(a - b) \underline{x}(t)$$

Comparison Lemma – Example

From the Bound for Derivative:

$$\underline{x}(t) \leq \underline{x}_0 + \int_{t_0}^t \dot{\underline{x}}(\tau) d\tau \leq \underline{x}_0 - (a - b) \int_{t_0}^t \underline{x}(\tau) d\tau$$

Note: This applies if $(a - b)x$ is continuous, positive definite, and non-decreasing.

Conclusion: Exponential Stability of the Perturbed System

$$\lim_{t \rightarrow \infty} \underline{x}(t) = 0$$

$$\underline{x}(t) \leq \underline{x}_0 e^{-(a-b)t}$$

Non-Vanishing Perturbations: The Problem

The Challenge:

- Perturbation doesn't disappear, perfect asymptotic stability to zero is not possible
- State \underline{x} will perpetually move away from the origin

Conclusion/Goal: Ultimate Boundedness

- We aim for Ultimate Boundedness
- Not exactly zero, but "close enough" for practical purposes

Intuition:

- Imagine balancing a pencil on its tip in a sufficiently strong wind
- It won't stay perfectly still
- Find out how big that wobble area is \Rightarrow guarantee the pencil always stays inside

Lyapunov Conditions for Ultimate Boundedness

Given:

- System $\dot{\underline{x}} = f(\underline{x}) + g(\underline{x}, t)$.
- Nominal system origin $\underline{x} = 0$ exponentially stable.

Criteria (Assumptions & Conditions):

- **Lyapunov Function:** Cont. diff., pdf, radially unbounded
- **Nominal Decay Condition:** Derivative of V along nominal system is ndf
- **Lyapunov Function Gradient Bound:** Gradient of V is bounded
- **Perturbation Bound:** Non-vanishing $g(\underline{x}, t)$ is bounded by a constant δ

The Key Trade-off: δ directly impacts size of ultimate bound

$$\|g(\underline{x}, t)\| \leq \delta < \frac{c_3}{c_4} \sqrt{\frac{c_1}{c_2}} \theta r, \quad \theta \in (0, 1), \quad r > 0$$

Result: Initial Decay and Ultimate Boundedness

Outcome for any initial condition $\|\underline{x}(t_0)\| \leq \sqrt{c_1/c_2} r$

Phase 1: Initial Exponential Decay

$$\|\underline{x}(t)\| \leq k e^{-\gamma(t-t_0)} \|\underline{x}(t_0)\|, \quad t_0 \leq t \leq t_0 + T$$

Phase 2: Ultimate Boundedness

$$\|\underline{x}(t)\| \leq b \quad \forall t \geq t_0 + T$$

What it Means:

- $\|\underline{x}(t_0)\|$ sufficiently close to origin \Rightarrow system initially heads towards origin rapidly
- Due to non-vanishing perturbation it will settle into ultimate around the origin
- b depends directly on δ and how "stable" the system is (c_1, c_2, c_3, c_4)

Example: Bounded Disturbance Response

Problem: Analyze Boundedness of a Perturbed Mass-Spring-Damper-System

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -2x_1 - 3x_2 + d$$

with bounded disturbance $|d| \leq \delta$ and the origin of the nominal system being exponentially stable.

Lyapunov Candidate Function: $V(\underline{x}) = \underline{x}^T P \underline{x}$

- $P > 0$ found by solving $A^T P + P A = -Q$
- For $Q = I$ and $A = \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix}$, P can be calculated
- $c_1 \|\underline{x}\|^2 \leq V(\underline{x}) \leq c_2 \|\underline{x}\|^2$.

Example: Bounded Disturbance Response

Applying Lyapunov Stability Conditions:

$$\dot{V} \leq -c_3 \|\underline{x}\|^2 + c_4 \|d\| \|\underline{x}\| \leq -c_3 \|\underline{x}\|^2 + c_4 \delta \|\underline{x}\|$$

Conclusion: Ultimate Boundedness Guaranteed

- System state $\|\underline{x}(t)\|$ eventually converges to and remains within a bounded region:

$$\|\underline{x}(t)\| \leq b \quad \forall t \geq t_0 + T$$

- The ultimate bound b and other parameters are:

$$b = \frac{c_4}{c_3} k \frac{\delta}{\theta}, \quad k = \sqrt{c_2/c_1}, \quad \gamma = \frac{(1-\theta)c_3}{2c_2}$$

- Size of the ultimate bound b directly **scales with the disturbance magnitude δ** .

Key Insights & Practical Implications

Theoretical Insights:

- Lyapunov methods: unify time-varying and perturbed system analysis
- Perturbation type: dictates achievable stability properties
- Ultimate boundedness: models real-world robustness

Design Implications:

- Small, vanishing perturbations: maintains exponential convergence
- Persistent disturbances: design for bounded operation
- Robustness: requires accurate perturbation characterization

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