About the loss of robustness of the LQG/LTR compensator

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Abstract: *It is known that the optimal LQR regulator (Linear Quadratic Regulator) with full state feedback has remarkable robustness properties, defined by gain margins of (1/2, ∞) and phase of at least ± 60 degrees. Representing a realistic approach to control synthesis, LQG (Linear Quadratic Gaussian) synthesis elegantly overcomes the difficulties of an unrealistic full output feedback synthesis LQR. LQG synthesis replaces the ideal case of complete feedback after the state by introducing a special, dynamic observer, the optimal Kalman estimator. LQG synthesis is considered the most powerful acquisition of automatic control science (i.e., control with feedback) which has a history of over 85 years. Unfortunately, LQG synthesis is not infallible either. In a famous article, John Doyle demonstrates that the LQG controller cannot guarantee any stability reserve. To counteract this shortcoming, thus appears the LQG/LTR method (Linear Gaussian Quadratic synthesis with Loop Transfer Recovery), in which the shape of the loop of the robust controller with full feedback after state LQR is restored/recovered, via certain specific procedures. This article shows that the LQG/LTR methodology can also lose its robustness. Therefore, our paper reveals a veritable dialectic of challenges: from LQR to LQG, from LQG to LQG/LTR, from LQG/LTR in search of a new, more efficient approach.*

Key Words: *LQR, LQG, LQG/LTR*

1. INTRODUCTION

Representing a realistic approach to control synthesis, LQG synthesis elegantly overcomes the difficulties of output feedback synthesis (this is the realistic case of incomplete information on the state of the controlled system, which replaces the ideal case of complete feedback after the state), by introducing a special, dynamic observer, the optimal Kalman estimator. As a negative effect of the state estimation, there is a loss of robustness specific to the problem of synthesis of the optimal controller with complete feedback after the state (LQR). Indeed, in the latter case the system proves a remarkable robustness, defined by gain margins of (1/2, ∞) and phase of at least ± 60 degrees [1]. In a famous article, Doyle [2] demonstrates that the LQG controller cannot guarantee any stability reserve. But this shortcoming cannot compromise the entire theory of optimal Linear Gaussian Quadratic synthesis. Being very likely, by its ramifications, the most representative acquisition of control theory to date, the LQG synthesis benefits from a fertile flexibility provided by some free parameters that can be introduced into the model: thus appears the LQG/LTR method (Linear Gaussian Quadratic synthesis with Loop Transfer Recovery), in which the shape of the loop (i.e., of the transfer function) of the robust controller with full feedback after state LQR is restored/recovered, via certain specific procedures for choosing these free parameters: these are fictitious noises, on state or on measure, of which asymptotic convergence to zero is used.

Let the dynamic system consisting of the state equation $\boldsymbol{x}$, the measured output equation $\boldsymbol{y}_o$ and the performance output equation $\boldsymbol{y}_p$ (quality, or regulated) (the matrices $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{D}$, $\boldsymbol{C}_o$, $\boldsymbol{C}_p$ have dimensions corresponding to the vectors involved)

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{D}\boldsymbol{w}, \quad \boldsymbol{y}_o = \boldsymbol{C}_o\boldsymbol{x} + \boldsymbol{\eta}, \quad \boldsymbol{y}_p = \boldsymbol{C}_p\boldsymbol{x}, \tag{1}$$

to which the performance index is attached

$$J_u = \lim_{t_f \to \infty} \frac{1}{t_f} \int_{t_0}^{t_f} \mathrm{E}\left[\boldsymbol{y}_p^T \boldsymbol{Q}_J \boldsymbol{y}_p + \boldsymbol{u}^T \boldsymbol{R}_J \boldsymbol{u}\right] \mathrm{d}t, \tag{2}$$

with $\boldsymbol{Q}_J$, $\boldsymbol{R}_J$ symmetric, $\boldsymbol{Q}_J > 0$, $\boldsymbol{R}_J > 0$. $\boldsymbol{w}$ and $\boldsymbol{\eta}$ are uncorrelated, stationary, white Gaussian noises with symmetric intensities. The separation theorem [3] states in principle that

$$\boldsymbol{u} \coloneqq -\boldsymbol{K}_{\boldsymbol{R}} \cdot \hat{x}, \tag{3}$$

where the control amplification matrix (the control gain)

$$\boldsymbol{K}_R \coloneqq -\boldsymbol{R}_J^{-1} \boldsymbol{B}^T \overline{\boldsymbol{P}} \tag{4}$$

is built on the basis of the unique and symmetric solution $\overline{\boldsymbol{P}} \geq 0$ of the "control" MARE (matrix algebraic Riccati equation) of control

$$\boldsymbol{A}^T\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} - \boldsymbol{P}\boldsymbol{B}\boldsymbol{R}_J^{-1}\boldsymbol{B}^T\boldsymbol{P} + \boldsymbol{C}_p^T\boldsymbol{Q}_J\boldsymbol{C}_p = 0 \tag{5}$$

completely "forgetting" the stochastic aspects. Also, completely "forgetting" the control problem and considering $\boldsymbol{u}$ deterministic, the vector $\hat{\boldsymbol{x}}$ is generated by the Kalman filter

$$\dot{\hat{\boldsymbol{x}}} = \boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{K}_E(\boldsymbol{y}_o - \boldsymbol{C}_o\hat{\boldsymbol{x}}) \tag{6}$$

having the amplification matrix (the Kalman filter gain)

$$\boldsymbol{K}_E \coloneqq \overline{\boldsymbol{Q}}\boldsymbol{C}_o^T\boldsymbol{R}_\eta^{-1} \tag{7}$$

built on the basis of the unique and symmetric solution $\overline{\boldsymbol{Q}} \geq 0$ of the "estimation" MARE

$$\boldsymbol{A}\boldsymbol{Q} + \boldsymbol{Q}\boldsymbol{A}^T - \boldsymbol{Q}\boldsymbol{C}_o^T\boldsymbol{R}_\eta^{-1}\boldsymbol{C}_o\boldsymbol{Q} + \boldsymbol{D}\boldsymbol{Q}_w\boldsymbol{D}^T = 0 \tag{8}$$

The conditions for the existence of the two gains can be summarized as follows: the stabilizability of the pairs ($\boldsymbol{A}$, $\boldsymbol{B}$), ($\boldsymbol{A}$, $\boldsymbol{D}\sqrt{\boldsymbol{Q}_w}$) and the detectability of the pairs ($\boldsymbol{C}_o$, $\boldsymbol{A}$), ($\boldsymbol{C}_p$, $\boldsymbol{A}$).

To describe the mechanism of the LQG/LTR technique, some interesting results are reproduced below, after Doyle and Stein [4].

Proposition 1. *The effect of introducing the Kalman estimator is the same as that of the full state feedback controller – in the sense of equivalent transfer functions, if the loop is cut outside the estimation part – if the relation holds*

$$\boldsymbol{K}_E[\boldsymbol{I} + \boldsymbol{C}_o(s\boldsymbol{I} - \boldsymbol{A})\boldsymbol{K}_E]^{-1} = \boldsymbol{B}[\boldsymbol{C}_o(s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B}]^{-1} \tag{9}$$

In other words, (9) is the condition for preservation the robustness of LQR.

Definition 1. [5]. *The complex numbers s_0 that satisfy the inequality*

$$\text{rang}\begin{bmatrix} \boldsymbol{A} - s_o\boldsymbol{I} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{D} \end{bmatrix} < n + \min(p, \ell).$$

are called ***transmission zeros*** *of the system*

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t), \qquad \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) + \boldsymbol{D}\boldsymbol{u}(t),$$

with $\boldsymbol{x} \in P^n, \boldsymbol{u} \in P^p, \boldsymbol{y} \in P^\ell$.

The given definition assumes that the system ($\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{D}$) is non-degenerate; the system ($\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{D}$) is degenerate if for any (n + 1) distinct real scalars λ_j substituting s_0 the above inequality holds [5].

Definition 2. [6], [7]. The system ($\boldsymbol{C}$, $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{D}$) is of minimal phase if its transfer matrix

$$\boldsymbol{G}(s) := \boldsymbol{C}(s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B} + \boldsymbol{D}$$

has all transmission zeros in the left (open) half-plane.

It is important to note that all transfer functions for which in the representation

$$H(s) = \frac{K}{s^q}\frac{r(s)}{p(s)}, \quad q \in Z, \quad K \in P,$$

with $r(0) = p(0) = 1$ we have: a) $K > 0$ and b) $r(s)$, $p(s)$ have no roots in the half-plane Re(s) > 0, are minimal phase functions [8]. Anderson and Moore [1] give a particular definition: $\boldsymbol{C}(s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B}$ – square matrix – to be nonsingular in Re(s) ≥ 0. Practically symptomatic for a theory in full motion – such as the theory of systems – each consulted reference ([9], [10] etc.), aspires to produce a contribution, in the form, at least, if not in the content of both the construction and the axiomatic basis.

Proposition 2. *If the Kalman filter amplification, parameterized with the parameter $q > 0$, has the asymptotic behavior $\boldsymbol{K}_E(q)/q \to \boldsymbol{BW}$, when $q \to \infty$, $\boldsymbol{W}$ being a non-singular matrix, then relation (18) holds asymptotically. Such an asymptotic behavior can be achieved, provided that the system ($\boldsymbol{C}_o$, $\boldsymbol{A}$, $\boldsymbol{B}$) is of minimum phase, if in the estimation EMAR is substituted (parametrized) $\boldsymbol{D}\boldsymbol{Q}_w\boldsymbol{D}^T$ with $\boldsymbol{D}\boldsymbol{Q}_w\boldsymbol{D}^T + q^2\boldsymbol{B}\boldsymbol{V}\boldsymbol{B}^T$, where $\boldsymbol{V} > 0$, symmetric.*

The following result [1] is also eloquent.

Proposition 3. *If the matrix $\boldsymbol{Q}_w(q) = q^2\boldsymbol{B}\boldsymbol{B}^T$ is a parameterization of the noise intensity per state for the minimum phase system having the square matrix $\boldsymbol{C}_o(s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B}$, then*

$$\lim_{q\to\infty} \boldsymbol{G}(i\omega) = -\boldsymbol{K}_R(i\omega\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B}, \qquad (\forall)\ \omega\ finit \tag{10}$$

$$\boldsymbol{G}(i\omega) := -\boldsymbol{K}_R\left(i\omega\boldsymbol{I} - \boldsymbol{A} + \boldsymbol{B}\boldsymbol{K}_R + \boldsymbol{K}_{Eq}\boldsymbol{C}_o\right)^{-1}\boldsymbol{K}_{Eq}\boldsymbol{C}_o(i\omega\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B} \tag{10'}$$

where $\boldsymbol{G}(i\omega)$ is the open-loop transfer matrix of the Kalman filter system, and $\boldsymbol{K}_{Eq}$ is the notation for the parameterized Kalman filter gain.

The phrase "LQG/LTR" first appears in [11]. Another version of LQG/LTR was developed by Safonov *et al.* [12].

Here, all LQG-type problems in the time domain and the similar Wiener-Hoph problems in the frequency domain were unified, showing that they are, in fact, H_2-weighted negotiations [13] between the various matrices involved in the robustness of the system. (It is worth noting that in both versions the theoretical vehicle is the concept of the *singular value* of a matrix [14], but the asymptotic formulation no longer appears in Safonov et al. [12]). In the same language of H_2 negotiation, the LQG/LTR problem is restated and presented by Stein and Athans [15], also in asymptotic formulation.

Table 1. Tolerated variations of the suspended mass M from the nominal value

compensator	$M\uparrow$	$M\downarrow$
LQ	382%	100%
LQG	3,31%	100%
LQG/LTR	523%	0%

Although apparently well-established and widely used, the robust LQG/LTR synthesis method is far from infallible [16], [14]. In concrete situations, the asymptotic LQG/LTR system may have even worse robustness qualities than the initial LQG system.

When applying the LQG/LTR mechanism, the uncertain parameters of the system must be well circumscribed, and the magnitude of the uncertainties must be well known or estimated.

In a recent study [17], a comparative table (Table 1) of the stability reserve of a mathematical model of active suspension with 2 DOF, with suspension travel measurement, for variations of the parameter M (suspended mass), in three cases of compensator synthesis is presented.

The privileged situation of the LQR controller, the “failures” of the LQG controller and, surprisingly, of the LQG/LTR controller, intolerant to decreases of the uncertain parameter, is observed. The investigation was carried out by inventorying some eigenvalue configurations of the closed-loop system.

2. APPLICATION TO ILLUSTRATE THE ROBUSTNESS LOSS MECHANISM FOR LQG/LTR COMPENSATOR

In the following, the robustness loss mechanism of the LQG/LTR compensator system is illustrated on a simplified model, with 1DOF (1 degree of freedom)

$$M\ddot{x} + c(\dot{x} - w) = u \tag{11}$$

with standard notation: M – mass, c – damping coefficient, x – horizontal displacement of the mass.

The control u will be synthesized by the LQG/LTR procedure, and the disturbance w is a white Gaussian noise of intensity q_w.

Transcribed in the form of the equation of state, (11) becomes

$$\dot{X} = aX + bu + dw, \quad X = \dot{x}, \quad a := -\frac{c}{M}, \quad b := \frac{1}{M}, \quad d := b \tag{12}$$

The measured output and performance equations are associated, respectively

$$y_0 = C_o X + \eta, \quad C_o = 1, \quad y_p = C_p X, \quad C_p = 1 \tag{13}$$

(with the measured noise intensity r_η), as well as the criterion

$$J_u = \lim_{T\to\infty} \frac{1}{T}\left(\int_0^T E\left(q_J X^2 + r_J u^2\right) dt \right) \tag{14}$$

Kalman filter

$$\dot{\hat{X}} = a\hat{X} + bu + K_E C_o\left(X - \hat{X}\right) + K_E C_o \eta, \cdots \hat{y} := u := -K_R \hat{X} \tag{15}$$

has (by virtue of the parameterization in Proposition 2, with $V = 1$), the gains derived from the positive roots of the scalar Riccati equations

$$\begin{aligned} &\frac{b^2}{r_J} X^2 - 2aX - C_p^2 q_J = 0, \quad K_R = \frac{b}{r_J} X, \\ &\frac{C_o^2}{r_\eta} Y^2 - 2aY - (d^2 q_w + q^2 b^2) = 0, \quad , \quad K_E = \frac{C_o}{r_\eta} Y. \end{aligned} \tag{16}$$

Taking the positive root for Y and making $q \to \infty$, we get $K_E(q)/q \to b/\sqrt{r_\eta}$, so $K_E \cong qb/\sqrt{r_\eta}$. But, in real conditions, equations (12), (13) are replaced by

$$\dot{X} = a_R X + b_R u + d_R w, \cdots\cdots y_o = C_{oR} X + \eta \tag{17}$$

(the index "R" marks the presence of real, but uncertain parameters); therefore, the closed-loop system, with the states (X, $\varepsilon = X - \hat{X}$), is structured by the matrix

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} := \begin{bmatrix} a_R - b_R K_R & b_R K_R \\ (a_R - a) - (b_R - b)K_R - K_E(C_{oR} - C_o) & a + (b_R - b)K_R - K_E C_o \end{bmatrix} \tag{18}$$

The eigenvalues of this matrix are the roots of the equation in λ

$$\lambda^2 - (a_{11} + a_{22})\lambda + a_{11}a_{22} - a_{21}a_{12} = 0 \tag{19}$$

and determines the stability and, implicitly, allows the evaluation of the robustness of the system.

Considering the data: $c = 1$ daNs/cm, $M = 0{,}25$ daNs^2/cm, $r_\eta = 13{,}5 \times 10^{-4}$ cm^2/s (5% of the velocity value), $q_w = 0{,}54$ cm^2/s, for $q = 100$, $K_E \cong 10^4$ is evaluated. This is the dominant term in the composition of the matrix (26), together with sgn($C_{oR} - C_o$).

Since a_{11} and a_{22} are structurally negative, provided that $b_R - b < 0$, the appearance of a positive root in equation (27) is conditioned by the negativity of the free term $a_{11}a_{22} - a_{21}a_{12}$, which is possible if $C_{oR} - C_o < 0$. So, if the real object has smaller values of the parameters compared to the mathematical model (21)–(22), the LQG / LTR compensator is sensitive, in other words, less robust. The finding is in agreement with the analysis revealed in table 5.1. Only apparently paradoxical, the result is explained precisely by the asymptotic structure of the method: qualitative reasoning is based on transfinite numbers, and the calculations are inevitably performed with finite numbers.

3. CONCLUSIONS

An alternative approach to the robustness problem is performed by Ioniţă and Ursu [18], [19], based on the concept of *sensitivity variable*, introduced by Wagie and Skelton [20] and developed by Okada and Skelton [21]. The shortcoming of this method consists in the appearance of a compensator that has the double order of the investigated system.

If the perimeter of the synthesis by the Riccati equation is not left, the appeal to the robust synthesis techniques of the H_∞ family is naturally imposed.

In conclusion, it is worth emphasizing that the robustness of a system, including an automatic system, is a criterion for preserving stability, and stability is a *sine qua non* condition for the existence of this system. Therefore, over time, on the occasion of various objectives of the projects in which we participated, we have pursued the analysis and preservation of stability. A special case is represented by systems based on artificial intelligence (neural networks, fuzzy logic) [22], [26], for which the control synthesis is not based on a mathematical model, but on the input-output behavior of the system. The stability problem here is much easier, since it no longer depends on a mathematical model, which is inevitably approximate. But the issue of stability has also been studied mainly in the cases of electrohydraulic and mechanohydraulic servomechanisms in primary flight controls [27], [30], active vibration control [31]-[33], input delay systems [34], [36], and systems for monitoring the health of structures [36]-[40].

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