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EXTENDED POPOV CRITERION VS FIXED POINT THEOREM FOR COMPLEX NONLINEAR SYSTEMS

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Abstract The development of modern technology leads to conceive always more complex nonlinear systems the analysis of which is requiring specific tools, especially as concerns their stability and robustness. Such tools are lacking in explicit form and analysis is mainly numerical, even if Popov criterion provides a (generally poor) sufficient stability condition. Here previously developed extended Popov criterion generalized for more manageable functions upper-bounding system nonlinearity is compared to straightforward and explicit application of Fixed Point Theorem in adapted function space. It is shown that the later gives sufficient conditions more restrictive than extended Popov criterion or at worst equivalent. As the conditions are expressed in terms of identifiable main power flows circulating in the system, they are much more accessible and of easier use than Popov condition for system final control.

I-Introduction

A great change in the approach to dynamical systems has been occurring in the recent years under the pressure of very fast advancing technology. New components are now everyday produced with reliable and accurate performances, mainly based on the extraordinary opening of electronic devices onto digital representation, allowing in turn represent almost any desired dynamical behaviour. The control of systems comprising such elements especially in high performance domain is thus requiring the development of methods able to handle a very large class of time functional dependences intrinsically embedded into the possible responses resulting from elements interaction inside the systems. This is the more necessary as a general trend in system design is to have them lighter and more compact under economic constraint, with much higher level of interactions between components and as a result, a broad range of nonlinearities. In parallel, the demand for higher robustness is increasing, because this appears now as the response for better safety in operation mode when dealing with systems of intrinsic high complexity only amenable to approximate representation. This is also the only way to add on top of classical control structure a new upper decision layer for task intelligent control[1] resulting from inevitable and always larger delegation from operator to the machine in high performance range. But it is still a very difficult problem in control of nonlinear systems to find explicit criteria giving reasonable parametric domain for full stability, as opposed to local, linearized, ones which have been thoroughly explored[2]. Since early studies the second Lyapounov method[3], based on the construction of an adequate Lyapounov function in each specific case, has been singled out due to its versatility and ease to use. Despite an extensive research for more than a century, there is still no general method for getting such a function guaranteeing non trivial information for application purpose. Even worse, as the general recipe is lacking, it cannot be concluded at system instability if this function cannot be found in a particular case. More trivially the only result is that the way to construct the function is not yet known. So other attempts have been developed, based on more functionally oriented methods, such as Popov criterion[4], closely related to circle criterion expressing a fixed point property[5], but only restricted to systems with a nonlinearity limited in norm within a sector bounded by a straight line. As many systems are today breaking this constraint, the problem of extending Popov criterion to situations where the nonlinearity norm is bounded by non decreasing functions – such as power law with power ρ ($\rho = 1$ corresponds to linear case) or exponential law –, has been considered[6]. Similarly, extension of Lyapounov method by fixed point theorem also provides explicit nonlinear stability condition expressed in terms of global system characteristics[7]. In both cases, the criteria are explicit and are meaningful in the sense that they express a general contractive property of the transformation represented by the differential operator of system equations[8]. As known, given a nonlinear n -dimensional controlled system with regular and nonlinear term bounded in norm by a non-decreasing function of state norm, local (asymptotic) stability condition is obtained from linearized equation and adequate P-control of system state. More restrictive condition for monotonic asymptotic stability may also be researched as it could fit closer smoothness

condition on system behaviour in the neighbourhood of nominal point as imposed by technical characteristics implying overshoot avoidance for instance. However, local conditions are often not sufficient for guaranteeing decay monotonic behaviour in the complete domain of utilization. Full nonlinear extension is required, and it is here proposed to compare extended Popov criterion to fixed point condition performance, both explicit and robust asymptotic stability conditions as they rest upon global system properties corresponding to equivalence classes based on main power flow in the system.

II-System Equations and BIBO Property

Let system dynamics be described by ODE

$$\frac{dx_s}{dt} = F_s(x_s(t), u(t), d(t), t) \quad (1)$$

where $F_s: R^n \times R^m \times R^p \times R^l_+ \rightarrow R^n \in C^1(R^n \times R^m)$, with system state $x_s(t)$, control input $u(t) \in U \subset L_\infty$, disturbance $d(t) \in D \subset L_\infty$, and solution $x_s(t, t_0, x_s^0, u, d)$. To fix system structure, it will be supposed here that function $F_s(\dots, t)$ is such that $F_s(0, 0, 0, t) = 0$ and satisfies Lipschitz-type generalized inequalities

$$\|F_s(x, u, d, t) - F_s(x', u', d', t)\| \leq L_0(t)\|x - x'\| + g_s(\|x - x'\|, t) + L_1(t)\|u - u'\|_\infty + L_2(t)\|d - d'\|_\infty \quad (2)$$

for $(x, u, d), (x', u', d') \in \Omega \times U \times D$, positive monotonic non decreasing function $g_s(\cdot)$, time dependent positive functions $L_j(t)$ ($j=0,1,2$), and with $\Omega_0 \subset R^n$ the domain where the solution of eqn(1) exists for $x_s^0 \in B_\rho$ the ball centered at origin with radius ρ . Eqn(2) typically correspond to Caratheodory condition[9] usually satisfied by most natural and technical systems. Taking the norm of eqn(1), one gets with eqn(2) the inequality

$$\|x(t)\| \leq \int_{t_0}^t R_s(t') dt' + \int_{t_0}^t [L_s(t')\|x(t')\| + g_s(\|x(t')\|, t')] dt' \quad (3)$$

Using generalized Bellman-Gronwall inequality[10] the following bound

$$X(t) \leq Y(t_0, t) \cdot G_s^{-1} \left[G_s(X_0) + \text{sgn}(G_s) \int_{t_0}^t \left(Y^{-1}(t_0, t') h(t') + \text{Max} \left\{ 0, \frac{W'(t)}{W(t)} \right\} \right) dt' \right] \quad (4)$$

can be found in the case where there exists $F_s(\cdot)$ and $h(\cdot)$ so that $g_s(X(t), t) \leq F_s(X(t)) \cdot h(t)$ with positive monotonic and non decreasing function $F_s(\cdot)$ such that $F_s(0) = 0$ and $F_s(X) \geq LX$ for all $X > 0$, where

$$Y(t_0, t) = \exp \int_{t_0}^t L_s(t') dt', \quad R_s(t) = L_1(t)\|u(t)\|_\infty + L_2(t)\|d(t)\|_\infty, \quad W(t) = \int_{t_0}^t R_s(t') Y(t_0, t') dt'$$

and defining $G_s(x) = \int^x dv F_s(v)^{-1}$. As $G_s(\cdot)$ is super-linear, $\text{sgn}(G_s(\cdot)) < 0$, and $X(t)$ is only defined for $[X(0), t]$ such that the argument of $G_s(\cdot)^{-1}$ does not change sign, ie $t < t_c$ defined by the zero of bracket expression in eqn(4)

$$G_s(X_0) = \int_{t_0}^{t_c} \left[Y^{-1}(t_0, t') h(t') + \text{Max} \left\{ 0, \frac{W'(t')}{W(t')} \right\} \right] dt' \quad (5)$$

So there is a critical initial ball X_{0c} so that $t_c = \infty$. For $X(0) < X_{0c}$ the solution is bounded for all time and simple BIBO stability result is expectable. For $X(0) \geq X_{0c}$ a Lagrange time instability does occur and there only exists a relatively loose BIBO bound for $t \in [0, t_c]$. However the BIBO bound may exist

for all $X(0)$ in specific cases. For instance, when Young inequality for polynomial bound of $g_s(\cdot)$ can be used, one gets $F_s(v) = v^{\lambda_s}$ so $G_s(v) = -v^{-(\lambda_s - 1)}/(\lambda_s - 1)$ explicit in the argument, and finer analysis of resulting eqn(3) gives instead in this case

$$\int_0^t Y(t_0, t')^{-1} R_s(t') dt' \geq \|X_s(t)\|_2 F_1\left(1, \lambda_s^{-1}, 1 + \lambda_s^{-1}, -\text{Sup}\left[\frac{L_s(t)}{R_s(t)}\right] \|X_s(t)\|^{\lambda_s}\right) - \|X_s(0)\|_2 F_1\left(1, \lambda_s^{-1}, 1 + \lambda_s^{-1}, -\text{Sup}\left[\frac{L_s(t)}{R_s(t)}\right] \|X_s(0)\|^{\lambda_s}\right) \quad (6)$$

with $X_s(t) = Y(t_0, t)^{-1} x_s(t)$, ${}_2F_1(\alpha, \beta, \gamma; z)$ the hypergeometric function. As the left hand side of eqn(6) is in general bounded for $t \rightarrow \infty$, so is $X_s(t)$ and $x_s(t)$ is now finite for all t finite $> t_0$ and $x_s(t) \approx Y(t_0, t)$ as $t \rightarrow \infty$. This indicates that the obtained global bound is sensitive to the way the integral is performed with respect to upper bounding of the various terms in the RHS of eqn(3). With respect to this rough property, the problem at hand is now to research if there exists a controller guaranteeing robust stability in as large as possible ball around the origin. The main remark is that to make the researched jump from BIBO result for the class of equations considered with appropriate time dependent bounding functions, only finite power input is required which is technically doable and justifies the analysis.

III-Robust Asymptotic Controllers

So the problem here is mainly to reduce BIBO intrinsic property to finer robust asymptotic one, where robustness constraint is imposed by the difficulty to model the system, in general only approximately known when complex. To get the analytical form of the controller performing this reduction, eqn(1) gives for error e the equation

$$\frac{de}{dt} = A(t)e + B_0(t)\Delta u + G_s(e, x_s, \Delta u, d, t) \quad (7)$$

after splitting the linear parts in e and Δu and with $x(t) = x_0(t) + e(t)$, $u = -Ke + \Delta u$. It is supposed that the nonlinear part satisfies the bounding inequality

$$\|G_s(e, x_s, \Delta u, d, t)\| \leq M_s(t) g_s(\|e(t)\|, t) \quad (8)$$

in agreement with eqn(2) and that the linear gain K is such that the linear part of eqn(7) for e is asymptotically stable (for time independent matrices A and B_0 this means that $A = A_0 - B_0K$ is Hurwitz). Supposing there exists positive definite matrices P and Q such that $PA + A^T P + dP/dt = -Q$, one can define the (positive definite) Lyapunov function

$$\mathcal{L}(x_s) = \langle ePe \rangle \quad (9)$$

using the bra ket formalism. Its derivative along system trajectories is given by

$$d\mathcal{L}(e)/dt = -\langle eQe \rangle + \langle ePB\Delta u \rangle + \langle ePG_s \rangle \quad (10)$$

Choosing from eqn(2) the controller form

$$\Delta u = -\beta M_s g_s \frac{B^T Pe}{\|Pe\| + \varepsilon f} \quad (11)$$

where β and ε are two positive parameters and $f = f(\cdot)$ is the driving function to be defined later, eqn(10) transforms after substitution into the inequality

$$d \mathcal{L}(e)/dt \leq - \langle e Q e \rangle + \varepsilon M_s g_s f + M_s g_s \frac{\|Pe\|^2 - \beta \|B^T Pe\|^2}{\|Pe\| + \varepsilon f} \quad (12)$$

When taking

$$\beta \geq \frac{|\lambda_{\max}(P)|^2}{|\lambda_{\min}(B^T P)|^2} \quad (13)$$

the last term on the RHS can be made negative by noting $\lambda(X)$ the eigenvalue of matrix X , in which case eqn(12) simplifies to

$$d \mathcal{L}(e)/dt \leq - \langle e Q e \rangle + \varepsilon M_s(t) g_s(\|e(t)\|, t) f(e, t) \quad (14)$$

showing the opposite action of the two terms as discussed in the text. If $f(\cdot)g_s(\cdot)$ is upper bounded over the whole interval, the RHS of eqn(14) is negative above some threshold value. On the other hand, because $g_s(\cdot)$ is for regular $f(\cdot)$ a higher order term at the origin by construction, the RHS of eqn(14) is negative close to the origin. So there may exist an interval on the real line where $d\mathcal{L}(e)/dt > 0$ separating two stable domains. If $f(\cdot)g_s(\cdot)$ is growing at infinity, there exists a threshold value above which the system is unstable. So there is an asymptotic stable ball around the origin, and the decay is fixed by the specific functional dependence of the functions $f(\cdot)$ and $g_s(\cdot)$. The next step is to fix the driving term $f(\cdot)$ for determining the upper bound on the time decay of Lyapunov function and finally on the norm of error vector $e(t)$. As $\langle e Q e \rangle$ and $\langle e P e \rangle$ are equivalent norms, there exists $k(t) > 0$ so that $\langle e Q e \rangle \geq k \mathcal{L}(e)$ and eqn(14) can be replaced by

$$d \mathcal{L}/dt \leq - k(t)\mathcal{L} + \varepsilon M_s(t) g_s(\mathcal{L}, t) f(\mathcal{L}, t) \quad (15)$$

with new dependent variable \mathcal{L} , bounded by the solution $Y(t)$ of eqn(15) with equal sign. Comparing eqn(15) with eqn(3) the marked difference is in the sign of the linear term which is made here a strict recall force by the choice of the controller with expected better result, a not so surprising fact as the global control method developed here is mainly to balance bounds on sources and sinks in the system. Of course $f(\cdot, t)$ is immediately determined for given functional form of $g_s(\cdot, t)$ with prescribed $Y_d(t)$. However a more useful approach is to consider the embedding problem where, for given $M_s(t)g_s(\mathcal{L}, t)$, a correspondence is researched between function spaces \mathcal{F} and \mathcal{Y} to which $f(t)$ and $Y(t)$ respectively belong, with \mathcal{Y} fixed by global properties such as continuity and decay for large t .

The most general way is to use substitution theorems relating different function spaces[9] and fixed point theorem[10]. Supposing that $Y(t) \in \mathcal{W}_1^p \rightarrow M_s(t)g_s(\mathcal{L}, t) \in \mathcal{W}_1^q$, with Sobolev space definition \mathcal{W}_m^n [11], application of Holder inequality shows that there should be $\mathcal{F} \subseteq \mathcal{W}_1^n$ with $n^{-1} = p^{-1} - q^{-1}$, $1 \leq p, q, n < \infty$ which relates the decays of $f(t)$ and of $Y(t)$ for large t . One can then define the driving function $f(t) = \mu Y^\phi$ now implicit in time through the error bound directly measurable. More specific results can be found for more explicit constraint $g_s(Y(t)\exp[k(t)dt], t) \leq \Gamma_s(Y(t)).h(t)$ in which case application of generalized Bellman-Gronwall inequality[12] gives for non decreasing function $\Gamma_s(\cdot)$

$$Y(t) \leq \exp - \int_0^t k(t') dt' \Gamma_s^{-1} \left[\Gamma_s(Y_0) + 2 \operatorname{sgn}(\Gamma_s) \varepsilon / \alpha \int_0^t \exp - \int_0^{t'} k(t'') dt'' M_s(t') h(t') dt' \right] \quad (16)$$

where $\Gamma_s(x) = \int^x dv g_s(v)^{-1}$. When $\Gamma_s(\cdot)$ is sub-linear, $\operatorname{sgn}(\Gamma_s(\cdot)) > 0$, and $Y(t)$ is defined for any $[Y(0), t]$, whereas if $\Gamma_s(\cdot)$ is super-linear, $\operatorname{sgn}(\Gamma_s(\cdot)) < 0$, and $Y(t)$ is only defined for $[Y(0), t]$ such that the argument of $\Gamma_s(v)^{-1}$ does not change sign, ie $t < t_c$ defined by the zero of bracket expression in eqn(11).

$$G(Y_0) = 2(\varepsilon / \alpha) \int_0^{t_c} \exp - \int_0^{t'} k(t') dt' M_s(t') h(t') dt' \quad (17)$$

in order to avoid Lagrange instability in finite time t_c . Here $Y(t)$ may have a decay different from exponential but in a limited ball of initial conditions and depending on $f(\cdot)$. This indicates a conditional asymptotic stability result only. In all cases, asymptotic stability can be found in conjunction with robustness constraint, in contrast to classical approach, and the role of $f(t)$ which drives the behaviour of $Y(t)$ is clearly shown.

IV - Example

As an example, when $g_s(Y, t) \leq b(t)Y^s$ with $b(\cdot) \in \mathcal{L}^\beta$ and $s^{-1} = q^{-1} - \beta^{-1}$ the bounding equation for $Y(t)$ from eqn(16) becomes a Bernoulli equation with solution for constant k

$$y(t) = \exp - kt \left\{ 1 - (\theta - 1) \frac{\varepsilon \mu}{k} Y_0^{\theta-1} \int_0^{kt} \exp - (\theta - 1) u M_s(u) b(u) du \right\}^{-1/(\theta-1)} \equiv \exp - kt U(kt, Y_0, \theta) \quad (18)$$

with $\theta = s + \phi$, $y(t) = Y(t) / Y(0)$ and normalized time $u = kt$, which exhibits a non exponential asymptotic decay for $\theta < 1$ and for any $Y(0)$, and a conditional decay when $\theta > 1$ directly depending on the balance between recalling linear spring and repulsive nonlinear forces. The present analysis is applicable in similar form to systems with unknown norm bound on nonlinear terms[13] by extending adaptive method, and also to systems with unknown dynamics[14] by developing nonlinear network representation, the parameters of which are adaptively constructed to converge toward system representation. When the coefficients A , B_0 and the bounding function g_s of eqns(1,2) are time independent, the more general (Lurie type) Lyapunov function[15]

$$\mathcal{L}(e) = \langle e P e \rangle + \lambda \int_0^{D.e} \Psi(\xi) d\xi \quad (19)$$

can also be used with D an adjustable vector and $\Psi(\cdot)$ a sector function with bound τ , ie such that $\Psi(\xi)[\Psi(\xi) - \tau\xi] \leq 0$. Using recent extension of Popov criterion[6] the explicit form of driving function $f(\xi) = \xi^{1/2}$ is finally found in eqn(15) leading to the same bound as in eqn(18) with $\phi = 1/2$ whereas the additional controller takes the simple form $\Delta u = -\Psi(D.e)$ instead of eqn(10). Analysis of $U = U(kt, Y_0, \theta)$ in eqn(18) shows that when $(\varepsilon\mu/k)Y_0^{\theta-1} < 1$, $y(t)$ has no singularity over the complete real positive line, and two cases can occur. If $\varepsilon\mu/k > 1$, Y_0 is always < 1 and larger limit value of Y_0 corresponds to larger exponent θ . So extension of Popov criterion gives smaller robustness ball than fixed point result. If $\varepsilon\mu/k < 1$, Y_0 can be > 1 in which case conversely, larger limit value of Y_0 corresponds to smaller exponent θ . So extension of Popov criterion is equivalent to fixed point result when taking the smallest allowable exponent value $1/2$. For completeness, when $(\varepsilon\mu/k)Y_0^{\theta-1} > 1$, there exists a critical time kt_c for which $y(t)$ is singular, showing finite time Lagrange instability. Only finite time boundedness is possible in this case, and given a ball \mathcal{B} , it is interesting to determine the largest initial ball $\mathcal{B}(0, Y_0)$ so that its transform $\mathcal{B}(T, Y(T))$ by eqn(11) satisfies $\mathcal{B}(T, Y(T)) \subseteq \mathcal{B}$ with largest T corresponding to smallest input-output amplification factor. In the same way, smallest exponent corresponds to largest T and largest Y_0 when $\varepsilon\mu/k < 1$ whereas a compromise has to be found when $\varepsilon\mu/k > 1$. So in all cases an adapted controller exists in explicit form, and is very robust as it only depends on global bounding functions for power sources and sinks in system equations. Here there are mainly two of them from the nonlinear repulsive force (the source) and the attractive linear force resulting from the action of the controller (the sink). Asymptotic stability is obtained here when the attractive force overpasses the repulsive one. The upper bounding attractive and repulsive forces are completely defining equivalence classes for systems with respect to their global dynamical behaviour. They cannot be distinguished from control point of view as concerns this property when they differ by finer details and only classes of trajectories belonging to defined manifolds can be considered. This is

interesting for system upper level task control when observing that these manifolds change with the task, so there is here a consistency link between the task assignment and the nature of system response through the controller guiding system trajectory whatever it starts from toward any trajectory belonging to the task manifold[16].

Conclusion

Analysis of general class of nonlinear dynamical equations describing most observed natural systems and main technical ones today used in industry has been developed. Because their norm satisfies generalized Bellman-Gronval inequalities, they are at best upper bounded by BIBO type limitation. To operate safely these systems however, and due to the inherent difficulty to model them adequately when they become complex enough, it is important to guarantee the existence of a robust ball around the origin where asymptotic stability property is satisfied. On the other hand, not only the controller has to be explicit in terms of system characteristics so that it can be directly implemented, but also the resulting effect of its action on the system should be expressed in these terms to evaluate the robustness ball it produces. This problem has been solved by extension of Lyapounov method to fixed point method and by defining explicit form of the controller in terms of global elements (sources and sinks) characterizing power flux circulation inside the system. Asymptotic stability is obtained inside the domain where the attractive force created by the controller surpasses the globally repulsive force from nonlinear terms, and the boundary defines in complete explicit terms the researched ball surface. In parallel, another explicit analysis, leading for nonlinear systems bounded in norm by a linear function to Popov criterion, and previously extended to any nonlinear, monotonic and non decreasing function, has also been used. Comparison has been made between the results of the two approaches for monomial nonlinear bound with time independent coefficients, and it is concluded that the second one is a particular case of the first. So depending on parameter values, the asymptotic stability ball radius may be either equivalent or worse than when using the first approach, but the controller expression is simpler and may be demanding less power for operation. In any case, both controllers are expressed in well identifiable and explicit elements extracted from initial system equations. They are furthermore satisfying the robustness constraint inevitably imposed by the complexity increase in systems. Because they operate at function space level, they are especially well suited for dealing with trajectory manifolds contrary to classical single trajectory control, and provide an interesting way to approach consistently the higher level task control which most systems are facing today.

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