Robust Stabilization of Marginally Stable Positive-Real Systems

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SUMMARY

This paper investigates the stability of the negative feedback interconnection of two positive-real systems which have poles in the closed left-half of the complex plane. A new definition of marginally strict positive real systems is introduced, and sufficient conditions are obtained for the stability of the feedback interconnection of such systems, using the Lyapunov method. The conditions obtained have direct applications to dynamic dissipative controllers for flexible spacecraft, and are the least restrictive ones published to date.

I. INTRODUCTION

A well known result in passivity theory [1] is the Passivity Theorem, which states that a stable passive dynamic system can be stabilized by a stable strictly passive controller. For linear, time-invariant (LTI) systems, passivity is equivalent to positive realness. However, the relationship between strict passivity and strict positive realness is somewhat more complicated because there are several definitions of strict positive realness. Strict passivity is equivalent to the strongest definition of strict positive realness (SPR) [2] for LTI systems. (We shall refer to this definition simply as "strict passivity", even for the LTI case). The Passivity Theorem, which is for general (possibly nonlinear) systems, can be directly applied to LTI systems; i.e., the feedback interconnection of a stable PR system and a strictly passive system is stable. However, the requirement of strict passivity is too stringent, as it includes only systems with a relative degree of zero. Another definition of strict positive realness was introduced in [2] for scalar systems, and was further investigated in [3, 4, 5] for multivariable systems. This definition (referred to as "strong SPR") is weaker than strict passivity.

In [6], an even less stringent definition of SPR, termed "weak SPR", was investigated, and it was stated that the feedback interconnection of a stable PR system and a weak SPR system is stable. That is, the strict passivity requirement was replaced by the "weak SPR" requirement. This was a significant improvement,
since weak SPR systems can include strictly proper systems, while strict passivity
requires the relative degree to be zero. However, in all the studies in the
published literature, both weak and strong definitions of SPR require the systems to
be stable (i.e., all poles are required to be in the open left-half of the complex
plane). In this paper, we shall remove this restriction.

Let G(s) denote an m×m matrix whose elements are proper rational functions of
the complex variable "s". Let the conjugate-transpose of a complex matrix T be
denoted by T*.

Definition 1: An m×m rational matrix G(s) is said to be positive real (PR) if
(i) all elements of G(s) are analytic in Re[s] > 0;
(ii) G(s) + G*(s) ≥ 0 in Re[s] > 0 , or equivalently,
   (iia) poles on the imaginary axis are simple and have Hermitian,
   nonnegative-definite residues, and
   (iib) G(jω) + G*(jω) ≥ 0 for ω ∈ (-∞,∞)

Given below are some definitions of strictly positive real systems. Definition
2, which represents the specialization to LTI systems of the general definition of
strict passivity, is the strongest definition of strict positive realness.

Definition 2: An m×m rational matrix G(s) is said to be strictly passive if
(i) all elements of G(s) are analytic in Re[s] ≥ 0;
(ii) there exists an ε > 0 such that
    G(jω) + G*(jω) ≥ εI for ω ∈ (-∞,∞)

Definition 3: An m×m rational matrix G(s) is said to be strictly positive real in the
strong sense (strong SPR, or SSPR) if G(s-ε) is PR for some ε > 0; that is, if
(i) all elements of G(s) are analytic in Re[s] ≥ 0;
(ii) G(jω) + G*(jω) > 0 for ω ∈ (-∞,∞)
(iii) Z = G(∞)+G*(∞) ≥ 0
(iv) \[ \lim_{\omega \to \infty} \omega^2 [G(j\omega) + G*(j\omega)] > 0 \] if Z is singular
**Definition 4:** An $m \times m$ rational matrix $G(s)$ is said to be **strictly positive real in the weak sense** (weak SPR, or WSPR) if

(i) all elements of $G(s)$ are analytic in $\text{Re}[s] \geq 0$;

(ii) $G(j\omega) + G^*(j\omega) > 0$ for $\omega \in (-\infty, \infty)$

Note that Definition 2 requires that $\mathcal{Z} = G(\infty) + G^T(\infty)$ to be positive definite; i.e., the system must have a relative degree of zero. This requirement makes the definition of strictly passive systems too restrictive. Definition 3 (SSPR) can include certain strictly proper systems which satisfy additional conditions (iii) and (iv). Definition 4 (WSPR) does not require these additional conditions, and is therefore less restrictive than Definition 3. However, all the definitions (2-4) of SPR require the system to be **stable**.

In this paper, we go one step further, and allow the system to have poles on the imaginary axis. The significance of this is that many physical systems can now be included in this (much larger) class of systems.

**Definition 5:** An $m \times m$ rational matrix $G(s)$ is said to be **marginally strictly positive real** (MSPR) if it is positive real, and

$$G(j\omega) + G^*(j\omega) > 0 \text{ for } \omega \in (-\infty, \infty)$$

Definition 5 of MSPR differs from Definition 1 (PR) because the frequency domain inequality ($\geq$) has been replaced by the strict inequality ($>$). The difference between Definitions 4 and 5 is that Definition 5 allows $G(s)$ to have poles on the imaginary axis. This is an important difference because many real-life systems contain pure integrators and oscillators, which are permitted under Definition 5, but not under Definitions 2, 3, and 4. For example, let $G(s) = \frac{\gamma}{s} + \frac{\delta s}{s^2 + \omega_0^2} + H(s)$, where $\gamma$ and $\delta$ are real non-negative scalars and $H(s)$ is weak SPR. Then $G(s)$ is marginally SPR.
Suppose $[A,B,C,D]$ is a minimal realization of a rational matrix $M(s)$. $M(s)$ (or $[A,B,C,D]$) is said to be minimum-phase if its transmission zeros are confined to the open left-half plane (OLHP); i.e., rank $\begin{bmatrix} sI-A \\ C \\ D \end{bmatrix}$ can drop below its normal value only for values of $s$ in the OLHP.

II. PROPERTIES OF MSPR SYSTEMS

Suppose $G(s)$ is positive real and has all poles (i.e., the eigenvalues of the system matrix of its minimal realization) in the closed left-half plane (CLHP). Following [7], $G(s)$ can be written as:

$$G(s) = G_1(s) + G_2(s)$$

where $G_1(s)$ has purely imaginary poles, and $G_2(s)$ has poles only in the open left-half plane (OLHP). Furthermore, $G_1(s)$ is of the form:

$$G_1(s) = \frac{\alpha_0}{s} + \sum_{i=1}^{p} \frac{\alpha_i}{s^2 + \omega_i^2} + \beta_i$$

where $\alpha_i$ and $\beta_i$ are $m \times m$ real matrices, and $\omega_i > 0$, $i=1,2,...,p$ ($\omega_i \neq \omega_j$ for $i \neq j$).

Some remarks regarding the nature of the poles on the imaginary axis are in order. The poles and zeros considered here are in the Smith-McMillan sense [8]; i.e., there can be more than one pole at a given location, without it being considered a "repeated" pole. In particular, using standard results in matrix fraction descriptions [8], it can be shown that the McMillan degree (i.e., the minimal order of a state space representation) of the term: $[\alpha_0/s]$ is equal to $\rho(\alpha_0)$, where $\rho(.)$ denotes the rank. That is, there are $v=\rho(\alpha_0)$ simple poles at $s=0$.

Suppose the McMillan degree of the term: $[\alpha_i s + \beta_i]/(s^2+\omega_i^2)$ is $2k_i$, where $k_i \leq m$. Then this term has $k_i$ simple poles (each) at $s=\omega_i$ and $-\omega_i$.

The following results state that $G(s)$ is PR (respectively, MSPR) iff its stable part is PR (resp. WSPR).
Lemma 1. \( G(s) \) is PR (resp. MSPR) iff all of the following hold;

(i) \( G_2(s) \) is PR (resp. WSPR);

(ii) \( \alpha_i = \alpha_i^T \geq 0, \ i = 0, 1, 2, ... p \);

(iii) \( \beta_i = -\beta_i^T, \ i = 1, 2, ... p \).

Proof. From the requirement that the residues at the imaginary-axis poles be nonnegative-definite, we get (ii) and (iii) (See [9]). Therefore, we have:

\[
G_1(j\omega) + G_1^*(j\omega) = 0, \text{ and } G(j\omega) + G^*(j\omega) = G_2(j\omega) + G_2^*(j\omega),
\]
which is positive semi-definite (resp. positive definite) for all real \( \omega \) iff \( G_2(s) \) is PR (resp. WSPR).

If \( G(s) \) is MSPR, the degree of \( [G(s) + G^*(s)] \) is generally less than the degree of \( G(s) \); also, \( G_2(s) \) is stable, and both \( G(s) \) and \( G_2(s) \) are minimum-phase.

We shall next consider a minimal realization of MSPR transfer functions.

III. MINIMAL REALIZATION OF MSPR SYSTEMS

Consider the realization of \( G_1(s) \). For the term \([\alpha_0/s]\), since \( \alpha_0 \) is symmetric and non-negative definite (Lemma 1), there exists an \( m \times m \) real orthogonal transformation matrix \( T \) which diagonalizes it, i.e.,

\[
T^T \alpha_0 T = \text{diag}[\lambda_1, \lambda_2, ..., \lambda_v, 0, ..., 0]
\]

where \( \lambda_i \) are positive scalars. Let \( \Lambda \) denote \( \text{diag}[\lambda_1, \lambda_2, ..., \lambda_v] \). A minimal realization (of order \( \nu \)) of \( T^T[\alpha_0/s]T \) is: \([A_0, \bar{A}_0, \bar{C}_0, 0]\), where

\[
A_0 = [0_{\nu}]; \quad \bar{A}_0 = [I_{\nu}, 0]; \quad \bar{C}_0 = \begin{bmatrix} \Lambda \end{bmatrix}
\]

where \( 0_{\nu} \) and \( I_{\nu} \) denote \( \nu \times \nu \) null and identity matrices. Therefore, a minimal (\( \nu^{th} \)-order) realization of \([\alpha_0/s]\) is given by \([A_0, \bar{A}_0, \bar{C}_0, 0]\), where
\[
\begin{align*}
\mathcal{A}_0 &= \mathcal{A}_0^T, & \mathcal{C}_0 &= \mathcal{C}_0^T
\end{align*}
\]  

Considering the term: \([\alpha, s + \beta, i/(s^2 + \omega_i^2)\), if its McMillan degree is \(2k_i (k_i \leq m)\), a minimal realization is given by [7]: \([A_i, \mathcal{A}_i, \mathcal{A}_i^T, 0]\), where \(\mathcal{A}_i \in \mathbb{R}^{2k_i \times 2k_i}\).

\[
A_i = \text{diag}(A_1, A_2, \ldots, A_k)
\]

where

\[
A_j = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}
\]

and \(A_i \in \mathbb{R}^{2k_i \times m}\). Then a minimal realization of \(G_1(s)\) is given by: \([A_1, B_1, C_1, 0]\), where \(A_1 = \text{diag}(A_0, A_1, A_2, \ldots, A_p); B_1 = \begin{bmatrix} \mathcal{A}_0^T, \mathcal{A}_1^T, \ldots, \mathcal{A}_p^T \end{bmatrix}^T; C_1 = \begin{bmatrix} \mathcal{C}_0, \mathcal{C}_1, \ldots, \mathcal{C}_p \end{bmatrix}^T; A_1 \in \mathbb{R}^{n_1 \times n_1}, B_1 \in \mathbb{R}^{n_1 \times m}, C_1 \in \mathbb{R}^{m \times n_1} (n_1 = n + 2k_i)\).

Let \([A_2, B_2, C_2, D]\) be a minimal realization \(G_2(s)\), where \(A_2 \in \mathbb{R}^{n_2 \times 2}, B_2 \in \mathbb{R}^{n_2 \times m}, C_2 \in \mathbb{R}^{m \times 2},\) and \(D \in \mathbb{R}^{m \times m}\). Let \(A = \text{diag}(A_1, A_2); B = [B_1^T, B_2^T]^T; C = [C_1, C_2]\). Then \(A \in \mathbb{R}^{nx}, B \in \mathbb{R}^{nx}, C \in \mathbb{R}^{mx},\) and \(D \in \mathbb{R}^{mx}\). Since \(G_1(s)\) and \(G_2(s)\) have no poles in common, \([A, B, C, D]\) is a minimal realization of \(G(s)\).

**IV. CHARACTERIZATION OF MSPR SYSTEMS**

We next present the state-space characterization of MSPR systems, which is an extension of the Kalman-Yacubovich lemma for WSPR systems, that was proved in [6].

**Lemma 2.** If \(G(s)\) is MSPR, there exist real matrices: \(P = P^T > 0, P \in \mathbb{R}^{nx}, \mathcal{L} \in \mathbb{R}^{kn \times 2},\) \(W \in \mathbb{R}^{km}\) (where \(k \geq m\)), such that

\[
A^T P + PA = -L^T L
\]

\[
C = B^T P + W^T L
\]

\[
W^T W = D + D^T
\]
\[ L = \begin{bmatrix} 0 & \mathcal{X} \end{bmatrix} \]  

where \([A_2, B_2, W] \) is minimal and minimum-phase.

**Proof.** \( G(s) \) has the form given by Eqs. (1) and (2). Since \( G(s) \) is MSF, conditions (i)-(iii) of Lemma 1 hold. Considering \( G_1(s) \) in Eq. (2), it consists of \((p+1)\) transfer functions in parallel. A minimal realization (Eqs. 4 and 5) of the first term, \([\alpha_0/s], \) is: \([\mathcal{A}_0, \mathcal{B}_0, \mathcal{C}_0, 0] \). Letting \( \Pi_0 = \Lambda \), it can be verified that the equations are satisfied:

\[ \mathcal{A}_0^T \Pi_0 + \Pi_0 \mathcal{A}_0 = 0 \]  

\[ \Pi_0 \mathcal{B}_0 = \mathcal{C}_0^T \]  

A minimal realization (Eqs. 6, 7) of the \( i \)th component of the second term, \([\alpha_i/s + \beta_i]/(s^2 + \omega_i^2), \) is given by \([\mathcal{A}_i, \mathcal{B}_i, \mathcal{C}_i^T, 0] \). Letting \( \Pi_i = I_{2k_i} \), it can be seen that this realization satisfies:

\[ \mathcal{A}_i^T \Pi_i + \Pi_i \mathcal{A}_i = 0 \]  

\[ \Pi_i \mathcal{B}_i = \mathcal{C}_i \]  

Finally, following [6,7], since \( G_2(s) \) is WSP, there exist \( P_2 = P_2^T > 0, P_2 \in \mathbb{R}^{n_2 \times n_2}, \) \( W \in \mathbb{R}^{k \times n}, \mathcal{X} \in \mathbb{R}^{k \times n} \) (where \( k \geq m \)) such that

\[ A_2 P_2 + P_2 A_2 = -\mathcal{X}^T \mathcal{X} \]  

\[ C_2 = B_2^T P_2 + W^T \mathcal{X} \]  

\[ W^T W = D + D^T \]  

where \([A_2, B_2, W] \) is minimal and minimum-phase.

Defining

\[ P_1 = \text{diag}(\Pi_0, \Pi_1, \ldots, \Pi_p) \]
we have the required result.

V. STABILITY OF FEEDBACK INTERCONNECTION

Consider the system in Figure 1, where \( G(s) \) and \( H(s) \) are \( m \times m \) proper rational matrices. This system is said to be stable if its state-space realization consisting of individual minimal realizations of \( G(s) \) and \( H(s) \), is asymptotically stable. We have the following stability result.

**Theorem 1.** The negative feedback interconnection of \( G(s) \) and \( H(s) \) is stable if all of the following conditions are satisfied:

(i) \( G(s) \) is MSPR;

(ii) \( H(s) \) is PR;

(iii) None of the \( j \omega \)-axis poles of \( G(s) \) is a transmission zero of \( H(s) \).

**Proof.** Let \([A,B,C,D]\) denote the minimal realization of \( G(s) \) described in Section III, and let \( x \) be the corresponding state vector of order \( n \). Let \( n_2 \) denote the number of poles of the stable part \( G_2(s) \) of \( G(s) \), and let \([A_2,B_2,C_2,D]\) denote its minimal realization. Let \([\hat{A},\hat{B},\hat{C},\hat{D}]\) denote a minimal realization of \( H(s) \), and let \( \hat{x} \) denote the corresponding \( n \)th-order state vector. Since \( G(s) \) is MSPR, from Lemma 2, there exist matrices \( P = P^T > 0, P \in \mathbb{R}^{nxn}, X \in \mathbb{R}^{mxn}, W \in \mathbb{R}^{mxm} \), such that Eqs. (8)-(11) are satisfied, and \([\hat{A},\hat{B},\hat{C},\hat{D}]\) is minimal and minimum-phase.

Since \( H(s) \) is PR, there exist matrices \( \hat{P} = \hat{P}^T > 0, \hat{P} \in \mathbb{R}^{nxn}, \hat{L} \in \mathbb{R}^{kxn}, \hat{W} \in \mathbb{R}^{kxm}, \) such that \([7]\)

\[
\hat{A}^T\hat{P} + \hat{P}\hat{A} = -\hat{L}^T\hat{L} \tag{21}
\]

\[
\hat{C} = \hat{B}^T\hat{P} + \hat{W}^T\hat{L} \tag{22}
\]

\[
\hat{W}^T\hat{W} = \hat{D} + \hat{D}^T \tag{23}
\]
Consider the candidate Lyapunov function:

\[ V(x,\dot{x}) = x^TPx + \dot{x}^TP\dot{x} \]  

(24)

Proceeding as in the proof of Theorem 1 in [6] we have:

\[ \dot{V} = 2u^Ty - z^Tz + \dot{\hat{x}}^T\hat{x} - z^Tz \]

(25)

where

\[ z = Lx + Wu = \hat{x}_2 + Wu \]

(26)

\[ \hat{z} = \hat{L}x + \hat{W}u \]

(27)

Since \( \hat{u} = y \) and \( \hat{y} = -u \),

\[ \dot{V} = -z^Tz - \hat{z}^T\hat{z} \leq -z^Tz \]

(28)

\[ \text{i.e., } \dot{V} \text{ is negative semi-definite. } \dot{V} = 0 \text{ implies } z = 0. \] However, \( z(t) \) is the output of the system: \( F(s) = W + L(sI-A)^{-1}B = W + L(sI-A_2)^{-1}B_2 \), which is minimum-phase. Every input \( u(t) \) that results in \( z(t) = 0 \) must have the form:

\[ u(t) = \sum_j \hat{u}_j e^{\zeta_j t} \]

where \( \zeta_j \)'s are zeros of \( F(s) \), and \( \text{Re}[\zeta_j] < 0 \). Therefore, \( u(t) \rightarrow 0 \) exponentially; i.e., \( \hat{y}(t) \rightarrow 0 \) exponentially. As a result, \( y(t) \) will consist of i) exponentially decaying terms corresponding to the zeros of \( F(s) \) as well as stable poles of \( G(s) \), and ii) persistent terms such as \( e^{\zeta_j t} \), corresponding to unstable poles at \( s = \pm j\omega_0 \) (including at \( s = 0 \)) of \( G(s) \). Since \( j\omega_0 \) are not the transmission zeros of \( H(s) \), this would imply that \( \hat{y}(t) \) \([-u(t)] \) will contain persistent terms such as \( e^{j\omega_0 t} \). However, this contradicts the fact proved previously that \( u(t) \) decays exponentially. Therefore, \( y(t) \) can consist only of exponentially decaying terms, i.e., \( y(t) \rightarrow 0 \) exponentially.

Because of the minimality of \([A,B,C,D]\) and \([\hat{A},\hat{B},\hat{C},\hat{D}]\), this implies \( x(t) \rightarrow 0, \hat{x}(t) \rightarrow 0 \) exponentially. Using LaSalle's invariance theorem [10], the system as asymptotically stable.

It should be noted that, in Theorem 1, \( G(s) \) and \( H(s) \) are completely interchangeable.

The following corollaries are an immediate consequence of Theorem 1.

**Corollary 1.1** The negative feedback interconnection of \( G(s) \) and \( H(s) \) is stable if \( G(s) \) is WSPR and \( H(s) \) is PR.
Corollary 1.1 is the same stability result which was given in [6].

**Corollary 1.2** The negative feedback interconnection of \( G(s) \) and \( H(s) \) is stable if both \( G(s) \) and \( H(s) \) are MSPR.

**Example:** Consider the rotational motion of a flexible spacecraft with \( m \) torque actuators and \( m \) collocated attitude sensors \((m \geq 3)\). Assume that there is at least one torque actuator for each (orthogonal) axis of rotation. The transfer function from the torque input to the attitude (position) output, \( y_p \), is given by:

\[
G(s) = G'(s)/s
\]  

(29)

where

\[
G'(s) = \frac{\alpha_0}{s} + \sum_{i=1}^{p} \frac{\alpha_i s}{s^2 + 2\rho_i \omega_i s + \omega_i^2}
\]  

(30)

where \( G'(s) \) is the transfer function from the torque input to the attitude rate \( y_r = y_p \); \( \alpha_i = \alpha_i^T \geq 0 \) \((i = 0, 1, 2, \ldots, p)\), and \( \alpha_0 \) is a rank-3 matrix; \( \omega_i > 0 \) represent the natural frequencies, and \( \rho_i > 0 \) represents the inherent damping ratio, for the \( i \)th elastic mode \((i=1,2,\ldots,p)\). It can be easily verified that \( G'(s) \) is PR, and therefore, from Theorem 1, it can be stabilized by any MSPR controller. Let \( \tilde{G}(s) \) denote an \( m \times m \) stable transfer function which has no transmission zeros on the imaginary axis, and suppose \( H(s) = [\tilde{G}(s)/s] \) is MSPR. Then \( H(s) \) stabilizes \( G'(s) \).

Examining the block diagram in Figure 2, \( \tilde{G}(s) \) stabilizes \( G(s) \). In other words, a flexible spacecraft, which has zero-frequency rigid-body modes as well as damped or undamped elastic modes, is stabilized by the controller \( \tilde{G}(s) \) which has the above properties. The stability does not depend on the number of elastic modes, or the parameter values, and is therefore robust.

**VI. CONCLUDING REMARKS**

The concept of marginally strictly positive real (MSPR) systems was introduced, which allows poles on the imaginary axis, and is therefore less restrictive than the
previous definitions of strict positive realness. A state-space characterization of MSPR systems was obtained, and it was proved that the negative feedback interconnection of an MSPR system and a positive real (PR) system, is asymptotically stable. The result significantly extends the previous passivity-based stability results for linear time-invariant systems.

VII. REFERENCES

Figure 1. Negative Feedback Loop.
Figure 2. Flexible Structure Example.
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