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A multiple model gap-metric based approach to nonlinear quantitative feedback theory

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Abstract: We propose a simple quantitative feedback theory (QFT) technique for designing robust nonlinear feedback systems. In the proposed approach, multiple linear models are obtained by linearization of the nonlinear plant model at each operating condition, and local QFT controller/filter obtained using standard QFT techniques. Then, global controller/filter effective over the entire operating range are constructed from the local ones by soft switching based on the gap-metric concept. The proposed approach is much simpler and easier than the existing NLQFT approaches where the so-called linear time invariant equivalent (LTIE) plants need to be constructed from the original nonlinear plant set. The proposed method is illustrated via a challenging nonlinear continuous stirred tank reactor (CSTR) example.

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Keywords: Multiple models, Nonlinear Control, Quantitative feedback theory, Robust Control.

Notation

$a(s)$, $b(s)$	Lower and upper tracking limit
G, F	Global controller and the global prefilter respectively
$g_i(s)$, $f_i(s)$	Local controller and the local prefilter at i^{th} operating point, respectively
$g_i(t)$, $f_i(t)$	Local controller output and the local prefilter output at time 't' for i^{th} operating point respectively
m	Number of linear models (P_i)
$\mathcal{N}$, N	Uncertain nonlinear plant and the nonlinear plant belonging to the uncertain set $\mathcal{N}$
P_{i0}, P_t	Nominal plant at i^{th} operating point and the linearized plant of the nonlinear plant N at time 't'
$\mathcal{P}_i(s)$, $P_i(s)$	Uncertain linearized model and the linearized model belonging to $\mathcal{P}_i(s)$ at i^{th} operating point
R, r	Set of predefined reference signals and the reference signal belonging to the set R
$W_i(t)$	Weight at time 't' for i^{th} operating point
$\{A^r\}$, y	Acceptable plant output set and the plant output respectively
$\delta(P_1, P_2)$	Gap metric between the linear plant P_1 and P_2

1. INTRODUCTION

Quantitative feedback theory (QFT) is an engineering approach to design the robust feedback systems (Horowitz (1993),Yaniv (1999)). For nonlinear systems (NL), a key step in QFT is to replace the nonlinear plant by so-called *linear time invariant equivalent* (LTIE) plants and then apply the standard linear QFT technique to the LTIE models (Horowitz (1993), Banos (2007)). Barnard (1993) presented an alternative method of nonlinear QFT in time domain using the homotopic invariance technique. Nataraj et al. (1997) introduced a frequency domain based LTIE model computation method using generalized frequency response function. This method approximates the nonlinear plant by a Volterra series which is applicable to weak nonlinear systems. Yaniv (1999) extended the nonlinear QFT in time domain (Barnard (1993)) to the frequency domain. Banos et al. (2003) proposed the local linearization of the nonlinear plant around any acceptable output to derive the LTIE plants. Recently, a non-parametric LTIE approach based on Fourier transforms was proposed in Shenton et al. (2014). For more literature on nonlinear QFT, we refer the reader to Banos et al. (2002), Banos et al. (2001). The main difficulty in the LTIE based NL QFT approach lies in deriving the LTIE plant for each acceptable output signal over a range of operating conditions.

On the other hand, the multiple model based approach is a simple and effective method for dealing with nonlinear system functioning over a wide range of operating conditions (Arkun et al. (2004), Sharad et al. (2008), Du et al. (2014)). It works on the principle of "divide and conquer" : first, decompose a nonlinear system into linear subsystems, next design a controller for every linear model using established techniques (for example, using LQG, MPC or H_∞) and lastly, combine the linear controllers into a global one, either by so-called hard switching or soft switching. Arkun et al. (2004), Du et al. (2014) illustrate these approaches and briefly described next.

Hard switching is based on a performance index, for example, on the index of output error, the index of

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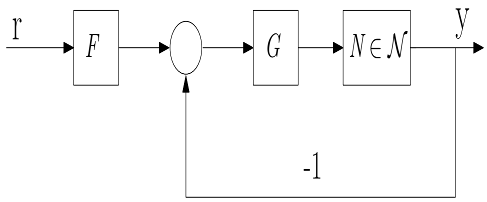

Fig. 1. The two degree of freedom feedback structure for the nonlinear plant N from a set $\mathcal{N}$.

estimation error, index of operating conditions, etc (Du et al. (2014)). In hard switching, the best possible local controller is selected and put into the feedback loop.

Hard switching has also been adopted in QFT (Ali et al. (2010)) using hysteresis based switching logic. In this, the nonlinear system is locally linzerized around the operating point to extract the LTIE model. The uncertain set of linearized model is divided into smaller subset. For each subset, a QFT controller and prefilter is designed. A switching supervisory architecture selects the controller based on the output estimation errors. However, the hard switching can lead to output chattering in systems with strong nonlinearities.

In soft switching (Arkun et al. (2004), Sharad et al. (2008)), the global controller is formed by a weighted sum of the local controller outputs. This way of combining makes the systems output more smooth, and reduces output chattering. It differs from the popular gain scheduling approach in that a *global* controller action is employed rather than a *scheduled* controller action. There are many weighting function, such as gap metric based weighting (Arkun et al. (2004)), Bayesian weighting functions (Sharad et al. (2008)), trapezoidal functions (Tan et al. (2004)), etc. Among these, the gap metric based weighting method has been extensively used, see Du et al. (2014), Du et al. (2009), Sharad et al. (2012).

The gap metric measures the 'distance' between the two linear operators and was developed to study the robust stability of the feedback systems in El-Sakkary (1985). From a control system design perspective, a small gap metric between two systems implies that there exists at least one feedback controller that stabilizes both the systems in Tan et al. (2004). Alternate definitions for the gap metric also exist, see El-Sakkary (1985). The gap metric has been applied to the multi-model control of nonlinear systems by several researchers, either for model bank selection (Sharad et al. (2012), Johansen et al. (2014)) or local controller combination (Arkun et al. (2004), Du et al. (2014)). By linearizing a nonlinear system about a set of operating points, the nonlinear system is approximated by multiple linear subsystems, and then the gap metric is applied .

The main contribution of this work is to propose a simple QFT technique for uncertain nonlinear systems, using the multiple model approach and the gap metric. The gap metric is chosen over the others because of its simplicity. For the first time in QFT, the gap metric based weighting method is employed in this work. The proposed method falls into the category of *soft* switching because the gap metric based weighting is used.

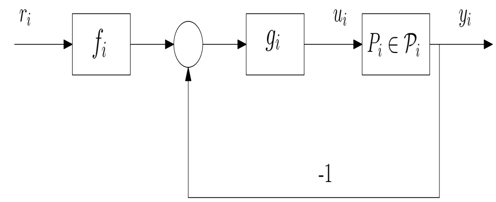

Fig. 2. The two degree of freedom control structure with linearized uncertain plant P_i from a set $\mathcal{P}_i$.

Section 2 presents the problem statement. Section 3 gives the background of the important components used in the proposed strategy. Section 4 presents the proposed multiple model based nonlinear QFT design approach in a stepwise fashion. Section 5 describes an application of the proposed approach to a benchmark nonlinear reactor example. Section 6 gives the conclusion of the work.

2. PROBLEM STATEMENT

Figure 1 shows the two degree of freedom structure for the nonlinear plant N, which belongs to set of uncertain nonlinear plants $\mathcal{N}$. In QFT, the tracking specification is specified as

$$\{A^r\} = \{y(s) | a(\omega) \leq |y(j\omega)| \leq b(\omega)\} \tag{1}$$

where $a(\omega), b(\omega)$ are the lower and upper tracking specifications on the output $y(j\omega)$.

Nonlinear Control design problem:

Design the prefilter F and the controller G such that the closed loop is stable and the plant output $y \in \{A^r\}$ for all $N \in \mathcal{N}$ in response to each command input $r \in R$. That is, the solution y of the below equation will be a member of the set $\{A^r\}$ (Yaniv (1999)).

$$GFr - Gy = u; \quad Nu = y \in \{A^r\} \tag{2}$$

The actual uncertain nonlinear system is converted into the uncertain linearized system in which the linear QFT design is easy to apply. There exists different approaches for converting the nonlinear plant into the LTIE plants as discussed in the introduction section.

Proposed Linear control design problem:

In figure 2, P_i is a linearized model around the i^{th} operating point which can be any member in uncertain linearized model $\mathcal{P}_i$. For i^{th} linearized model, design the prefilter $f_i(s)$ and the controller $g_i(s)$ such that the plant output $y_i(t) \in \{A^r\}$ for all $P_i \in \mathcal{P}_i$ in response to each command input $r_i \in R$. That is, the solution $y_i(t)$ of the below equation will be a member of the set $\{A^r\}$.

$$g_i(s)f_i(s)r - g_i(s)y_i = u_i; \quad P_i(s)u_i = y_i \in \{A^r\} \tag{3}$$

Next, formulate the proposed global controller (G) and prefilter (F) based on the local controllers g_i and prefilters f_i as

$$G = \sum_{i=1}^{m} W_i(t)g_i(t)$$

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