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Design of robust fault detection filter for uncertain linear systems with modelling errors

ZHONG Mai-ying[1], ZHANG Cheng-hui[1], DING S X[2]

(1. School of Control Science and Engineering, Shandong University, Shandong Jinan 250061, China;
2. Institute of Automatic Control and Complex Systems, Gerhard-Mercator-University Duisburg, Germany)

Abstract: The problems related to the design of observer-based robust fault detection filter (RFDF) for uncertain linear systems with both modellling errors and unknown inputs were studied. By introducing a new performance index, the RFDF design problem could be formulated as an H_∞-optimization problem, which was solved by suitably selecting RH_∞ post-filter and observer gain matrix such that the generated residual could achieve the best trade-off between the sensitivity to fault and the robustness to unknown input, modeling errors as well as control input. The design example and its simulation results demonstrate the effectiveness of the proposed approach.

Key words: robustness; H_∞-optimization; fault detection; observer; post-filter

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模型不确定性线性系统的鲁棒故障检测滤波器设计

钟麦英[1], 张承慧[1], DING S X[2]

(1. 山东大学 控制科学与工程学院,山东 济南 250061; 2. 德国 Duisburg 大学 自动化与复杂系统研究所,德国)

摘要: 基于给定的性能指标函数,将受模型不确定性和范数有界未知输入影响的线性不确定系统的基于观测器的鲁棒故障检测滤波器设计问题归结为 H_∞ 优化问题,并通过选取适当的后置滤波器和观测器增益矩阵,使产生的残差达到对于未知输入和模型不确定性的鲁棒性与对于故障的灵敏度的最佳均衡.简例验证了本文提出算法的有效性.

关键词: 鲁棒性; H_∞ 优化; 故障检测; 观测器; 后置滤波器

1 Introduction

The rapid development of robust control theory in the last two decades has given a decisive impulse to the progress of model-based fault detection and isolation (FDI) methods, in particular, in solving robustness problems[1~5]. Different from the robust control problems, robust fault detection should be considered in the situation where the FD system is designed as robust as possible to the model uncertainty and unknown input, without loss of its sensitivity to the faults to be detected. The study on the design of robust FD systems has received much attention during the recent years, such as the H_2 and H_∞ optimization techniques to nominal case[1,2,6] or more recently the H_∞-filtering approach for systems with model uncertainty[7,8]. The main problem to be addressed is the RFDF optimal design for linear systems with both unknown input and modelling errors. The core of our study is to extend an optimization FDI method in [6] to the uncertain case RFDF design. The obtained solutions are given in terms of Riccati equation.

2 Problem statement

Consider uncertain dynamic systems described by:

$$\dot{x} = (A+\Delta A)x+(B+\Delta B)u+B_f f+B_d d, \quad (1)$$

$$y = Cx + Du + D_f f + D_d d, \quad (2)$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^p$ and $y \in \mathbb{R}^q$ are state, control input and measurement output respectively. $d \in \mathbb{R}^m$ is the unknown input, $f \in \mathbb{R}^l$ the fault to be detected. $A, B, C, D, B_f, B_d, D_f$ and D_d are known matrices with appro-

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priate dimensions. Assume d and f are L_2-norm bounded. Modelling errors ΔA and ΔB are given by

$$[\Delta A \quad \Delta B] = [E_1\Sigma_1(t)F_1 \quad E_2\Sigma_2(t)F_2]$$

where E_1, E_2, F_1, F_2 are known matrices. Denote

$$\Omega_1 := \{\Delta A \mid \Delta A = E_1\Sigma_1(t)F_1, \Sigma_1^{\mathrm{T}}(t)\Sigma_1(t) \leqslant I\},$$

$$\Omega_2 := \{\Delta B \mid \Delta E = E_2\Sigma_2(t)F_2, \Sigma_2^{\mathrm{T}}(t)\Sigma_2(t) \leqslant I\}.$$

Throughout this contribution, it is assumed that:

A1) $A + \Delta A$ is stable, (C, A) is detectable;

A2) $\begin{bmatrix} A - \mathrm{j}\omega I & B_d \\ C & D_d \end{bmatrix}$ has full row rank for $\omega \in [0, \infty)$.

General speaking, fault detection system usually consists of two parts: a residual generator and a residual evaluator including a threshold and a decision logic unit. The following observer-based FDF is used as the residual generator:

$$\dot{\hat{x}} = A\hat{x} + Bu + H(y - \hat{y}), \tag{3}$$

$$\hat{y} = C\hat{x} + Du, \tag{4}$$

$$\varepsilon = y - \hat{y}, \tag{5}$$

$$r = R(s)\varepsilon(s). \tag{6}$$

where $\hat{x}, \hat{y}$ are state and output estimation respectively; the so called post-filter $R(s)$ is to be designed; r is the generated residual.

Denote $e = x - \hat{x}$, we get

$$\dot{x} = (A + \Delta A)x + (B + \Delta B)u + B_f f + B_d d, \tag{7}$$

$$\dot{e} = (A - HC)e + \Delta Ax + \Delta Bu + (B_f - HD_f) + (B_d - HD_d)d, \tag{8}$$

$$\varepsilon = Ce + D_f f + D_d d, \tag{9}$$

$$r = R(s)\varepsilon(s). \tag{10}$$

The nominal case FDF design problem can be formulated as to find H and stable $R(s)$ such that $A - HC$ is asymptotically stable and satisfies

$$J = \min_{H, R(s) \in \mathrm{RH}_\infty} \frac{\| G_{rd}(s) \|_\infty}{\sigma_i(G_{rf}(\mathrm{j}w))}, \tag{11}$$

where $G_{rf}(s)$ and $G_{rd}(s)$ are transfer function matrices from f, d to r respectively, $\sigma_i(\cdot)$ denotes a non-zero singular value. However, in the case of $\Delta A \in \Omega_1, \Delta B \in \Omega_2$ and $\Sigma_i(t)(i = 1.2)$ being time-varying, there exists no transfer function from d and f to r for system (7) ~ (10). So the performance index (11) has no sense. The main purpose of this contribution is to extend the result of nominal case FDF in [6] to solve the uncertain case (i.e $\Delta A \in \Omega_1, \Delta B \in \Omega_2$) of RFDF.

3 Basic idea of our study

Re-write (7) ~ (10) as

$$r(s) = R(s)[G_{\varepsilon d}(s)d(s) + G_{\varepsilon f}(s)f(s) + \Delta\varepsilon_d(s) + \Delta\varepsilon_f(s)]$$

where

$$G_{\varepsilon d}(s) = D_d + C(sI - A + HC)^{-1}(B_d - HD_d),$$

$$G_{\varepsilon f}(s) = D_f + C(sI - A + HC)^{-1}(B_f - HD_f).$$

$\Delta\varepsilon_d, \Delta\varepsilon_f$ are governed by

$$\dot{x}_d = Ax_d + Bu + B_d d + E_1 d_2 + E_2 d_u,$$

$$\dot{e}_d = (A - HC)e_d + E_1 d_2 + E_2 d_u + (B_d - HD_d)d,$$

$$\dot{x}_f = A x_f + B_f f + E_1 f_2,$$

$$\dot{e}_f = (A - HC)e_f + E_1 f_2 + (B_f - HD_f)f,$$

$$\Delta\varepsilon_d = Cx_d, \Delta\varepsilon_f = Cx_f, d_u = \Sigma_2(t)F_2 u,$$

$$[d_2 \quad f_2] = \Sigma_1(t)F_1[x_d \quad x_f].$$

Define vectors $\hat{d}, \hat{f}$ and operator $G_{rf}(s, \Delta)$ as

$$\hat{d} = [d^{\mathrm{T}} \quad d_u^{\mathrm{T}} \quad d_2^{\mathrm{T}}]^{\mathrm{T}}, \ \hat{f} = [f^{\mathrm{T}} \quad f_2^{\mathrm{T}}]^{\mathrm{T}},$$

$$G_{rf}(s, \Delta)f(s) = r(s)\mid_{d=0, u=0} = r_f(s),$$

$$\| G_{rf}(s, \Delta) \|_\infty =: \sup_{f \neq 0, \Delta A \in \Omega_1, \Delta B \in \Omega_2} \frac{\| r_f \|_2}{\| f \|_2}.$$

We have

$$r(s) = R(s)[G_{\varepsilon\hat{d}}(s)\hat{d}(s) + G_{\varepsilon\hat{f}}(s)\hat{f}(s)] = G_{rd}(s)\hat{d}(s) + G_{rf}(s, \Delta)f(s),$$

where

$$\hat{B}_d = [B_d \quad E_1 \quad E_2], \ \hat{D}_d = [D_d \quad 0 \quad 0], \tag{12}$$

$$\hat{B}_f = [B_f \quad E_1], \ \hat{D}_f = [D_f \quad 0], \tag{13}$$

$$G_{\varepsilon\hat{d}}(s) = C(sI - A + HC)^{-1}(\hat{B}_d - H\hat{D}_d) + \hat{D}_d,$$

$$G_{\varepsilon\hat{f}}(s) = C(sI - A + HC)^{-1}(\hat{B}_f - H\hat{D}_f) + \hat{D}_f,$$

$$G_{rf}(s, \Delta)f(s) = G_{r\hat{f}}(s, \Delta)\hat{f}(s) = R(s)G_{\varepsilon\hat{f}}(s)\hat{f}(s).$$

Then, the RFDF design problem can be formulated as to find H and $R(s) \in \mathrm{RH}_\infty$ such that $A - HC$ is asymptotically stable and satisfies

$$\min_{H, R(s) \in \mathrm{RH}_\infty} J, \text{where } J = \frac{\| G_{r\hat{d}}(s) \|_\infty}{\| G_{rf}(s, \Delta) \|_\infty}. \tag{14}$$

Furthermore, such an optimization problem can be solved in a way proposed in [6].

As for the residual evaluator, we propose to determine the evaluation function and threshold over a finite evaluation time window $[t_1, t_2)$, i.e.

$$\| r \|_{2,T} = \left(\int_{t_1}^{t_2} r^{\mathrm{T}}(t)r(t)\mathrm{d}t\right)^{1/2}, \ T = t_2 - t_1, \tag{15}$$

$$J_{th} = \sup_{f=0} \| r \|_{2,T}, \tag{16}$$

where t_1 is the evaluation initial time, see [5]. The occurrence of fault can then be diagnosed on the basis of following:

$$\| r \|_{2,T} > J_{th} \Rightarrow \text{fault} \Rightarrow \text{alarm}, \tag{17}$$

$$\| r \|_{2,T} \leqslant J_{th} \Rightarrow \text{no fault}. \tag{18}$$

Remark 1 Notice thatis $\hat{d}$ independent of f, while $\hat{f}$ is independent of d and u. The H_∞ norm $\| G_{r\hat{d}}(s) \|_\infty$ and introduced operator norm $\| G_{rf}(s,\Delta) \|_\infty$ can be respectively used to represent the influences of input signals and faults. In some of the early contributions, the uncertain part $\Delta Ax + \Delta Bu$ is directly considered as unknown input. Since fault f has influence on ΔAx when $\Delta Ax \neq 0$, this paper holds that it is more suitable to treat the modelling errors.

4 Outline of solution

4.1 RFDF design

The following lemmas are required to derive our main result.

Lemma 1[6] Given system (1),(2) with $\Delta A = 0$ and $\Delta B = 0$, suppose A1),A2) hold true, then

$$H^* = (B_d D_d^T + YC^T)Q^{-1}, \quad R^*(s) = Q^{-1/2}$$

is one solution of optimization problem (11), and $R^*(s)G_{\varepsilon d}^*(s)$ is a co-inner matrix, where $Q = D_d D_d^T$, $Y \geqslant 0$ is a solution of Riccati equation:

$$Y(A - B_d D_d^T Q^{-1} C)^T + (A - B_d D_d^T Q^{-1} C)Y +$$
$$YC^T Q^{-1} CY + B_d(I - D_d^T Q^{-1} D_d)^2 B_d^T = 0.$$

Lemma 2[6] Suppose

$$\hat{M}_1(s) = V_1 - V_1 C(sI - A + H_1 C)^{-1} H_1,$$
$$\hat{M}_2(s) = V_2 - V_2 C(sI - A + H_2 C)^{-1}) H_2,$$

where H_1, H_2 are matrices that ensure the stability of $A - H_1 C$, $A - H_2 C$, V_1 and V_2 are invertible, Then there exists an RH_∞ $Q(s)$ for the equation

$$Q(s)\hat{M}_1(s) = \hat{M}_2(s).$$

Moreover, the solution is given by

$$Q(s) = V_2(I + C(sI - A + H_2 C)^{-1}(H_1 - H_2))V_1^{-1}.$$

Theorem 1 Given system (1),(2) with $\Delta A \in \Omega_1$, $\Delta B \in \Omega_2$, suppose assumptions A1),A2) hold true, then

$$\hat{H}^* = (\hat{B}_d \hat{D}_d^T + YC^T)\hat{Q}^{-1}, \tag{19}$$

$$\hat{R}^*(s) = \hat{Q}^{-1/2}, \ \hat{Q} = \hat{D}_d \hat{D}_d^T \tag{20}$$

is a solution of optimization problem (14), where $\hat{B}_d$, $\hat{D}_d$ are denoted in (12),(13), $Y \geqslant 0$ is a solution of Riccati equation

$$(A - \hat{B}_d \hat{D}_d^T \hat{Q}^{-1} C)^T Y + Y(A - \hat{B}_d \hat{D}_d^T \hat{Q}^{-1} C) -$$
$$YC^T \hat{Q}^{-1} CY + \hat{B}_d(I - \hat{D}_d^T \hat{Q}^{-1} \hat{D}_d)^2 \hat{B}_d^T = 0.$$

Proof Denote

$$G_{\varepsilon\hat{d}}^*(s) = C(sI - A + \hat{H}^* C)^{-1}(\hat{B}_d - \hat{H}^* \hat{D}_d) + \hat{D}_d,$$
$$G_{\varepsilon\hat{f}}^*(s) = C(sI - A + \hat{H}^* C)^{-1}(\hat{B}_f - \hat{H}^* \hat{D}_f) + \hat{D}_f,$$
$$\hat{M}^*(s) = I - C(sI - A + \hat{H}^* C)^{-1}\hat{H}^*.$$

Using Lemma 1 we know that $R^*(s)G_{\varepsilon\hat{d}}^*(s)$ is a co-inner matrix. For $\forall H$ to ensure the asymptotic stability of $A - HC$, denote

$$G_{\varepsilon\hat{d}}(s) = C(sI - A + HC)^{-1}(\hat{B}_d - H\hat{D}_d) + \hat{D}_d,$$
$$G_{\varepsilon\hat{f}}(s) = C(sI - A + HC)^{-1}(\hat{B}_f - H\hat{D}_f) + \hat{D}_f,$$
$$\hat{M}(s) = I - C(sI - A + HC)^{-1}H.$$

It is well known that both $(\hat{M}(s), G_{\varepsilon\hat{d}}(s))$ and $(\hat{M}^*(s), G_{\varepsilon\hat{d}}^*(s))$ are left coprime factorization of $G_{y\hat{d}}(s)$.

Applying Lemma 2, there exists $\Gamma(s) \in RH_\infty$ such that

$$\hat{M}(s) = \Gamma(s)\hat{R}^*(s)\hat{M}^*(s),$$

where

$$\Gamma(s) = [I + C(sI - A + HC)^{-1}(\hat{H}^* - H)]\hat{Q}^{1/2}.$$

As a result,

$$G_{\varepsilon\hat{d}}(s) = \hat{M}(s)(\hat{M}^*(s))^{-1}G_{\varepsilon d}^*(s) = \Gamma(s)R^*(s)G_{\varepsilon\hat{d}}^*(s).$$

In a similar way, it is obtained that

$$G_{\varepsilon\hat{f}}(s) = \Gamma(s)\hat{R}^*(s)G_{\varepsilon f}^*(s).$$

Therefore

$$\frac{\| G_{r\hat{d}}(s) \|_\infty}{\| G_{rf}(s,\Delta) \|_\infty} = \frac{\| R(s)\Gamma(s)\hat{R}^*(s)G_{\varepsilon\hat{d}}^*(s) \|_\infty}{\| R(s)\Gamma(s)G_{rf}^*(s,\Delta) \|_\infty} \geqslant \frac{\| R(s)\Gamma(s) \|_\infty}{\| R(s)\Gamma(s) \|_\infty \| G_{rf}^*(s,\Delta) \|_\infty} = \frac{1}{\| G_{rf}^*(s,\Delta) \|_\infty}.$$

So, $(\hat{R}^*(s), \hat{H}^*)$ is a solution problem (14).

4.2 Design of adaptive threshold

Decompose $r(t)$ into $r(t) = r_d(t) + r_u(t)$, which are defined by

$$\dot{x}_d = (A + \Delta A)x_d + B_d d,$$
$$\dot{e}_d = (A - \hat{H}^* C)e_d + \Delta A x_d + (B_d - \hat{H}^* D_d)d,$$
$$r_d = \hat{Q}^{-1/2} C e_d + \hat{Q}^{-1/2} D_d d,$$
$$\dot{x}_u = (A + \Delta A)x_u + (B + \Delta B)u,$$
$$\dot{e}_u = (A - \hat{H}^* C)e_u + \Delta A x_u + \Delta B u,$$

$$r_u = \hat{Q}^{-1/2} C e_u.$$

Let

$$J_{th,d} = \sup_{\Delta A \in \Omega_1, \Delta B \in \Omega_2, d \in l_2} \| r_d(t) \|_{2,T}^2 = M_T,$$

$$J_{th,u} = \gamma_u \| u \|_{2,T},\ \gamma_u = \sup_{\Delta A \in \Omega_1, \Delta B \in \Omega_2} \frac{\| r_u \|_2^2}{\| u \|_2^2}.$$

Note that

$$\| r_d + r_u \|_{2,T}^2 \leqslant \| r_d \|_{2,T}^2 + \| r_u \|_{2,T}^2.$$

Under the assumption of d being L_2-norm bounded, we can further choose J_{th} as

$$J_{th} = [M_T + \gamma_u^2 \| u \|_{2,T}^2]^{1/2}.$$

Obviously, the defined J_{th} is composed of two parts: constant M_T, and $J_{th,u}$ which depends on the plant input u. Changing the plant input u implies a new determination of J_{th}. In this sense, the threshold Jth is called adaptive.

5 Design example

Considering a linearization model of inverted pendulum system described by (1),(2) with

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 6.5268 & 24.7770 & 157.3689 & 35.5661 \\ -12.5675 & -47.7085 & -284.1468 & -68.5009 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0.5 \end{bmatrix},\ B_d = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -0.01 \\ 0 & 0 & 0 \\ 0 & 0 & 0.005 \end{bmatrix},\ B_f = \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0.5 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},\ D_d = \begin{bmatrix} 0.01 & 0 & 0 \\ 0 & 0.01 & 0 \end{bmatrix},$$

$$D_f = 0,\ E = [0 \quad 0.1 \quad 0 \quad 0.1]^{\mathrm{T}},$$

$$F_2 = 0.1,\ F_1 = [0.2 \quad 0.1 \quad 0.1 \quad 0.1].$$

The design result is

$$\hat{H}^* = \begin{bmatrix} 5.6807 & -2.1962 \\ 18.5469 & -9.3892 \\ -2.1962 & 1.0538 \\ -5.4013 & 2.9670 \end{bmatrix},\ \hat{R}^*(s) = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix}.$$

Let u be the unit step input, the unknown inputs are band-limited white noise with power 0.01. The sampling period is 0.01 s. The fault signal is simulated with amplitude 1 over interval [5 s, 10 s]. Fig.1 shows the faulty case residual $r(t) = \begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix}$. Fig.2 presents the residual evaluation function (fault free case: dashed line; faulty case: solid line). The threshold is $J_{th} = 0.6512$. Simulation results show that $\| r(t) \|_{2,50} \approx 0.658 > J_{th}$. Therefore, the fault can be defected after 40 s of its occurrence.

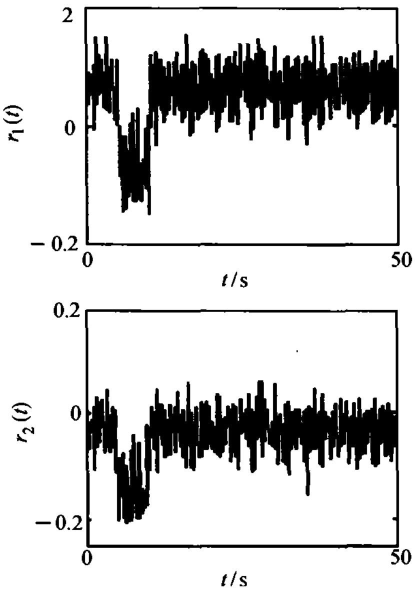

Fig. 1 Generated residual signals

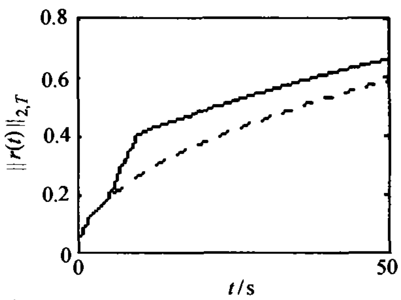

Fig. 2 Evaluation function $\| r \|_{2,T}$

6 Conclusion

The observer-based RFDF design problem has been studied for linear systems with both unknown input and modelling errors. By introducing a new performance index, the RFDF design problem can be formulated as an H_∞-optimization problem, while it can be solved by suitably selecting RH_∞ post-filter and observer gain matrix. The design example and its simulation results demonstrate that the proposed approach is feasible enough. This approach can also be used to solve the general observer-based integration of feedback controller and RFDF, such as robust stabilizing controllers, H_∞ or H_2 controller etc. The integrated design problem is going to be carried out in our future study.

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作者简介:

钟麦英 (1965 —),女,山东大学控制学院教授,主要研究方向:鲁棒控制,故障诊断,E-mail: zhong_maiying@yahoo.com;

张承慧 (1964 —),男,博士,山东大学控制学院教授,主要研究方向:系统辨识与自适应控制,E-mail: zchui@sdu.edu.cn;

DING S X (1959 —),男,博士,德国 Duisburg 大学教授,山东大学控制学院客座教授,主要研究方向:故障诊断,容错控制及其在工业中的应用.

《现代控制系统设计方法在倒立摆基准设计问题中的应用专辑》
征 稿 启 示

近二十年来,现代控制理论研究的一个焦点就是在有不确定性存在的前提下,如何有效地控制被控对象,尽可能地减小实际系统中不可避免的各种不确定性因素对控制系统品质的影响.围绕着这个焦点,现代控制理论学者提出了许多有效的控制系统设计方法,如鲁棒控制、自适应控制、模糊控制、智能控制等等.但是,与这些现代控制理论成果的先进性以及丰富程度相比,其在实际工程应用中的渗透程度还远远不够,而且从不同的角度开发出来的理论设计手段缺乏用统一的语言、统一的尺度来进行比较和交流.

为此,本刊拟编辑出版《现代控制系统设计方法在倒立摆基准设计问题中的应用专辑》,为控制理论研究人员提供一个基准设计问题,以便各方学者从不同的角度、用不同的理论方法提供设计结果,并在同一个应用背景下进行探讨比较,为现代控制理论研究领域提供一个最新的横向断面镜象.具体事项如下:

(1) 本基准设计问题以大家熟悉的直线型倒立摆为具体控制对象,其动态数学模型以及设计要求由《倒立摆基准设计问题》一文另行给出.该文可从网页 http://adaptive.nankai.edu.cn 下载,或通过 E-mail 从以下特邀编辑索取.

(2) 投稿论文所采用的设计理论不限,但是必须对《倒立摆基准设计问题》给出完整的解,并且给出基于指定模型的、MATLAB 仿真或实验结果.

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特邀编辑　申铁龙(上智大学):tetu - sin@sophia.ac.jp

梅生伟(清华大学):meishengwei@mail.tsinghua.edu.cn

王　宏(曼彻斯特大学):mcfsshw@galaxy.umist.ac.uk

陈增强(南开大学):chenzq@nankai.edu.cn