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The theoretical mechanism of grey GM(1,1) model for coupled systems

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Abstract. The GM(1,1) gray forecasting model is a type of short-term forecasting technique that has been successfully applied to management and engineering problems with only four dates. However, when a new system is built, the system is uncertain and variable, so the data collected is usually not clear, which cannot be used to predict the GM(1,1) gray model. To solve this problem, the fuzzy system derived from the collected fuzzy gray control parameter data is considered as derivation of GM(1,1) fuzzy gray model to obtain the projection values under the fuzzy system to be predicted. The method isn't restricted to either the TS fuzzy or Mamdani type. The proposed solution based on stability guarantee is a local one. Finally, an example will be described for clarification. A single controller can compensate for the effects of noise and harmonic noise at many performance points. And the dynamic performance of a single controller is satisfactory during the transient. for fairness Numerical and computer experiments are described in the perfection of the methods we offer in research.

Keywords: coupled mechanics; forecasting; Fuzzy grey GM(1,1) model; Grey GM(1,1) model; inequality controlling & nonlinear stability analysis

1. Introduction

In related mechanical applications, the GM(1,1)-Gray prediction model has been successfully used to solve time series data in management and engineering with a relatively small data set of only four observations. In management, Hsu and Wen (1999) used the gray GM model (1,1) to accurately predict the number of passengers in international flights, then the gray GM model (1,1) and an objective schedule multiplier for projected airport cities. to predict Lin and Yang (2022) applied the gray(1,1) GM model to forecast the production value of the optical industry in Taiwan. In technology, Hsu and Chen (1988) also improved the GM(1,1) gray model for electricity demand forecasting in Taiwan to obtain more accurate forecast values than the original gray model, Chiao and Wang (2018) provided a practical way to Lifetime improvement for fluorescent lamps with higher reliability and Hsu (2021) applied three types of residual transformation models to the

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gray(1,1) GM model to forecast short-term demand in the integrated circuit industry. For a new system, information is incomplete and the system is variable to define it as a fuzzy system derived from fuzzy initial data. For such a new system, it is important for the decision maker to gather analytical information to extrapolate the evolution of the system under development. For such problems, Zadeh (1985) introduced the concept of fuzzy sets and considered possible outcomes with different degrees of membership. Based on fuzzy set theory, Tanaka *et al.* introduced the fuzzy regression model and Song and Chissom (2000) pioneered the fuzzy time series model for robust statistical model forecasting methods. Therefore, when the system is uncertain and variable to generate fuzzy data, a gray fuzzy control variable is proposed instead of the gray prediction model GM(1,1) to be a fuzzy model -Gray GM(1,1) under the fuzzy system obtains more powerful . prediction model. Recently, some of these methods have been proposed to study the stability in the literature and the stability of large systems (Yang and Chang 1996, Bedirhanoglu 2014, 2004). 2005, Chiang *et al.* 2007, Liu *et al.* 2009, Liu *et al.* 2010, Hung *et al.* 2019, Eswaran and Reddy 2016 and references included).

Therefore, the analysis of system latency is stable in research (Mori 1985, Trine Aldeen 1995, Tsai *et al.* 2012, 2015, Tim *et al.* 2019, Chen 2011, 2014, Tim *et al.* 2020) has been published and demonstrated. In recent years, there have been many interesting topics related to system administration. Numerous applications have been received successfully, some have been received. Of course, many fundamental issues still need to be resolved. And the main problem with control systems is designing systems that ensure stability. Several stability studies have recently been conducted (see Tanaka Sugeno 1992, Tim *et al.* 2021, Zhen *et al.* 2021, Chen *et al.* 2022, Hsiao *et al.* Wang *et al.* 1996, Tanaka *et al.* 2021, 1996, Feng *et al.* 1997 and references therein). For example, Chiang *et al.* (2001, 2002, 2004) provided a new criterion for the system, Cheng *et al.* (2002) provided IMT units for the system, Hsiao *et al.* (2003, 2005) Application of Artificial Intelligence Theory to Nonlinear Systems, Hsieh *et al. (*2006) Proposition of Stability Analysis for Artificial Intelligence, Lin *et al. (*2010) implementation of control in the TLP system, Chen. and more. (2006, 2007), 2009) have also demonstrated the efficiency of neural networks using LDI theory. Recently, Chen *et al.* However, published studies have not yet addressed the stability and instability problems of large systems with multiple delays. Furthermore, some promising methodologies would be better choices, for example, Rafatnia *et al. (*2018) proposed a new recurrent wavelet neural network (RWNN)-based algorithm is designed for data fusion in the proposed in-move aligned SINS/GNSS system. Several vehicular field tests have been carried out to assess the long-term performance and accuracy of the proposed navigation algorithm. By the novel founding in Doostdar *et al. (*2020), in order to gain the accuracy of the aided INS/GNSS in GNSS gap intervals, a heuristic neural network structure based on the recurrent fuzzy wavelet neural network (RFWNN) is applicable for INS velocity and position error compensation purpose. During frequent access to GNSS data, the RFWNN should be trained as a highly precise prediction model equipped with the Kalman filter algorithm. To attain this, Rafatnia *et al. (*2019) proposed an applied data fusion algorithm for indirect centralized (IC) integrated SINS/GNSS. The proposed data fusion algorithm is based on fuzzy-adaptive constrained estimation filter. Velocity and altitude constraints are embedded in the integration scheme of the proposed SINS/GNSS system to preserve system reliability during abrupt GNSS outage. Hossein and Jafar (2018) aimed to enhance long-term performance of conventional SINS/GPS navigation systems using a fuzzy adaptive integration scheme. The main concept behind the proposed adaptive integration is the good performance of attitude-heading reference system (AHRS) in low-accelerated motions and its degradation in maneuvered or accelerated motions.

Thus, this study provides a stability formula based directly on Lyapunov's method, which provides asymptotic stability for large multi-delay systems. According to this explanation and limited control system, fuzzy control groups are involved in stabilizing large-scale systems in multi-delay systems with many interconnected systems. Furthermore, these subsystems are represented in the models by a simple Takagi-Sugen law model. Each of these layers is represented by a linear model of the system. Therefore, the linear control response can be used as a fixed response. Therefore, the coverage design type based on the fuzzy model is the Parallel Distributed Coverage (PDC) model. Lines in all linear spaces use the same assumptions. and we highlight the results that show the best performance of the proposed damage propagation theory for the structural analysis of composites in space.

The stability measurements are obtained and verified using the Lyapunov method to ensure the asymptotic stability of the multi-delay system, and we highlight the results that show the best performance of the proposed damage propagation theory for the analysis of complex land structures. Finally, descriptive results and conclusions for the numerical model are presented.

2. Coupled system description

In the gray system, the gray model GM(1,1) is central to the theory, which treats all variables within a given interval as a gray quantity. The GM(1,1) gray model then aggregates the available data to achieve intrinsic smoothness to handle the unstructured primitive data. Then, the model was created by transforming the ordered series into a differential equation. The following description describes how the GM(1,1) gray model is constructed.

Suppose that the prime order of a given F° is defined as

$$F^0 = (F_1^0, F_2^0, \dots, F_n^0), \tag{1}$$

where n is the number of observed data points. To build a gray model, Deng (1994) applied the cumulative generation order function (AGO) to the original sequence data to return the intermediate messages and weaken the tendency of variation. Therefore, F^1 obtained from the data of the AGO series is of the order of magnitude F° and

$$F^1 = (F_1^1, F_2^1, \dots, F_n^1), \tag{2}$$

where $F_1^1 = F_0^1$ and $F_t^1 = \left(\sum_{k=1}^{t} F_k^0\right), t = 1,2,\dots,n.$

To obtain the internal regularity from the primitive sequence, the gray model GM(1,1) is constructed by setting a differential equation for F^1 as below

$$\frac{dF^1}{dt} + aF^1 = b, \tag{3}$$

where a represents the expanded coefficient which needs to be a non-negative value to have a stable dynamic, b represents the control variable Gray, both unknown variables.

The first order of differential equations, ${}^{\mathrm{d}F^1}/_{dt}$ is denoted by

$$\frac{dF^1}{dt} = \lim_{h\to 0}\frac{F_{t+h}^1 - F_t^1}{h}, \quad \forall t \geq 1. \tag{4}$$

Let be the unit sampling interval, then the difference of the generation series F^1 can be described as a discrete time series F_{t+1}^1, $\forall t \geq 1$ which

$$\frac{dF^1}{dt} = \frac{F^1_{t+1} - F^1_t}{1} = F^1_{t+1} - F^1_t = F^0_{t+1}, \quad \forall t \geq 1. \tag{5}$$

Approximation in (5) and therein equations lie in the linear assumptions. The second part of the first-order gray model is the mean F^1_te F^1_{t-1}. Then we can rewrite Eq. (3) as

$$F^0_{t+1} = a\left[-\frac{1}{2}(F^1_{t+1} + F^1_1)\right] + b, \quad \forall t \geq 1. \tag{6}$$

If $t = 1,2,\ldots,n$, then Eq. (6) can be rewritten in matrix form as

$$\begin{bmatrix} F^0_2 \\ F^0_3 \\ \vdots \\ F^0_n \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}(F^1_2 + F^1_1) & 1 \\ -\frac{1}{2}(F^1_3 + F^1_2) & 1 \\ \vdots & \vdots \\ -\frac{1}{2}(F^1_n + F^1_{n-1}) & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix}. \tag{7}$$

Using the least squares method, the variables *a* and *b* in Eq. (7) can be solved as

$$\hat{a} = \begin{bmatrix} a \\ b \end{bmatrix} = (B^\top B)^{-1} B^\top F^0, \tag{8.}$$

where the states

$$F_0 = \begin{bmatrix} F^0_2 \\ F^0_3 \\ \vdots \\ F^0_n \end{bmatrix}, \quad B = \begin{bmatrix} -\frac{1}{2}(F^1_2 + F^1_1) & 1 \\ -\frac{1}{2}(F^1_3 + F^1_2) & 1 \\ \vdots & \vdots \\ -\frac{1}{2}(F^1_n + F^1_{n-1}) & 1 \end{bmatrix}.$$

By obtaining the solutions of the variables a and the matrix *bi* (8), we can solve the differential Eq. (3) to obtain the F^1_{t+1} estimated cumulative value at

$$\hat{F}^1_{t+1} = \left(F^0_1 - \frac{b}{a}\right) e^{-at} + \frac{b}{a}, \quad \forall t \geq 1. \tag{9}$$

Finally, it is possible to obtain a forecast value for period *t*+1 which

$$\hat{F}^0_{t+1} = \hat{F}^1_{t+1} - \hat{F}^1_t, \quad \forall t \geq 1. \tag{10}$$

Suppose that the original series with fuzzy data $F^{\circ *}$ is defined as

$$\tilde{F}^{0*} = \left(\tilde{F}^{0*}_1, \tilde{F}^{0*}_2, \ldots, \tilde{F}^{0*}_n\right), \tag{11}$$

where *n* is the number of observed data points. For simplicity, we have also defined $\tilde{F}^{1*}_t$ the fuzzy number, $\forall t = 1,2,\ldots,n$, as a symmetric triangular fuzzy number with mean value $\sum_{k=1}^{t} F^0_k$ and spread value $\sum_{k=1}^{t} c^0_k$, $\forall k = 1,2,\ldots,n$. For fuzzy input sequences we can use it to $\tilde{F}^{0*}$get fuzzy data output from AGO as $\tilde{F}^{1*}$

$$\tilde{F}^{1*} = \left(\tilde{F}^{1*}_1, \tilde{F}^{1*}_2, \ldots, \tilde{F}^{1*}_n\right), \tag{12}$$

where *n* is the number of observed data and fuzzy number $\tilde{F}^{1*}_t$, $\forall t = 1,2,\ldots,n$, is a symmetric triangular fuzzy number with center value $\sum_{k=1}^{t} F^0_k$ and variance value $\sum_{k=1}^{t} c^0_k$, $\forall k = 1,2,\ldots,n$. Then the fuzzy gray model GM(1,1) under the fuzzy system can be constructed as follows.

DEFINITION 1 The fuzzy gray model GM(1, 1) is constructed as follows $\left({\mathrm{d}\tilde{F}^{1*}}/{dt}\right) + A\tilde{F}^{1*} =$

$\tilde{B}$, where the sequence $\tilde{F}^{1*}$produces fuzzy input values, A is the augmented factor and $\tilde{B}$ is the fuzzy gray rule variable.

The first order differential equation $(d\tilde{F}^{1*}/dt)$ in Definition 1 is denoted by

$$\frac{\mathrm{d}\tilde{F}^{1*}}{dt} = \lim_{h\to 0} \frac{\tilde{F}^{1*}_{t+h} - \tilde{F}^{1*}_{t}}{h}, \quad \forall t \geq 1. \tag{13}$$

Let the sampling interval be unitary, i.e., $h = 1$, then the difference of the generation series can be described $\tilde{F}^{1*}$as a discrete time series

$$\frac{\mathrm{d}\tilde{F}^{1*}}{dt} = \frac{\tilde{F}^{1*}_{t+h} - \tilde{F}^{1*}_{t}}{h} = \tilde{F}^{1*}_{t+1} - \tilde{F}^{1*}_{t} = \tilde{F}^{0*}_{t+1}, \quad \forall t \geq 1, \tag{14}$$

where the input value for $\tilde{F}^{0*}_{t+1}$ a fuzzy number with mean F^0_t and variance is c^0_t, $\forall t \geq 1,2 \ldots, n$. the first-order fuzzy gray model GM(1,1) $\tilde{F}^{1*}_t$ is i.e., the mean $\tilde{z}^1_{t+1} = \left(\frac{1}{2}\right)\left(\sum_{k=1}^{t} c^0_k\right)$e , $\tilde{F}^{1*}_{t+1}$. Since the fuzzy numbers $\tilde{F}^{1*}_t$e $\tilde{F}^{1*}_{t+1}$ are trigonometric fuzzy numbers, $\tilde{z}^1_{t+1} = \left(\frac{1}{2}\right)\left(\tilde{F}^{1*}_t + \tilde{F}^{1*}_{t+1}\right)$ is also a trigonometric fuzzy number with mean z_{t+1} at $\left(\frac{1}{2}\right)\left(\sum_{k=1}^{t} F^0_k + \sum_{k=1}^{t+1} F^0_k\right)$ and distribution d_{t+1} at $\left(\frac{1}{2}\right)\left(\sum_{k=1}^{t} c^0_k + \sum_{k=1}^{t} c^0_k\right)$, $\forall t \geq 1$.

So we can rewrite the gray model GM(1,1) as

$$\tilde{F}^0_t = -A * \tilde{z}^1_t + \tilde{B}, \quad \forall t = 2, \ldots, n. \tag{15}$$

For simplicity, the membership function of the fuzzy gray control variable in the fuzzy gray model GM(1,1) is defined as a symmetric triangular shape with center value $\tilde{B}B$ and spread value B1, composed as follows

$$u_{\tilde{B}}(\psi) = f(x) = \begin{cases} 1 - \frac{|\psi - B|}{B_1}, & B - B_1 \leq \psi \leq \ B + B_1, \\ \quad 0, & otherwise. \end{cases} \tag{16}$$

As in Fig. 1, a measure of how well the estimated fuzzy number $\tilde{F}^0_t$matches the input fuzzy number is shown $\tilde{F}^0_t = (\tilde{F}^0_t, c^0_t)$ the maximum value *h* $_t$, *0* ≤*hours* $_-$ ≤1, $\forall t = 2, \ldots, n$.

By using the expansion principle, it was possible to obtain $\tilde{F}^0_t$ an adaptation score for the fuzzy number $\tilde{F}^{0*}_t$as

$$h_t = \begin{cases} 1 - \frac{\left|\tilde{F}^{0*}_t - (B - Az_t\right|}{(B_1 - Ad_t) - c^0_t}, & (B_1 - Ad_t) - c^0_t \neq 0, \ \forall t = 2,3, \ldots, n, \\ \quad 0, & otherwise. \end{cases} \tag{17}$$

To solve the unknown factor for the evolved coefficient *A* and the median value *B*, the distribution value of the distributed gray $\tilde{B}$ controlled in the model (15), we decided to choose B_1 the value *H* as a function of *ht* ≥*H*, therefore the collected series

Data $\tilde{F}^{0*}_t$, $\forall t = 2,3, \ldots, n$, includes the prediction interval for the fuzzy gray model with the least satisfactory degree *H*, $\forall t = 2,3, \ldots, n$, corresponds to

$$1 - \frac{\left|\tilde{F}^{0*}_t - (B - Az_t\right|}{(B_1 - Ad_t) - c^0_t} \geq H, \quad \forall t = 2,3, \ldots, n \tag{18}$$

Also, to achieve the least possible ambiguity, the target value for must be minimized B_1 to $\forall t = 2,3, \ldots, n$ obtain the following linear programming model:

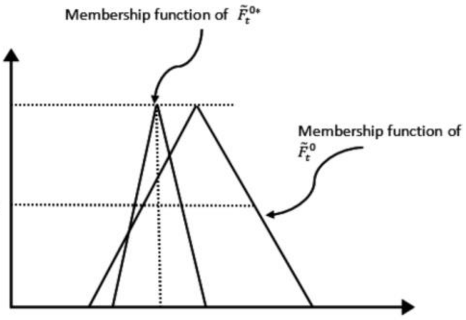


Fig. 1 The relationship between membership functions of $\tilde{F}_t^0$ and $\tilde{F}_t^{0*}$

$$\begin{gathered}\text{minimum } B_1\\ \text{St}(B-Ad_t)+(1-H)(B_1-Ad_t)\geq F_t^0+(1-H)c_t^0,\quad t=2,3,\ldots,n\\ (B-Ad_t)-(1-H)(B_1-Az_t^1)\leq F_t^0+(1-H)c_t^0,\quad t=2,3,\ldots,n\\ A,B,B_1\in R,0\leq H\leq 1.\end{gathered}\tag{19}$$

solving for the unknown variables A, B and B_1. In model (19), there are three variables to solve, so slightly less than four constraints are needed. Therefore, the GM(1,1) fuzzy gray model needs at least three collected data points to solve the proposed model, which is less than the four-data gray model. The H-value is also referred to as the level of agreement between the estimated fuzzy-gray GM model (1,1) and the collected data, which determines the size of the probability distribution of the proposed model. Since H is subjectively chosen by the decision maker as an input to the model, it is important to choose an appropriate value in the fuzzy gray model. In this study, we proposed the value H=0 to obtain the minimum estimated range.

Thus, $\hat{\tilde{F}}_t^1=(\hat{F}_t^{1,L},\hat{F}_t^{1,R})$ after solving for the parameter A and the fuzzy gray control variables, we clip the gray model GM(1,1) under the fuzzy system defined in Definition 1 and solve for the fuzzy gray GM(1 ,1) by extrapolating the $\tilde{B}$ value of, where $\hat{F}_t^{1,L}$ and $\hat{F}_t^{1,R}$ are the lower bound and the upper bound of the fuzzy number, respectively $\hat{\tilde{F}}_t^1$.

THEOREM 1 For fuzzy gray model GM(1,1) with fuzzy input and fuzzy output under fuzzy system, the estimated fuzzy number is cut into $\hat{\tilde{F}}_t^1=(\hat{F}_t^{1,L},\hat{F}_t^{1,R})$ fuzzy gray model GM(1,1) can be obtained to derive the lower limit $\hat{F}_t^{1,L}=[F_1^0-(1-\alpha)c_t^0-(B-(1-\alpha)B_1/A]e^{-A(t-1)}+{}^{(B-(1-\alpha)B_1)}\!/_{A}$ and upper limit $\hat{F}_t^{1,R}=[F_1^0+(1-\alpha)c_t^0-(B+(1-\alpha)B_1/A]e^{-A(t-1)}+{}^{(B+(1-\alpha)B_1)}\!/_{A},\forall t\geq 2.$

Proof If the fuzzy gray GM(1,1) is a cut under the fuzzy system defined in Definition 1, the process of solving the fuzzy numbers can be obtained $\hat{\tilde{F}}_t^1$ as follows

$$\frac{dF_t^{1,L}}{dt}=[B-(1-\alpha)B_1]-AF_t^{1,L}.$$

$$\therefore\int\frac{1}{[B-(1-\alpha)B_1]-AF_t^{1,L}}dF_t^{1,L}=\int 1\,dt$$

$$\text{Allow}Z=[B-(1-\alpha)B_1]-AF_t^{1,L}\Rightarrow -AdF_t^{1,L}=dZ$$

$$\therefore \int \frac{1}{[B-(1-\alpha)B_1]-AF_t^{1,L}}\,dF_t^{1,L} = \int \frac{1}{Z}\times\frac{-1}{A}\,dZ = \int 1dt$$

$$\Rightarrow \ln Z = -At + C, \qquad C \text{ it is stable}$$

$$\Rightarrow Z = e^{-At+C}$$

$$\because [B-(1-\alpha)B_1]-AF_t^{1,L} = Z = e^{-At+C}$$

$$\therefore F_t^{1,L} = \frac{B-(1-\alpha)B_1}{A} - \frac{1}{A}e^{-At+C}$$

$$\text{So } \tilde{F}_1^1 = \tilde{F}_1^0 \text{ implied } F_t^{1,L} = F_1^0 - (1-\alpha)c_1^0$$

$$\Rightarrow F_t^{1,L} = \frac{B-(1-\alpha)B_1}{A} - \frac{1}{A}e^{-At+C} = F_1^0 - (1-\alpha)c_1^0$$

$$\Rightarrow A + \ln\{-A[F_0^1 - (1-\alpha)c_1^0] + [B-(1-\alpha)B_1]\}$$

$$\therefore \hat{F}_t^{1,L} = \left[F_1^0 - (1-\alpha)c_1^0 - \tfrac{B-(1-\alpha)B_1}{A}\right]e^{-A(t-1)} + \tfrac{B-(1-\alpha)B_1}{A}.$$

Based on the above algorithm, we can $F_t^{1,R}$ obtain as

$$\hat{F}_t^{1,R} = \left[F_1^0 + (1-\alpha)c_1^0 - \tfrac{B+(1-\alpha)B_1}{A}\right]e^{-A(t-1)} + \tfrac{B+(1-\alpha)B_1}{A}.$$

then $\hat{\tilde{F}}_t^1 = \left(\hat{F}_t^{1,L}, \hat{F}_t^{1,R}\right)$ fixed.

to obtain the largest interval for the fuzzy number by setting α=0. $\hat{\tilde{F}}_t^1 = \left(\hat{F}_t^{1,L}, \hat{F}_t^{1,R}\right)$. Also based on Theorem 1 approximate fuzzy number $\hat{\tilde{F}}_{t+1}^0 = \left(\hat{F}_{t+1}^{0,L}, \hat{F}_{t+1}^{0,R}\right)$ with bottom bracket $\hat{F}_{t+1}^{0,L}$ and upper limit $\hat{F}_{t+1}^{0,R}$ for period *t+1* you get as

$$\hat{F}_t^{0,L} = \hat{F}_t^{1,L} - \hat{F}_{t-1}^{1,L}, \;\; \forall t \geq 2, \tag{20}$$

$$\hat{F}_t^{0,R} = \hat{F}_t^{1,R} - \hat{F}_{t-1}^{1,R}, \forall t \geq 2, \tag{21}$$

You can get $\tilde{F}_1^{0*}, \tilde{F}_2^{0*}, \dots, \tilde{F}_n^{0*}$ explained fuzzy values $\hat{\tilde{F}}_{n+1}^0, \hat{\tilde{F}}_{n+2}^0, \dots, \hat{\tilde{F}}_{n+k}^0, \forall t \geq 1$ through the input data. Theorem 1 shows that a fuzzy number $\hat{\tilde{F}}_t^1, \forall t \geq 2$ is not a symmetric fuzzy number, so $\hat{\tilde{F}}_t^0$ it is also not a symmetric fuzzy number. Conversely, $\hat{\tilde{F}}_t^0$ to estimate the forecast error, the mean is defined as $\hat{F}_t^{0,Aver}$, given by

$$\hat{F}_t^{0,Aver} = \frac{F_t^{0,L} + F_t^{0,R}}{2}, \quad \forall t \geq 2.$$

Therefore, the gray time series model GM(1,1) is used. $F_2^0, \dots, F_n^0$ is specified to extrapolate the values for. $\hat{F}_{t+1}^0, \hat{F}_{t+2}^0, \dots., \hat{F}_{t+k}^0, \; \forall k \geq 1$. The main features of the Takagi-Sugeno multilayer fuzzy model are the expression of each rule by a linear equation of state, and the model is as follows (Chen 2014, Chen *et al.* 2019, Chen *et al.* 2020)

$$\begin{aligned} &\text{Rule } i: \text{If present } x_{1j}(t) \text{ is } M_{i1j} \text{ and} \cdots \text{and } x_{gj}(t) \text{ is } M_{igj} \\ &\text{As } \dot{x}_j(t) = A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \end{aligned} \tag{22}$$

where $x_j^T(t) = [x_{1j}(t), x_{2j}(t), \cdots, x_{gj}(t)]\_u_j^{\,T}(t) = [u_{1j}(t), u_{2j}(t), \cdots, u_{mj}(t)]$

r_j is the IF-THEN rule number for this A_{ij} *j*. Subsystem, A_{ikj} and B_{ij} are paired system matrices, state $x_j(t)$, input $u_j(t)$, τ_{kj} delay fuzzy set M_{ipj}($p = 1, 2, \cdots, g$) and assumption are used $x_{1j}(t) \sim x_{gj}(t)$ to derive the dynamic fuzzy model:

$$\dot{x}_j(t) = \frac{\sum_{i=1}^{r_j} w_{ij}(t)\left\{ A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \right\}}{\sum_{i=1}^{r_j} w_{ij}(t)}$$

$$= \sum_{i=1}^{r_j} h_{ij}(t)\left\{ A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \right\}$$

with

$$w_{ij}(t) = \prod_{p=1}^{g} M_{ipj}(x_{pj}(t)),\quad h_{ij}(t) = \frac{w_{ij}(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} \tag{23}$$

where $h_{ij}(t) \ge 0$, is $M_{ipj}(x_{pj}(t))$ the M_{ipj} position of relatives if , $x_{pj}(t)$ _ _ $w_{ij}(t) \ge 0,\ \ i = 1, 2, \cdots, r_j$ and $\sum_{i=1}^{r_j} w_{ij}(t) > 0\ \ i = 1, 2, \cdots, r_j$, $\sum_{i=1}^{r_j} h_{ij}(t) = 1$.

According to the above analysis, c.f., *i* could be _F_j

$$\dot{x}_j(t) = \sum_{i=1}^{r_j} h_{ij}(t)\left\{ A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \right\} + \sum_{\substack{n=1\\ n\neq j}}^{J} C_{nj}x_n(t) \tag{24}$$

In this case the approximation is quadratic, and assuming H_0 is positive definite, it has a global minimum at $\partial E/\partial w=0$. Good.

$$\frac{\partial E}{\partial \omega} = g_0 + H_0(\omega - \omega_0) = 0. \tag{25}$$

and solving for **w** we get

$$\omega = \omega_0 - H_0^{-1} g_0. \tag{26}$$

For a quadratic function, Eq. (26) would give the exact minimum. This is usually just an approximation, in which case an iterative strategy should be used, with -*H* –1*g* as the search strategy, the same as -*g* in the steepest descent algorithm. So d_k is given at each iteration

$$d_k = -H_{k-1} g_k. \tag{27}$$

This is known as Newton's search strategy and is usually obtained by solving the system of linear equations

$$H_k d_k = -g_k \tag{28}$$

This can be achieved by inserting an intermediate vector *z* to store the product Mt and organizing the calculations as follows

$$q = s^{\mathrm{T}} t, \qquad z = Mt, \qquad p = t^T z,\ \phi = \frac{q^2}{q+p}, \tag{29}$$

$$Q = \frac{s^T s}{\phi}, \qquad R = \frac{zs^T + [zs^T]^T}{q},\ M_{k+1} = M_k + Q - R. \tag{30}$$

3. Coupled system criterion of smart control

According to the decentralized fuzzy controllers using the parallel distributed compensation (PDC) method to stabilize the coupled system *F*, the option of the distributed compensation is each distributed control rule is designed in parallel. The fuzzy based controller shares the same fuzzy set with the fuzzy model in the spatial parameters with coupled aviation stability. Since each rule of the fuzzy model is described by a linear state equation, linear coupled control theory can be used to design the following aviation components of the fuzzy controller. The resulting overall fuzzy controller, usually non-linear, is obtained by combining each linear controller.
The fuzzy controller of the *j*th subsystem is in the following form

$$\text{IF } x_{1j}(t) \text{ is } M_{i1j} \text{ and} \cdots \text{and } x_{gj}(t) \text{ is } M_{igj} \text{ THEN } u_j(t) = -K_{ij} x_j(t), \tag{31}$$

where $i = 1, 2, \cdots, r_j$. Hence, the final output of the fuzzy controller is

$$u_j(t) = -\frac{\sum_{i=1}^{r_j} w_{ij}(t) K_{ij} x_j(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} = -\sum_{i=1}^{r_j} h_{ij}(t)\, K_{ij} x_j(t). \tag{32}$$

$$\dot{x}_j(t) = \sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t) h_{fj}(t) [A_{ij} - B_{ij} K_{fj}] x_j(t) + \phi_j(t) \tag{33}$$

A stability criterion is given below to guarantee the asymptotic stability of the fuzzy large-scale system ***F***.

Theorem 1: The fuzzy large-scale system ***F*** is asymptotically stable, if the feedback gains (K_{ij}) are chosen to satisfy

$$\textbf{(I)} \quad \hat{\lambda}_{ij} = \lambda_m(Q_{ij}) - \beta_j > 0 \ \text{ and } \ \tilde{\lambda}_{ifj} = \lambda_m(Q_{ifj}) - \beta_j > 0 \tag{34}$$

for $i = 1, 2, \cdots, r_j,\ i < f \le r_j,\ j = 1, 2, \cdots, J$

or

$$\textbf{(II)} \quad \Lambda_j = \begin{bmatrix} \hat{\lambda}_{1j} & \tilde{\lambda}_{12j} & \cdots & \tilde{\lambda}_{1r_j j} \\ \tilde{\lambda}_{12j} & \hat{\lambda}_{2j} & \cdots & \tilde{\lambda}_{2r_j j} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{\lambda}_{1r_j j} & \tilde{\lambda}_{2r_j j} & \cdots & \hat{\lambda}_{r_j j} \end{bmatrix} > 0, \quad \text{for } j = 1, 2, \cdots, J \tag{35}$$

where

$$\beta_j = \sum_{\substack{n=1 \\ n \neq j}}^{J} (\|C_{nj}^T P_j\| + \|C_{jn}^T P_n\|),$$

$$Q_{ij} = -[(A_{ij} - B_{ij}K_{ij})^T P_j + P_j(A_{ij} - B_{ij}K_{ij})], \tag{36}$$

$$Q_{ifj} = -(G_{ifj}^T P_j + P_j G_{ifj}), \tag{37}$$

with $G_{ifj} = \dfrac{(A_{ij} - B_{ij}K_{fj}) + (A_{fj} - B_{fj}K_{ij})}{2}$, $P_j = P_j^T > 0$,

and $\lambda_m(Q_{ij})$ as well as $\lambda_m(Q_{ifj})$ denote the minimum eigenvalues of Q_{ij} and Q_{ifj}, respectively.

Let the Lyapunov function for the fuzzy large-scale system ***F*** be defined as

$$V = \sum_{j=1}^{J} v_j(t) = \sum_{j=1}^{J} x_j^T(t) P_j x_j(t) \tag{A1}$$

where $P_j = P_j^T > 0$. We then evaluate the time derivative of V on the trajectories of Eq. (3.3) to get

$$\dot{V} = \sum_{j=1}^{J} \dot{v}_j(t) = \sum_{j=1}^{J} [\dot{x}_j^T(t) P_j x_j(t) + x_j^T(t) P_j \dot{x}_j(t)] = D_1 + D_2 + D_3, \tag{A2}$$

$$\dot{V} \leq -\sum_{j=1}^{J} \{\sum_{i=1}^{r_j} h_{ij}^2(t)\lambda_m(Q_{ij}) + 2\sum_{i<f}^{r_j} h_{ij}(t)h_{fj}(t)\lambda_m(Q_{ifj}) - \sum_{i=1}^{r_j}\sum_{f=1}^{r_j} h_{ij}(t)h_{fj}(t)\beta_j\} \|x_j(t)\|^2$$

$$\dot{V} \leq -\sum_{j=1}^{J} \{\sum_{i=1}^{r_j} h_{ij}^2(t)\hat{\lambda}_{ij} + 2\sum_{i<f}^{r_j} h_{ij}(t)h_{fj}(t)\tilde{\lambda}_{ifj}\} \|x_j(t)\|^2$$

$$= -\sum_{j=1}^{J} \{ \begin{bmatrix} h_{1j}(t) & h_{2j}(t) & \cdots & h_{r_j j}(t) \end{bmatrix} \begin{bmatrix} \hat{\lambda}_{1j} & \tilde{\lambda}_{12j} & \cdots & \tilde{\lambda}_{1r_j j} \\ \tilde{\lambda}_{12j} & \hat{\lambda}_{2j} & \cdots & \tilde{\lambda}_{2r_j j} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{\lambda}_{1r_j j} & \tilde{\lambda}_{2r_j j} & \cdots & \hat{\lambda}_{r_j j} \end{bmatrix} \begin{bmatrix} h_{1j}(t) \\ h_{2j}(t) \\ \vdots \\ h_{r_j j}(t) \end{bmatrix} \} \|x_j(t)\|^2$$

$$= -\sum_{j=1}^{J} H_j^T \Lambda_j H_j \|x_j(t)\|^2,$$

in which $H_j^T \equiv [h_{1j}(t) \quad h_{2j}(t) \quad \cdots \quad h_{r_j j}(t)]$.

4. Example

In this section, we will examine Fisher's equations and the thermal control of high-speed aircraft cooling coils to demonstrate the effectiveness of the proposed design method. Fisher's

Table 1 Collected data

Time period	1	2	3	4
Collected data	(79,8,4)	(74.4)	(61.4)	(51.4)

Table 2 The solutions of the variables

changeable	ONE	b	YES1_ _
Solution	0.1818	90.9636	9.5786

Table 3Extrapolation values for $\hat{\hat{F}}_t^0$

period t	Lower limit for $\hat{\hat{F}}_t^0$	upper limit for $\hat{\hat{F}}_t^0$	average of $\hat{\hat{F}}_t^0$
2	57.82	82	69.91
3	51,54	65.04	58,29
4	42.97	54.22	48.60

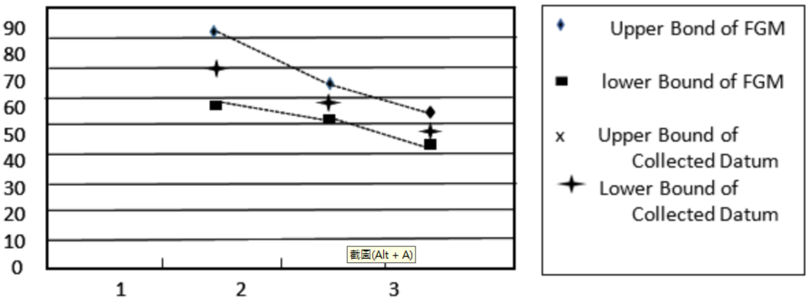
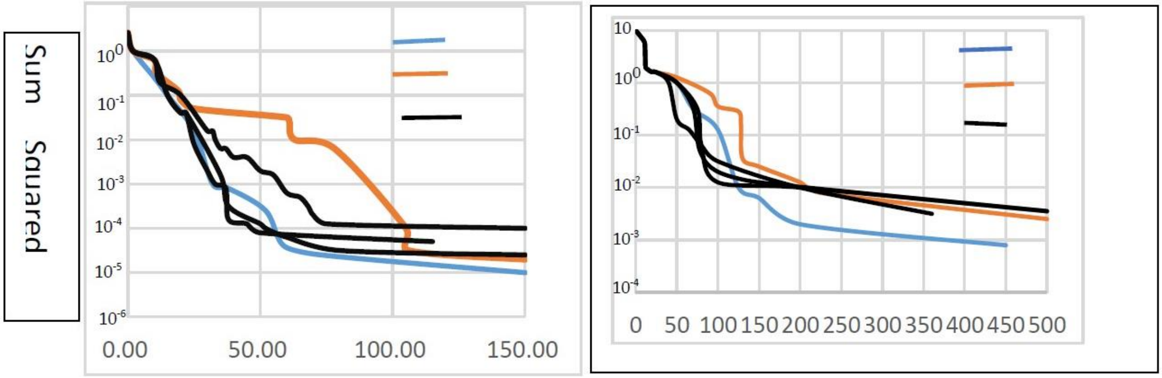


Fig. 2 Prediction results

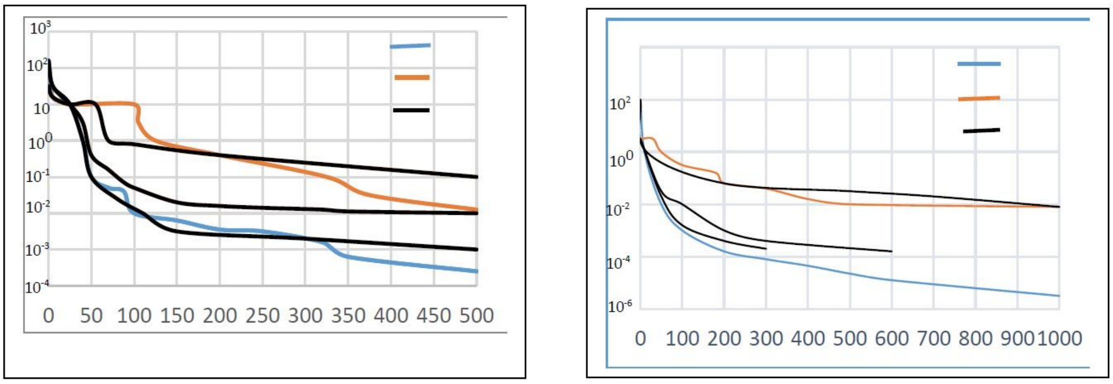
equations have been used as a basis for various models of spatial distribution of strain, chemical wave propagation, flame propagation, branching edge motion processes and reactor theory. Consider a flight stability-based system consisting of three input and output configurations described as follows.

Since the collected data is fuzzy, the model (19) is used under the fuzzy system to solve the variables A, B and and is shown in Table 2 with the setting value H=0 In this larger prediction range, we set a- stopping value in the fuzzy gray model GM(1,1) to zero. Therefore, the fuzzy number can be obtained from Table 2 and Theorem 1, so that the estimated value $\hat{\hat{F}}_t^1 = \left(\hat{F}_t^{1,L}, \hat{F}_t^{1,R}\right)$ of period t can be solved $\hat{\hat{F}}_t^0$ as shown in Table 3 and Fig. 2. It can be seen in Fig. 2 that the fuzzy number model -gray GM (1, 1) could effectively extrapolate the possible evolution, the interval under the fuzzy system, to reduce the potential loss in decision making

Fig. 3 shows a comparison between PM and the LM and FM types of Mechnics for each of the four coupled systems of theoretical solutions. In the individual case, we have to ensure three different results shown for the VM, based on L_{mem}=5, 10 and 20. From these provided results, everyone can be believed that, as shown, the performance of Proposed Mechanism (VM) varies between that of Linear Mechanism (LM) and Fuzzy Mechanism (FM) feasibility accounting on the amount of available problems.



(a) VM algorithm on Problem 1 (b) VM algorithm on Problem 2



(c) VM algorithm on Problem 3 (d)VM algorithm on Problem 4

Fig. 3 Coupled system results of VM with different inputs with proposed control

5. Conclusions

In this study, we succeeded in constructing a gray GM(1,1) model with fuzzy input under a fuzzy system. The relationship between the GM(1,1) gray model and the fuzzy set is built in such a way that when the system is uncertain and variable, the GM(1,1) fuzzy gray model can be used under the fuzzy set, for predicting possible trends to future According to the study, there is a fundamental relationship between the fuzzy method and the Gray method to solve the forecasting problem with powerful short-term forecasting models. We highlight results that demonstrate the high performance of the proposed theory applied to damage propagation for structural analysis of aircraft composites.

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