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Design of Fuzzy Based Improved Disturbance Observer for Non-Minimum Phase Time Delay System

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Abstract:

This paper investigates the disturbance rejection control for stable non-minimum phase (NMP) systemswith time delay. A robust disturbance observer (DOB) based control structure is proposed. Specifically,the robust DOB is employed to compensate the uncertain plant into a nominal one, based on which aprefilter is adopted to acquire desired performance. Then, a novel DOB configuration strategy for stableNMP systems is proposed. This strategy synthesizes the internal and robust stability, relative order andmixed sensitivity design requirements together to establish the optimization function. The optimal solution is obtained by standard theory under the condition of guarantying the presentedrequirements. We also investigate how the DOB can compensate the uncertain plant into a nominalone. The special design procedure is presented for an uncertain plant with both unstable zeros andtime delay. In such an IDOB–FUZZY scheme, the FUZZYcontroller acts as a prefilter and generates appropriate control actions such that a desired setpoint tracking response is achieved. The IDOB is used to estimate the various disturbances dynamically and suppress them by feed forward compensation design. Both theory analysis and simulation comparisons have shown good disturbance estimationand rejection performances of the proposed method.

Index Terms:\

Disturbance observer (DOB), improved DOB(IDOB), multivariable control,Non-minimum phase.

I. INTRODUCTION:

In most practical industrial processes, the inevitable systemuncertainties and external disturbances will have great influenceon the performance of control system. The efficient disturbancerejection method is the compensation by the estimation of modelmismatch and external disturbances.

The disturbance observer (DOB) based control method was originally proposed by Ohnishi in 1987, whose effectiveness in disturbance rejectionshas been shown in many applications, such as humanoid jointControl [7], robot manipulators control [8], aircraft con trol [9], optical disk control [10], motor control [11], vibration control ball mill grinding circuits control etc. Introduce a feed forward compensation part for the disturbances into the control system besides the conventional feedback part. In this case, an effective method is disturbance observer (DOB) technique, which can estimate the disturbances and suppress them without changing the input–output behaviour. The DOB technique was originally presented byOhnishitoestimate disturbances in a position servo system. These are motivated by the fact that good disturbance estimation can case the control task for perturbed uncertain dynamic systems. For example, this information can be employed toconstruct the controller which can cancel the disturbances [1],[2].

Due to the simple structure and a powerful capabilityto reject disturbances and compensate plant uncertainties, theDOB-based control technique has been widely applied to manyindustrial systems or processes, such as robot manipulator,hard-disk drive system, mineral processing process, magneticbearing systems, etc. In spite of various DOBs having been proposed for the systems with or without time delay [2], [5], [9] [12], [14], DOB design for non-minimum-phase delay systems remains a challenge in the system engineering community even though many practical systems are non-minimum phase and with time delay, such as the grinding circuit system, the vibration suppression systems for dc motor, etc. [6], [10]–[15]. It is known that the non-minimum-phase delay systems are difficult to control due to the existence of a fundamental limitation to the control performance. This brief aims to present an improved DOB (IDOB) method for the non-minimum phase delay system. Also, to improve the disturbance rejection performance for the multivariable MPC control, a compound IDOB-MPC control scheme

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is proposed by combining the IDOB feed forward compensation part and the MPC feedback regulation part. Finally, several simulations have been performed to demonstrate the effectiveness of the proposed approach.

II.IDOB DESIGN FOR NON-MINIMUM-PHASE DELAY SYSTEMS:

Notation 1 [9]: Let $D(s)$ be a polynomial with real coefficients expressed as
The polynomial $D(s) = dnsn+ \cdot \cdot \cdot + d1s + d0$.
$D(s)$ is said to be of degree n if *dnis not equal to* 0, which will be denoted by
deg(D) = n. For a rational single-input–single output (SISO) transfer function $g(s) = N(s)/D(s)$ [it is assumed that $N(s)$ and $D(s)$ are coprime polynomials and deg(D) ≥ deg(N)], the degree and the relative degree of $g(s)$ are defined as deg(D) and deg(g) = deg(D) − deg(N), respectively. _
Notation 2 [16]: For a nonzero SISO transfer function $g(s)$ expressed by $g(s) = N(s)e{-}\tau Ns/D(s)$, where $D(s)$ and $N(s)$ are all scalar nonzero polynomials of s. Define the time delay of $g(s)$ as τ (g) = τN; define Z+gto be the set of unstable zeros of $g(s)$, i.e., Z+g∆={z ∈C+|$g(z)$ = 0}, where C+ stands

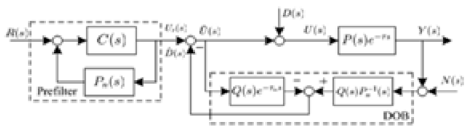

Fig.1. Block diagram of the standard DOB.

For the closed right half of the complex plane. Define ηz(g) tobe an integer v such thatlims→z g(s)/(s − z)v, zZ+gexists and is nonzero.

A. Brief Overview of Conventional DOB;

The block diagram of the standard DOB [11] is shown in Fig. 1, where ˜g(s) is the real plant to be controlled and g(s) is the nominal model of ˜g(s); u and y are the input and output of ˜g(s), respectively; diand dodenote the input and output disturbances, respectively; and q(s) is the low-pass filter. It can be seen that the procedure of the DOB closes a loop around the controlled plant to reject disturbances and force the input–output characteristics of this loop to approximate the nominal plant model. Tuning of the loop is accomplished through the adjustment of q(s). Generally, q(s) is designed to be q(s) = 1/(αs+ 1), where the time constant α is the most meaningful parameter which determines the ability to resistdisturbances. For the system with time delay ˜g(s) = ˜g0(s)e−˜τs, the inverse function of time delay part is physically unrealizable, so the standard DOB is no longer available.

To this end, a structure of modified DOB with the considerations of the time delay is proposed in [2] and [5] by designing q(s) = e−τ(g)s/(αs + 1).Here, the plant model g(s) = g0(s)e−τsis separated into a rational part g0(s) and a time delay part e−τs. Moreover, thetime delay part is inserted into the channel of the plant input, plant output to substitute g(s).

B. IDOB Design for Non-minimum-Phase Delay Systems:

It has long been known that non-minimum-phase systems are not easy to control and observe and there exists a fundamental limitation to their achievable control performance. Although the modified DOB technique proposed in [2] and [5] can deal with disturbance observation problem for the minimum-phase delay systems well, it no longer suits for the non-minimum-phase delay systems because the inverse function of the non-minimum phase part is unstable. Therefore, an IDOB design with the considerations of time delay and non-minimum phase is presented in this brief. According to the H2 optimal performance specification of IMC theory [16], q(s) in our design is specified as

$$q(s) = \underbrace{e^{-\tau(g)s}}_{q_a(s)} \times \underbrace{\prod_{k=1}^{\eta_z(g)} \left(\frac{z_k - s}{\bar{z}_k + s}\right)}_{q_b(s)} \times \underbrace{\frac{1}{(\alpha s+1)^{\deg(g)+1}}}_{q_c(s)} \quad (1)$$

which consists of three parts.
1) qa(s)is used to cancel the time delay part in the denominator of g(s)−1.
2) qb(s)is used to cancel the unstable zeros zkofg(s), Wherezk, k = 1, . . . , ηz(g), denotes the non-minimum-phase or right half plane zeros of g(s), and zk the complex conjugate of zk.
3) qc(s)is the low-pass filter with steady-state gain of one, and it has two main functions: First, to ensure q(s)g(s)−1 is proper via determining the degree of the filter as deg(g) + 1 and, second, to achieve the desirable performance by adjusting the adjustable parameter α online.

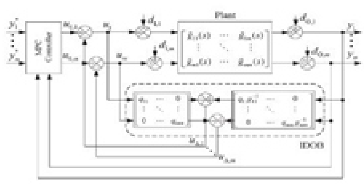

Fig.2.Proposed IDOB–MPC control strategy for multivariable delay system.

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III. IDOB-BASED MULTIVARIABLE FUZZY AND MPC CONTROLLERS:

Although MPC is widely recognized as the dominant control technology for multivariable systems in process industries, itturns out some shortages when controlling the multivariabledelay systems in the presence of strong external disturbancesand severe model mismatches. Here, we present a compoundIDOB-MPC scheme by configuring the IDOB and the multiple inputmultiple-output plant as the multiple loop form, as shownin Fig. 2.

1)The MPC controller acts as a pre filter used togenerate the initial control actions U0(s) = [u0,i(s)]m×1 by minimizing the following function:

$$J=\sum_{j=0}^{N_P}\left(\Delta Y(j)^{\mathrm{T}}W_Y\Delta Y(j)\right)+\sum_{j=0}^{N_C-1}\left(\Delta U_0(j)^{\mathrm{T}}W_U\Delta U_0(j)\right)$$

where NP is the prediction horizon, NC is the control horizon, ΔY is the prediction error, ΔU0 is the control error, and WR and WY represent the diagonal weighting matrix.
2) The IDOB acts as a compensator to enhance the disturbance rejection performance by dynamically compensating
U0 with UΔ(s) = [uΔ,i(s)]m×1
according to the observed various disturbances and plant uncertainties.

Remark 1: The proposed IDOB-MPC scheme has a twoloop structure. One is the external-loop MPC controller for setpoint tracking; the other is the internal-loop IDOB compensator for robustness. The IDOB generates a corrective control input to reject disturbance as much as possible to force theactual system to become the given nominal model, where the disturbance is defined as the sum of the external disturbance and the plant uncertainty. Hence, the actual plant with such an internal-loop compensator can be regarded as the nominal model if the IDOB works well. In addition, the external-loop MPC controller is equivalent to control an approximate nominal system for desired performance specification. Fig. 3 shows an equivalent block diagram of the proposed IDOB-MPC structure (as shown in Fig. 2), in which the input disturbance DI (s) and the DOB output UΔ(s) have been transformed to the form of output disturbance. Moreover, the process

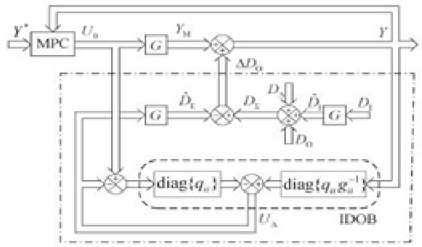

Fig.3. Equivalent block diagram of the proposed

IDOB–MPCstructure:

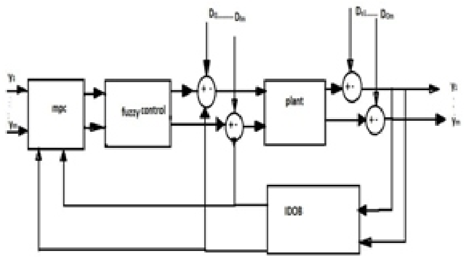

Fig.4.Equivalent block diagram of MPC-FUZZY-IDOB controller.

Most of the real-world processes that require automatic control are non-linear in nature. That is, their parameter values alter as the operating point changes over time or both. As conventional control schemes as they are linear in nature, a controller can only be tuned for a limited period of time are to give good attainment at a specific operating point. From time to time, with the every change in the operating point the controller needs to be retuned. This requirement to retune has driven the demand for adaptive controllers which can match the current process characteristics by automatically retuning themselves.

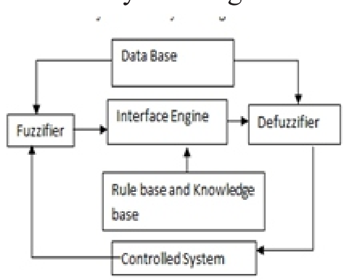

Fig. 4: Fuzzy logic controller

Fuzzy logic is an innovative technology that enhances conventional system design with engineering expertise. Using fuzzy logic, we can avoid the need for accurate mathematical modeling.

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The basic configuration of Fuzzy logic control based as shown in Fig. 4. Consists of four main parts i.e.
(i) Fuzzification,
(ii) Knowledge base,
(iii) Inference Engine and
(iv) Defuzzification.
4.1 Fuzzification
Fuzzificationmaps from the crisp input space to fuzzy sets in certain, input universe of discourse. So for a specific input value x, it is mapped to the degree of membership A(x). The Fuzzification involves the following functions which measures the value of input variables.Assigned triangular membership functions are used as inputs and the output of the fuzzy controller as shown in Figs. 5(a), 5(b), 5(c). Using simulations the universe of discourse for the torque error and the duty ratio is adjusted to get optimal torque ripple reduction. Since there are three membership functions for each input, it follows that there are nine rules in each set of fuzzy rules. The presented fuzzy controller is for both forward and backward rotation, for backward rotation the absolute value of the torque error is used, and the flux position calculation is adjusted according to the rotation direction.

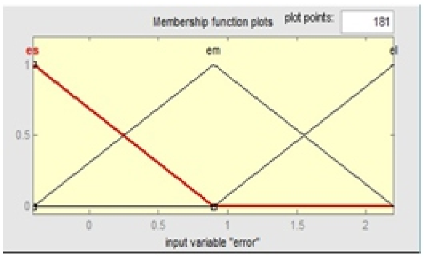

Fig. 5(a) Membership functions distribution for the fresh ore (input).

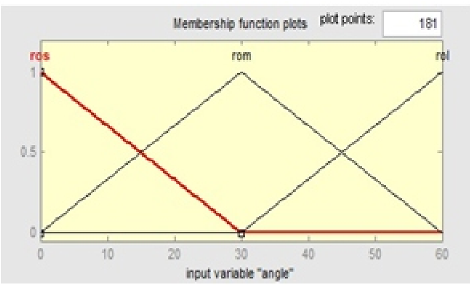

Fig. 5(b) Membership functions distribution for the feed water (input)

If (ore size is medium) and (feed water position is small) then (product size ratio is small) If (ore size is large) and (feed water position is small) then (product size is medium) Using the above reasoning and simulation to find the fuzzy rules, the two sets of fuzzy rules are summarized in Table II.

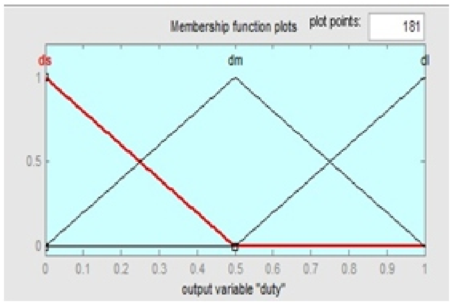

Fig. 5(c) Membership functions distribution for the product particle size (output)

4.2 Knowledge Base:

Table II shows rule base of the FLC .Max–Min and Max-Dot are planned within the literature of several composition methods. In the entire paper Minimum methodology is used. Knowledge base comprises of the definitions of fuzzy membership functions for the input and output variables and the required control rules, which defines the control action by using linguistic terms.

4.3 Defuzzification:

Defuzzification covers the linguistic variables to determine numerical values. Centroid method of Defuzzification is used in this study.
(1)A scale mapping, this converts the range of values of input variables into corresponding universe of discourse.
(2)Defuzzification, which yields a non-fuzzy control action from an inferred fuzzy control action.

TABLE II: Fuzzy Rules

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PRODUCT PARTICLE SIZE	ORESIZE / FEED WATER	SMALL	MEDIUM	HIGH
EXACT SIZE	SMALL	SMALL	SMALL	MEDIUM
	MEDIUM	SMALL	MEDIUM	LARGE
	LARGE	SMALL	MEDIUM	LARGE
OTHER SIZES OF PARTICLE THAN RERUIRED	SMALL	SMALL	MEDIUM	LARGE
	MEDIUM	SMALL	MEDIUM	LARGE
	LARGE	MEDIUM	LARGE	LARGE

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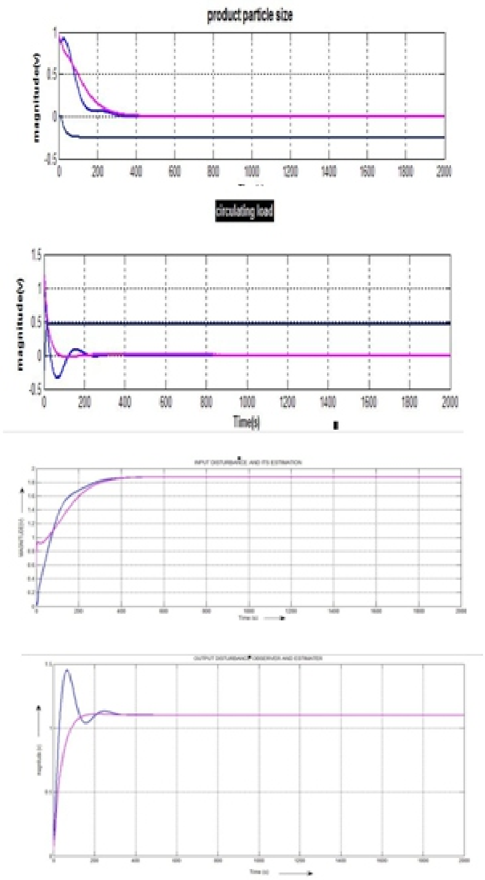

Fig. 4.Performances of (a) disturbance rejection and (b) estimation in thepresence of step output disturbances under IDOB–FUZZY and FUZZY schemes.

Remark 3: Since almost all practical systems
operate in lowfrequencyranges, (2) implies that the real uncertain closedloopsystem with the IDOB behaves as if it was the nominalclosed-loop system in the absence of disturbance. In other words, the IDOB can be combined with the external-loop FUZZY controller to enhance the robustness and disturbance rejection performance. _

Remark 4: (3) indicates that the IDOB-FUZZYmultivariable control can ensure that the system possesses the features of the open-loop system; thus, the high-frequency measurement noise can be filtered out.

Remark 5: Since the implementation of IDOB is rather simple, the introduction of the IDOB compensator to the FUZZY control does not increase much computational complexity. Moreover, the FUZZY controller and the IDOB can be designed separately, so the performance of set point tracking and disturbancerejection also can be regulated separately by tuning their corresponding adjustable parameters online. This is very convenient for its practical engineering application.

IV. DESIGN CASE:

Consider a multivariable grinding circuit system, whose input–output model at a certain operating condition was developed as follows [15]:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} \frac{-0.5(-2.2s+1)e^{-8.5s}}{(1.2s+1)(20s+1)} & \frac{0.057(70s+1)e^{-1.5s}}{(1.8s+1)(17s+1)} \\ \frac{2.67e^{-6s}}{(14s+1)(2s+1)} & \frac{0.91(-4.8s+1)e^{-0.8s}}{(3.6s+1)(2.2s+1)} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

wherey1and y2 denote the controlled variables and u1 and u2 stand for the manipulated variables.Because g11 and g22 are the non-minimum-phase delay systems, the standard DOB and the one modified in [2] and cannot be used here to deal with disturbance observation problem. Thus, the proposed IDOB design method is used to design the DOB for this grinding circuit as follows:

$$\mathrm{diag}\left\{\frac{q_{11}}{g_{11}}, \frac{q_{22}}{g_{22}}\right\} = \mathrm{diag} \times \left\{\frac{-2(1.2s+1)(20s+1)}{(2.2s+1)(\alpha_{11}s+1)}, \frac{(3.6s+1)(2.2s+1)}{0.91(4.8s+1)(\alpha_{22}s+1)}\right\}$$

Where

$$\mathrm{diag}\{q_{11}, q_{22}\} = \mathrm{diag} \times \left\{\frac{(-2.2s+1)e^{-8.5s}}{(2.2s+1)(\alpha_{11}s+1)}, \frac{(-4.8s+1)e^{-0.8s}}{(4.8s+1)(\alpha_{22}s+1)}\right\}$$

The parameters of the FUZZY design are determined as follows: control interval T = 5, control horizon NC = 20, prediction horizon NP = 60, input weightsWU= diag{4, 4}, and output weights WY = diag{2, 2}.
Assume that the real grinding circuit system [15] is described as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \frac{-0.45(-1.8s+1)e^{-9s}}{(0.9s+1)(17s+1)} & \frac{0.06(64s+1)e^{-1.8s}}{(2s+1)(20s+1)} \\ \frac{3.15e^{-6.4s}}{(16s+1)(2.5s+1)} & \frac{1.05(-5s+1)e^{-1.1s}}{(4s+1)(2.8s+1)} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Fig. 4 shows the disturbance rejection (a) and estimation (b) performances of the perturbed grinding circuit in the presence of step output disturbances under IDOB–FUZZY and FUZZY schemes. Fig. 5 shows the response curves of the manipulated variables in this case. It can be observed that the proposed IDOB has good performance of disturbance estimation. This is because the estimation in the disturbance channel under the IDOB–FUZZY scheme coincides with the actual disturbance very well.

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This feature makes the proposed IDOB-FUZZYoutput from the single FUZZY scheme in terms of disturbance rejection performance. For example, compared to the single FUZZY scheme, the proposed scheme has faster convergence speed, shorter settling time, and smaller adjusting magnitudes for both y1 and y2. Moreover, it is observed that the IDOB-FUZZY control with smaller adjustable parameters α11 and α22 can speed up the disturbance rejection; however, it results in large and even jittery dynamic response. Further analysis reveals that if α11and α22 are selected too small, it will make the control system be too sensitive to measurement noise and even destroy the system stability. Fig. 6 shows the disturbance rejection (a) and estimation (b)performances of the perturbed grinding circuit in the presence of sinusoidal input disturbances under IDOB-FUZZY and single FUZZY schemes. It can be observed that the IDOB can estimate and reject the sinusoidal disturbances very well. The fluctuation amplitudes of both y1 and y2 under the proposed method are much smaller than those using the FUZZY method. Although their fluctuation frequencies under the two control methods are almost the same, their response speeds under the proposed method are much quicker than those under the single FUZZY method. Thus, this simulation demonstrates that the proposed IDOB-FUZZY can overcome such sinusoidal disturbance more effectively than the single FUZZY scheme.

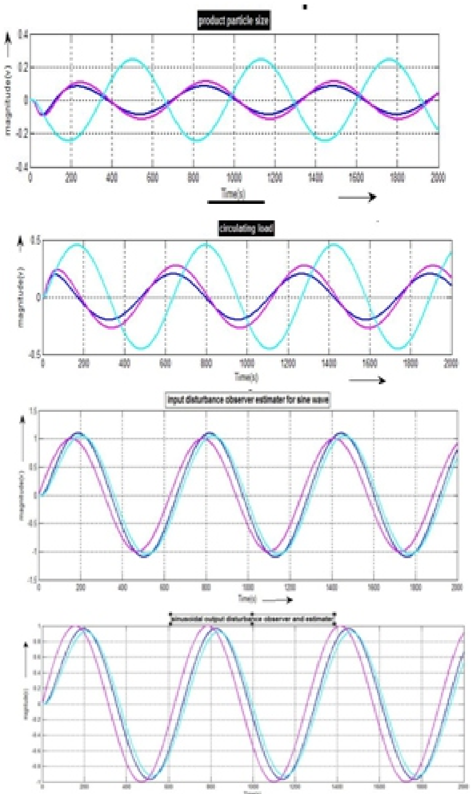

Fig. 6.Performances of (a) disturbance rejection and(b) estimation in the presence of sinusoidal input disturbances underIDOB–FUZZY and FUZZY schemes.

V. CONCLUSION:

It is known that non-minimum-phase systems are difficult to control and observe. Focusing on these practical problems, this brief presents an IDOB structure for the non-minimum phase time delay systems. Meanwhile, an IDOB–FUZZY compound control strategy is proposed to handle multivariable delay systems with non-minimum phase zero in the presence of strong disturbances and various process uncertainties. To demonstrate the effectiveness of the proposed approach, an application case and several simulations have been performed in this brief.

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