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AN ADAPTIVE PRESSURE CONTROLLER DESIGN OF HYDRAULIC SERVO SYSTEM WITH DEAD ZONE

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ABSTRACT

This paper develops a design of adaptive pressure controller for hydraulic servo valve with unknown dead zone. In general to reduce leakage flow, the servo valves adopt positive lap structures. This makes dead zone larger and is obstacle for precise positioning control. To compensate of such dead zone and unknown physical parameters of system, adaptive control strategy is examined for simple pressure control system. First it is assumed that only the flow gain of servo valve can be known by experiment and the adaptive controller is designed. This controller is examined on water hydraulic servo system which has larger leakage and positive lap for lower viscosity of tap water. The experimental results show that the better tracking performance is obtained comparing with PI or conventional adaptive controller without dead zone compensation. Then the controller is extended for unknown flow gain case.

KEYWORDS

Water Hydraulic Servo System, Dead Zone, Adaptive Control, Lyapunov Design, Robustness

INTRODUCTION

In electrohydraulic servo valves with high positioning performance, positive lap structures are adopted between land and sleeve to attenuate the leakage of fluid in general. In addition, a nozzle-flapper structure is also adopted to reduce friction. However, when the nonlinearities caused by these structural properties are neglected in designing control system, it often causes deterioration in the control performance. In the water hydraulic case, which is paid attention for its lower environmental load, the high availability and the high energy density owing to lower compressibility, this characteristic is more obvious. Especially the dead zone and/or the leakage flow around neutral position of spool displacement should be compensated to improve the control performance of hydraulic actuators.

In this research, we discuss the design of an adaptive controller to track a given desired pressure compensating the dead zone in servo valve as well as unknown physical parameters. In general, the dead zones depend on the direction of spool displacement of a servo valve, and some approach has been reported to overcome this nonlinearity in oil hydraulic systems. In [1] and [2], the dead zone was estimated by using neural network technique and PWM signal was generated to cancel the effect. On the other hand, the research results on applying the adaptive control technique to compensate the effect of dead zone directly are very few[3]. In this paper, an adaptive controller which compensate unknown dead zone is constructed and the performance is examined by experiments. In addition, the adaptive controller is extended to unknown flow gain case.

PROBLEM FORMULATION

The hydraulic circuit discussed in this paper is shown in Figure 1.

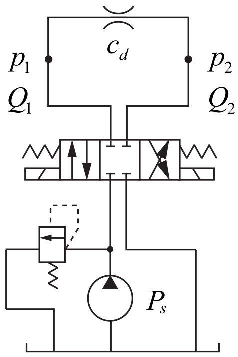

Figure 1: Hydraulic circuit

By linearizing the flow equation around neutral position of sool in servo valve and introducing load pressure $p = p_1 - p_2$, the pressure dynamics is given by

$$\dot{p} = -\mathrm{sgn}(p)\theta_1\sqrt{|p|} - \theta_2 p + f(u) \tag{1}$$

where $\theta_i > 0\,(i = 1,2)$ and $\mathrm{sgn}(\cdot)$ is the signature function. The input nonlinearity f can be described

$$f(u) = \begin{cases} u - \theta_3 \ , & u \geq \theta_3 \\ 0 \ , & -\bar{\theta}_3 \leq u \leq \theta_3 \\ u + \bar{\theta}_3 \ , & u \leq -\bar{\theta}_3 \end{cases} \tag{2}$$

where u is input to be determined later. The parameters $\theta_3, \bar{\theta}_3 > 0$ are positive and negative dead zone, respectively, depending on the servo valve displacement direction (See Figure 2).

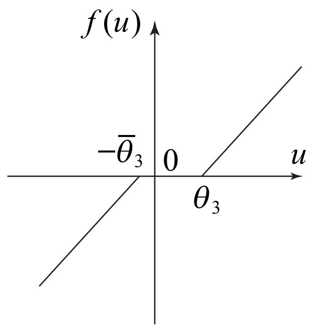

Figure 2: Dead zone of servo valve

The problem that should be solved in this paper is defined as follows.

Problem 1 Find an adaptive controller that makes the load pressure p track to the reference pressure p_r guaranteeing global boundedness of all signals in the system

$$\begin{aligned} u &= u(p, \hat{\theta}) \\ \dot{\hat{\theta}} &= \phi(p) \end{aligned} \tag{3}$$

where $\hat{\theta}$ is adaptive parameter. ∎

Here we assume that the gain of input u is known in Figure 2 and in fact this can be almost done by experiment. However, in general, this parameter depends on working point therefore in later, we discuss another adaptive controller design considering this unknown input positive gain.

CONTROLLER DESIGN

The desired pressure response is given by

$$\dot{p}_r = -\alpha p_r + \alpha r \tag{4}$$

where $\alpha(>0)$ is a design parameter and r is a reference signal. Defining pressure error as $e = p - p_r$, we have error system

$$\begin{aligned} \dot{e} &= \dot{p} - \dot{p}_r \\ &= -\alpha e + \alpha(p - r) - \mathrm{sgn}(p)\theta_1\sqrt{|p|} - \theta_2 p \\ &\quad + \begin{cases} u - \theta_3 \ , & u \geq \theta_3 \\ 0 \ , & -\bar{\theta}_3 \leq u \leq \theta_3 \\ u + \bar{\theta}_3 \ , & u \leq -\bar{\theta}_3 \end{cases} \end{aligned} \tag{5}$$

In the following, we design the controller and discuss the stability, depending on the magnitude of input u.

Case (i) : $u \geq \theta_3$ or $u \leq -\bar{\theta}_3$

Introducing adaptive parameter $\hat{\theta}_i\,(i = 1,2,3)$, we give adaptive input as

$$u = -\alpha(p - p_r) + \hat{\theta}_1\mathrm{sgn}(p)\sqrt{|p|} + \hat{\theta}_2 p + \hat{\theta}_3 \tag{6}$$

Then Eq.(5) can be expressed

$$\dot{e} = -\alpha e + \tilde{\theta}_1\mathrm{sgn}(p)\sqrt{|p|} + \tilde{\theta}_2 p + \tilde{\theta}_3 \tag{7}$$

where $\tilde{\theta}_i = \hat{\theta}_i - \theta_i\,(i = 1,2,3)$. The Lyapunov-like function is constructed as

$$V_1 = \frac{1}{2}\left(e^2 + \sum_{i=1}^{3}\frac{1}{\gamma_i}\tilde{\theta}_i^2\right) \tag{8}$$

and the time derivative of V_1 along the solution of error system Eq.(7) is evaluated as

$$\begin{aligned} \dot{V}_1 &= -\alpha e^2 + \frac{\tilde{\theta}_1}{\gamma_1}\left(\dot{\hat{\theta}}_1 + \gamma_1\mathrm{sgn}(p)\sqrt{|p|}e\right) \\ &\quad + \frac{\tilde{\theta}_2}{\gamma_2}\left(\dot{\hat{\theta}}_2 + \gamma_2 pe\right) + \frac{\tilde{\theta}_3}{\gamma_3}\left(\dot{\hat{\theta}}_3 + \gamma_3 e\right) \end{aligned}$$

where $\gamma_i > 0\,(i = 1,2,3)$. This leads to the parameter update law

$$\dot{\hat{\theta}}_1 = -\gamma_1\mathrm{sgn}(p)\sqrt{|p|}e, \quad \dot{\hat{\theta}}_2 = -\gamma_2 pe, \quad \dot{\hat{\theta}}_3 = -\gamma_3 e \tag{9}$$

Using Eq.(9), we have $\dot{V}_1 = -\alpha e^2$ and Barbalat's Lemma [4] shows the pressure error goes to 0 and all signals are bounded. The similar discussion can be shown in the case for $u \leq -\bar{\theta}_3$ and the positive definite function V_2 and is omitted. Therefore, in these cases we have Eq.(6) as the adaptive control input for $V = \frac{1}{2}(V_1 + V_2)$ outside of the dead zone.

Case (ii): $-\bar{\theta}_3 \leq u \leq \theta_3$

In this region the input u is invalid. However we consider the behaviour of the dead zone compensation parameter $\hat{\theta}_3$.

(a) $p > 0$ and $u < 0$

We have $e > 0$ and the right-hand side of the error dynamics

$$\dot{e} = \alpha(p_r - p) - \theta_1 \mathrm{sgn}(p)\sqrt{|p|} - \theta_2 p \qquad (10)$$

is negative. This makes e a monotonically decreasing and there exists a time t_0 such that $e(t_0) = 0$ crossing from positive value.

(b) $p > 0$ and $u > 0$

We have $e < 0$ and the right-hand side of Eq.(10) is negative. This keeps e be decreasing. At the same time the fact that the parameter update law guarantees $\theta_i > 0\,(i = 1,2,3)$ and monotonically increasing. This leads that the input u is positive and being monotonically increasing. This implies that there exists a time t_1 such that $u(t_1) > \theta_3$ and the situation moves to above Case(i).

(c) $p < 0$ and $u > 0$

We have $e < 0$ and in a similar to (a), there exists a time t_0 such that $e(t_0) > 0$.

(d) $p < 0$ and $u < 0$

We have $e > 0$ and in a similar to (b), there exists a time t_1 such that $u(t_1) < -\bar{\theta}_3$ and the situation moves to above Case(i).

Therefore the input signal surpass the dead zone after finite time even if the magnitude of input u becomes smaller than the dead zone.

Theorem 1 Consider the pressure control system with dead zone Eq.(1),(2) and desired pressure model Eq.(4). The adaptive input Eq.(6) and parameter update law Eq.(9) solve the Problem1. ∎

EXPERIMANTAL RESULTS

To evaluate the effectiveness of the proposed controller, the pressure control experiment was done. The dead zone of the servo valve used this time was estimated almost as $\theta_3 = 0.3$[V], $\bar{\theta}_3 = 0.4$[V] by experiment. The external reference r is a rectangular wave signal that changed at each 10[s], and the design parameter is $\alpha = 3$. We examined the PI controller and the normal adaptive controller without dead zone compensation[5] as well as proposed controller. The PI control parameters are determined by try and error.

The experimental result that the maximum reference pressure is set to 3[MPa] is shown in Figure 3. From this figure, the normal adaptive controller without dead zone compensation shows lower performance in reference signal change. The PI controller have better tracking performance, however, the small vibration can be seen around zero reference pressure for dead zone. The proposed adaptive controller shows best tracking performance for both reference signal change and zero state.

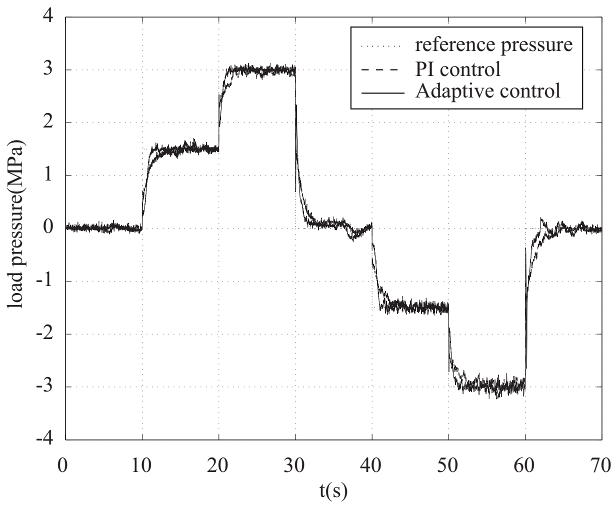

Figure 3: Experimental result: maximum fererence pressure 3[MPa]

Another experimental result that maximum reference pressure is close to corresponding dead zone is shown in Figure 4. In this system, the dead zone corresponds to the pressure from +0.6[MPa] to -0.8[MPa] approximately. In

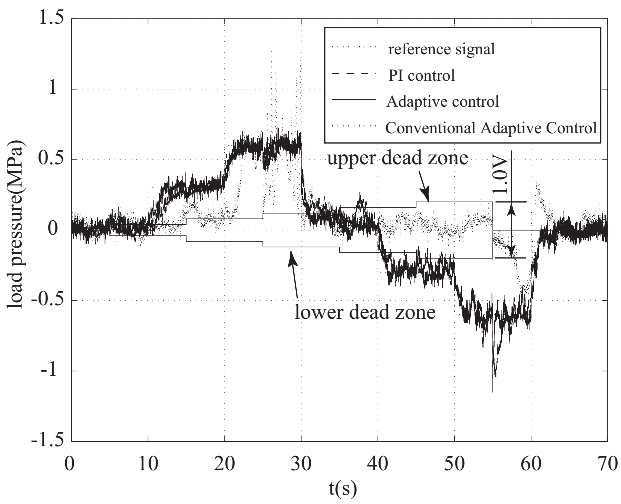

Figure 4: Experimental result: maximum fererence pressure 0.6[MPa], with software dead zone

addition, the external stepwise software dead zone from 0 to 1.0[V] is also applied to examine the robustness of each controller. In this result, the sensor noise is relatively larger therefore the tracking performance becomes lower for all cases. The proposed controller can only almost keeps better tracking performance for smaller reference signal and software dead zone. And it also shows best performance on the 0 pressure regulation. It is observed that the normal adaptive controller fails reference tracking. This is on the fact that the adaptive controller is not possible have good approximation of nonlinear function with larger bias term by only the combination of linear and the square root functions. PI controller also shows lower performance than that shown in Figure 4 and the vibration becomes larger.

EXTENSION OF CONTROLLER

In previous section, it was assumed that the flow gain of the servo valve was known. However, this flow gain changes depending on the operation point generally, therefore we solve the design problem including the unknown flow gain estimation.
The flow gain is assumed to be θ_3, $\bar{\theta}_3 (> 0)$ and nonlinear function $f(u)$ of the input of Eq.(1) is modified as follows (See Figure 5).

$$f(u) = \begin{cases} \theta_3(u-\theta_4) \ , & u \geq \theta_4 \\ 0 \ , & -\bar{\theta}_4 \leq u \leq \theta_4 \\ \bar{\theta}_3(u+\bar{\theta}_4) \ , & u \leq -\bar{\theta}_4 \end{cases} \tag{11}$$

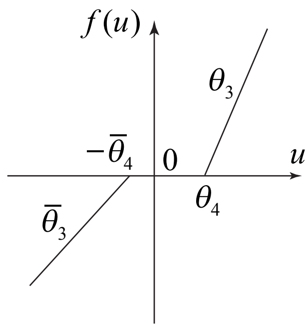

Figure 5: Dead zone of servo valve with unknown flow gain

Adaptive Controller Design

The modified error system is given by

$$\begin{aligned} \dot{e} \ &= \ -\alpha e + \alpha(p-r) - \mathrm{sgn}(p)\theta_1\sqrt{|p|} - \theta_2 p \\ &+ \begin{cases} \theta_3(u-\theta_4) \ , & u \geq \theta_4 \\ 0 \ , & -\bar{\theta}_4 \leq u \leq \theta_4 \\ \bar{\theta}_3(u+\bar{\theta}_4) \ , & u \leq -\bar{\theta}_4 \end{cases} \end{aligned} \tag{12}$$

Motivated by R.Marino's idea, the inverse parameters are introduced to estimate θ_3, $\bar{\theta}_3$ [6].

Case (i) : $u \geq \theta_4$
Defining the adaptive parameter $\hat{\theta}_i \, (i = 1, \cdots, 4)$, we construct the adaptive input as

$$u \ = \ \hat{\theta}_4 + \frac{v}{\hat{\theta}_3} \tag{13}$$

$$v \ = \ -\alpha(p-r) + \mathrm{sgn}(p)\hat{\theta}_1\sqrt{|p|} + \hat{\theta}_2 p \tag{14}$$

Then error dynamics can be expressed as

$$\begin{aligned} \dot{e} \ &= \ -\alpha e + \alpha(p-r) - \mathrm{sgn}(p)\theta_1\sqrt{|p|} - \theta_2 p \\ &\quad + \theta_3(\hat{\theta}_4 - \theta_4) + \frac{\theta_3}{\hat{\theta}_3} v \\ &= \ -\alpha e + \alpha(p-r) - \mathrm{sgn}(p)\theta_1\sqrt{|p|} - \theta_2 p \\ &\quad - \theta_3\tilde{\theta}_4 + \frac{\hat{\theta}_5}{\theta_5} v \end{aligned}$$

where $\tilde{\theta}_i = \theta_i - \hat{\theta}_i \, (i = 1, \cdots, 5)$ and

$$\theta_5 = \frac{1}{\theta_3}, \ \hat{\theta}_5 = \frac{1}{\hat{\theta}_3} \tag{15}$$

Therefore

$$\begin{aligned} \dot{e} \ &= \ -\alpha e + \alpha(p-r) - \mathrm{sgn}(p)\theta_1\sqrt{|p|} - \theta_2 p \\ &\quad - \theta_3\tilde{\theta}_4 + \left(1 - \frac{\tilde{\theta}_5}{\theta_5}\right) v \\ &= \ -\alpha e - \mathrm{sgn}(p)\tilde{\theta}_1\sqrt{|p|} - \tilde{\theta}_2 p - \theta_3\tilde{\theta}_4 - \frac{\tilde{\theta}_5}{\theta_5} v \\ &= \ -\alpha e - \mathrm{sgn}(p)\tilde{\theta}_1\sqrt{|p|} - \tilde{\theta}_2 p + \tilde{\theta}_3\frac{v}{\hat{\theta}_3} - \tilde{\theta}_4\theta_3 \end{aligned} \tag{16}$$

We give a positive definite function

$$V_1 = \frac{1}{2}\left(e^2 + \sum_{i=1}^{4}\frac{1}{c_i}\tilde{\theta}_i^2\right), \ c_i > 0 \tag{17}$$

and evaluate its time derivative along the solution of Eq.(16):

$$\begin{aligned} \dot{V}_1 \ &= \ -\alpha e^2 - \frac{\tilde{\theta}_1}{c_1}\left(\dot{\hat{\theta}}_1 + c_1 \mathrm{sgn}(p)\sqrt{|p|}e\right) \\ &\quad - \frac{\tilde{\theta}_2}{c_2}\left(\dot{\hat{\theta}}_2 + c_2 pe\right) \\ &\quad - \frac{\tilde{\theta}_3}{c_3}\left(\dot{\hat{\theta}}_3 - c_3\frac{v}{\hat{\theta}_3}e\right) - \frac{\tilde{\theta}_4}{c_4}\left(\dot{\hat{\theta}}_4 + c_4\theta_3 e\right) \end{aligned}$$

Noticing that all unknown parameters are positive, we have parameter update law:

$$\begin{aligned} &\dot{\hat{\theta}}_1 = -c_1 \mathrm{sgn}(p)\sqrt{|p|}e, \ \dot{\hat{\theta}}_2 = -c_2 pe, \\ &\dot{\hat{\theta}}_3 = c_3\frac{v}{\hat{\theta}_3}e, \ \dot{\hat{\theta}}_4 = -c_4 e \end{aligned} \tag{18}$$

Eq.(18) guarantees e goes to 0 and the boundedness of all signal in pressure control system.

Case (ii)： $u \leq -\underline{\theta}_4$

Different from **Case (i)**, we give the input as

$$u = -\breve{\underline{\theta}}_4 + \frac{v}{\breve{\underline{\theta}}_3} \quad (19)$$

$$v = -\alpha(p-r) + \mathrm{sgn}(p)\hat{\theta}_1\sqrt{|p|} + \hat{\theta}_2 p \quad (20)$$

Similarly, defining $\tilde{\underline{\theta}}_j = \underline{\theta}_j - \breve{\underline{\theta}}_j\,(j = 3,4,5)$ and we introduce

$$\underline{\theta}_5 = \frac{1}{\underline{\theta}_3},\ \breve{\underline{\theta}}_5 = \frac{1}{\breve{\underline{\theta}}_3} \quad (21)$$

Then we have the error dynamics and Lyapunov-like function as

$$\dot{e} = -\alpha e - \mathrm{sgn}(p)\tilde{\theta}_1\sqrt{|p|} + \hat{\theta}_2 p + \tilde{\underline{\theta}}_3\frac{v}{\breve{\underline{\theta}}_4} + \tilde{\underline{\theta}}_4\underline{\theta}_3 \quad (22)$$

$$V_2 = \frac{1}{2}\left(e^2 + \frac{1}{c_1}\tilde{\theta}_1^2 + \frac{1}{c_2}\tilde{\theta}_2^2 + \sum_{i=3}^{4}\frac{1}{c_i}\tilde{\underline{\theta}}_i^2\right),\ c_i > 0 \quad (23)$$

To make $\dot{V}_2 < 0$, we have the parameter update law

$$\dot{\breve{\theta}}_1 = -c_1\mathrm{sgn}(p)\sqrt{|p|}e,\ \dot{\breve{\theta}}_2 = -c_2 pe, \\ \dot{\breve{\underline{\theta}}}_3 = c_3\frac{v}{\breve{\underline{\theta}}_3}e,\ \dot{\breve{\underline{\theta}}}_4 = c_4 e \quad (24)$$

With Eq.(24), we arrive same result in Case (i).

Case (iii)： $-\underline{\theta}_4 \leq u \leq \theta_4$

Similar to the previous section, we can show that the input signal surpass the dead zone after finite time even if the magnitude of input u becomes smaller than the dead zone.

In this control system, we have the Lyapunov-like function

$$V = \frac{1}{2}(V_1 + V_2) \quad (25)$$

for whole system. Note that if Case (ii) is turned off when Case (i) is valid and vice versa depending on in which side the spool is. Then the following theorem is obtained from the above discussion.

Theorem 2 Consider the pressure control system with dead zone Eq.(1),(11) and desired pressure model Eq.(4). The adaptive input Eq.(13),(14),(19),(20) and parameter update law Eq.(18),(24) solve the Problem 1. ∎

Remark 1 In this design, some technical routine preventing from θ_3, $\breve{\underline{\theta}}_3$ being divided by zero are needed in applications. ∎

Numerical Examples

Figure 6 and Figure 7 show the numerical simulation of pressure control and the input signal obtained by the proposed technique. The design parameter is set to $\alpha = 3$. The control performance is good even for small reference signal. The transient delay can be observed when the reference signature changes, however, this diminishes as adaptation develops. The adaptive control input also generate reasonable magnitude signal.

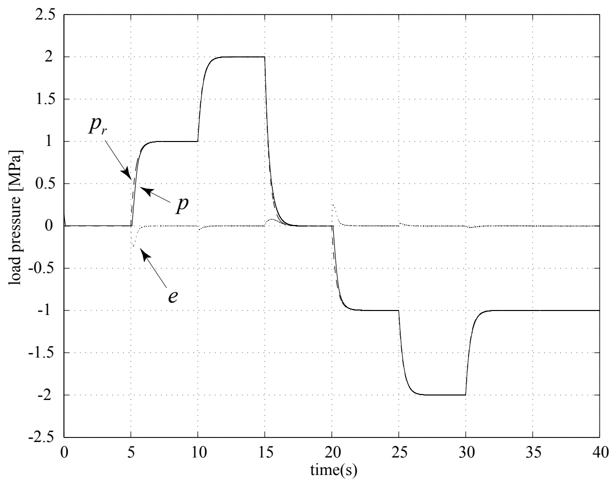

Figure 6: Simulation result: pressure error

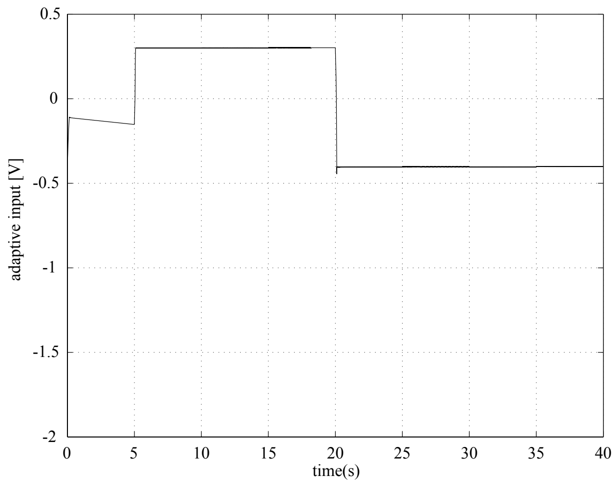

Figure 7: Simulation result: adaptive input

CONCLUSIONS

In this paper, two designs of adaptive controller for pressure tracking of servo valve with dead zone are discussed. Both methods compensate the dead zone directly. The effectiveness of former controller was evaluated in experiment and it is shown that the tracking performance is rather good for small reference pressure comparing with PI or conventional adaptive controller. Motivated by

R.Marino's idea, the latter method can accommodate unknown flow gain and simulation result show good performance. In future, we will obtain the experimental result on latter method and also for water hydraulic motor and water hydraulic cylinder control with these two control strategy.

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