

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 6, June 2016

SMC-PID for Electromechanical Plant

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ABSTRACT: Sliding mode control (SMC) has excellent robustness to model uncertainties and disturbances. This would make SMC an ideal scheme for process control applications where model uncertainties and disturbances are common. The existing SMC, however, has the major drawback of control chattering; i.e., the controller output is a discontinuous high-frequency switching signal. This makes SMC not suitable for most chemical processes where the manipulated variables are continuous and where high-frequency changes are not permitted. To eliminate chattering, a new proportional-integral-derivative (PID)-based sliding mode control (PIDSMC) suitable for the nonlinear process is proposed here. The proposed control system consists of three components: a compensation of process nonlinearity, a linear feedback of state tracking errors, and a PID control of the sliding surface function. The chattering is eliminated via the replacement of the discontinuous switching in the SMC by a continuous input determined by a PID scheme. An adaptive strategy is proposed to tune the PID parameters online to control the process states onto a sliding surface that characterizes the closed-loop performance.

KEYWORDS: Sliding mode control; PID sliding surface; Nonlinear control.

1. INTRODUCTION

It is well known that physical systems are nonlinear in nature. The control of these systems which have the characteristics of parameter inaccuracy (structured uncertainty), neglected dynamics (unstructured uncertainty) as well as time varying has been a serious challenge to the control community. Nonlinear control design methods such as feedback linearization and sliding mode control have been proved sound and successful in control problems. Sliding mode control (SMC), first proposed in the early 1950s, has been proved to be able to tackle system uncertainties and external disturbances with good robustness. The dynamic performance of the system under the SMC method can be shaped according to the system specification by an appropriate choice of switching function. Robustness is the best advantage of a sliding mode control and systematic design procedures for sliding mode controllers are well known and available in the literature. Basically, there are two main advantages of the SMC method: i) the dynamic behaviour of the system may be tailored by the particular choice of switching functions and ii) the closed-loop response becomes totally insensitive to a particular class of uncertainty. In addition, the ability to specify performance directly makes sliding mode control attractive from the design perspective. Moreover, for the class of systems to which it applies, sliding mode control design provides a systematic approach to the problem of maintaining stability and consistent performance in the phase of modeling imprecisions. Furthermore, by allowing the tradeoffs between modeling and performance to be quantified in a simple fashion, it can illuminate the whole design process. Finally, it offers the potential of simplifying higher-level programming, by accepting reduced information about task and system.

A key step in the design of sliding mode controllers is to introduce a proper sliding surface so that tracking errors and output deviations can be reduced to a satisfactory level. Unfortunately, an ideal sliding mode controller has a discontinuous switching function and it is assumed that the control signal can be switched from one value to another infinitely fast. In practical systems, however, it is impossible to achieve infinitely fast switching control because of finite time delays for the control computation and limitations of physical actuators. Due to imperfect switching in practice it raises the issue of chattering. The chattering, which is highly undesirable, appears as a high-frequency oscillation near the desired equilibrium point and may excite the unmodelled high frequency dynamics of the system. Instead of a discontinuous switching function, continuous functions have been used to avoid the chattering of the control and to achieve the exponential stability such as saturation functions, sigmoid functions, relay functions,

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hyperbolic functions, and hysteresis-saturation functions. An ultimate roundedness of the error within some predetermined boundary layer is considered in these continuous functions. Some other studies have also been used to overcome chattering phenomena such as use of a first-order low-pass filter between the controller and the plant. Sliding mode control has been widely studied in recent years and has started to play an important role in the application of control theory to practical problems. It has been successfully applied to underwater vehicles, automotive transmissions and engines, and power systems, induction motor, robots, electric drives, human neuromuscular process, and elevator velocity. Sliding mode control has also been applied to dc motors using simulations. In this paper, a real application is performed such that a sliding mode controller is designed using a PID sliding surface for the speed control of an electromechanical plant, a dc motor connected to a load via a shaft. The feasibility and effectiveness of the proposed sliding mode controller is experimentally demonstrated and the system is controlled using a computer. The results obtained from the present study are compared with the traditional PID control in dynamic responses of the closed-loop control system.

II. DESCRIPTION OF ELECTROMECHANICAL PLANT

The electromechanical plant to implement theoretical results, a dc motor connected to a load via a shaft, is shown in Fig.1, since the dc motors, as components of electromechanical systems, have been widely used in several industrial applications as actuating elements to follow a predetermined speed or position trajectory under load for their advantages of easy speed and position control and wide adjustability range. Consequently, examination of dc motor behaviour constitutes a useful effort for analysis and control of many practical applications. The electrical and mechanical equations for the electromechanical plant, shown in Fig. 3.1, consisting of a dc motor connected to a load via a long shaft can be given as:

$$V_a(t) = L_a \frac{d}{dt} i_a(t) + R_a i_a(t) + K_m \omega_m(t) \quad (1)$$

$$J_m \left(\frac{d\omega_m(t)}{dt} \right) = T_m(t) - T_s(t) - R_m \omega_m(t) - T_f(\omega_m) \quad (2)$$

$$J_L \left(\frac{d\omega_L(t)}{dt} \right) = T_s(t) - R_L \omega_L(t) - T_d(t) - T_f(\omega_L) \quad (3)$$

$$T_s(t) = k_s (\theta_m(t) - \theta_L(t)) + B_s (\omega_m(t) - \omega_L(t)) \quad (4)$$

$$\frac{d\theta_m(t)}{dt} = \omega_m(t)$$

$$\frac{d\theta_L(t)}{dt} = \omega_L(t)$$

where V_a is the motor armature voltage, R_a and L_a are the armature coil resistance and inductance respectively, i_a is the armature current, K_m is the torque coefficient, T_m is the generated motor torque, ω_m and ω_L are the rotational speeds of the motor, J_m and J_L

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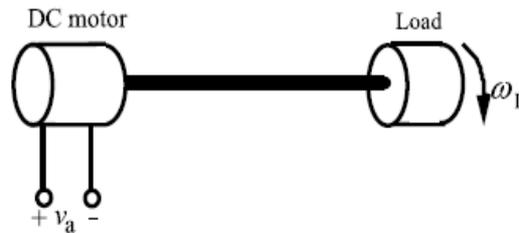


Fig.1 Diagram of the electromechanical plant.

are the moments of inertia, R_m and R_L are the coefficients of viscous friction, T_d is the external load disturbance, T_f is the nonlinear friction, and T_s is the transmitted shaft torque, t is the time. Model of the nonlinear friction T_f can be obtained by considering an asymmetrical characteristic as,

$$T_f = (\alpha_0 + \alpha_1 e^{-\alpha|\omega|}) \text{sgn}(\omega) + (\alpha_3 + \alpha_4 e^{-\alpha_5|\omega|}) \quad (5)$$

Where α_i are positive constant, $\alpha_i > 0$, $i = 0, \dots, 5$, $\alpha_0 \neq \alpha_3$, $\alpha_1 \neq \alpha_4$, $\alpha_2 \neq \alpha_3$.

There are several parameters in the plant model, Eq. (1) to Eq. (5) such that it is experimentally difficult to define all these parameters individually. To simplify the modelling process, model of the electromechanical plant can be approximated using a second-order model including disturbances and uncertainties as,

$$\ddot{\omega}_m(t) = -(A_n \pm \Delta A)\dot{\omega}_m(t) - (B_n \pm \Delta B)\omega_m(t) + (C \pm \Delta C)V_a(t) + f(t) \quad (6)$$

where A_n , B_n and C_n are the nominal known system parameters, ΔA , ΔB and ΔC are the model uncertainties introduced by plant parameters, nonlinear friction, and unmodelled dynamics, and $f(t)$ presents external disturbance.

III. SLIDING MODE CONTROL

The study of sliding mode control has gained popularity in recent years as a methodology for controlling nonlinear systems with modeling uncertainties and external disturbances. It is known that the crucial and the most important step of SMC design is the construction of the sliding surface $s(t)$ which is expected to response desired control specifications and performance. The trajectories are enforced to lie on the sliding surfaces. Let the tracking error in a closed-loop control system be $e(t)$, then a sliding proportional + integral + derivative (PID) surface in the space of error can be defined as

$$s(t) = k_1 e(t) + k_2 \int_0^t e(\tau) d\tau + k_3 \frac{de(t)}{dt} \quad (7)$$

where the coefficients k_1, k_2, k_3 are strictly positive constants, $k_1, k_2, k_3 \in \mathbb{R}$. If the initial error $e(0) = 0$, then the tracking problem can be considered as the error remaining on the sliding surface $s(t) = 0$ for all $t \geq 0$. If the system trajectory has reached the sliding surface $s(t) = 0$, it remains on it while sliding into the origin $e(t) = 0$, $e'(t) = 0$ as shown in Fig. 2. The purpose of sliding mode control law is to force error $e(t)$ to approach the sliding surface and then move along the sliding surface to the origin. Therefore it is required that the sliding surface is stable. The error will die out asymptotically. This implies that the system dynamics will track the desired trajectory asymptotically.

The control objective is to determine a control $U(t)$ such that the closed-loop system will follow the desired trajectory, that is, the tracking error $e(t)$ should converge to zero.

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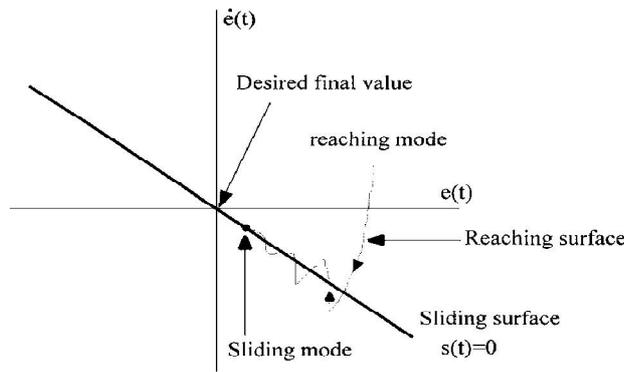


Fig. 2 Graphical interpretation of Sliding Mode Control

The process of sliding mode control can be divided into two phases, that is, the sliding phase with $s(t)=0$, $s'(t)=0$, and the reaching phase with $s(t) \neq 0$. Corresponding to two phases, two types of control law can be derived separately. Conceptually, in sliding mode the equivalent control is described when the trajectory is near $s(t)=0$, while the hitting control is determined in the case of $s(t) \neq 0$.

The derivative of the sliding surface defined by Eq. (7) can be given as

$$\dot{s}(t) = k_1 \dot{e}(t) + k_2 e(t) + k_3 \ddot{e}(t) \quad (8)$$

A necessary condition for the output trajectory to remain on the sliding surface $s(t)$ is $\dot{s}(t) = 0$

$$k_1 \dot{e}(t) + k_2 e(t) + k_3 \ddot{e}(t) = 0 \quad (9)$$

If the control gains k_1 , k_2 , and k_3 are properly chosen such that the characteristic polynomial in Eq. (9) is strictly Hurwitz, that is, a polynomial whose roots lie strictly in the open left half of the complex plane, it implies that $\lim_{t \rightarrow \infty} e(t) = 0$ meaning that the closed-loop system is globally asymptotically stable.

The error $e(t)$ can be defined in terms of physical plant parameters as

$$e(t) = \omega_r(t) - \omega_m(t) \quad (10)$$

where $\omega_r(t)$ is the command signal and $\omega_m(t)$ is the measured output signal. The second derivative of the error $e(t)$ is

$$\ddot{e}(t) = \ddot{\omega}_r(t) - \ddot{\omega}_m(t) \quad (11)$$

If Eqs. (6) and (11) are substituted into Eq. (9) using the nominal plant parameters where $\Delta A=0$, $\Delta B=0$, $\Delta C=0$, and $F=0$, then Eq. (8) becomes

$$k_1 \dot{e}(t) + k_2 e(t) + k_3 [\ddot{\omega}_r(t) + A\dot{\omega}_m(t) + B\omega_m(t) - Cu(t)] = 0 \quad (12)$$

The equivalent control $u_{eq}(t)$, first mentioned by Utkin, is obtained as the solution of the problem $\dot{s}(t) = 0$ which leads to

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$$u_{eq}(t) = (k_3 C)^{-1} [k_1 \dot{e}(t) + k_2 e(t) + k_3 \ddot{\omega}_r(t) + k_3 A \dot{\omega}_m(t) + k_3 B \omega_m(t)] \quad (13)$$

If the initial output trajectory is not on the sliding surface $s(t)$, or there is a deviation of the representative point from $s(t)$ due to parameter variations and/or disturbances, the controller must be designed such that it can drive the output trajectory to the sliding mode $s(t)=0$. The output trajectory, under the condition that it will move toward and reach the sliding surface, is said to be on the reaching phase. For this purpose, the Lyapunov function can be chosen as

$$V(t) = \frac{1}{2} s^2(t) \quad (14)$$

with $V(0)=0$ and $V(t) > 0$ for $s(t) \neq 0$. A sufficient condition to guarantee that the trajectory of the error will translate from reaching phase to sliding phase is to select the control strategy, also known as the reaching condition

$$\dot{V}(t) = s(t)\dot{s}(t) < 0, \quad s(t) \neq 0 \quad (15)$$

To satisfy the reaching condition, the equivalent control $u_{eq}(t)$ given in Eq. (13) is augmented by a hitting control term $u_{sw}(t)$ to be determined. Consider the system given by Eq. (6) with uncertainties and disturbances and the sliding mode controller is designed such that

$$u(t) = u_{eq}(t) + u_{sw}(t) \quad (16)$$

The argument “t” is omitted in the rest of this section for simplicity. To obtain the hitting control signal u_{sw} , Eq. (15) is rewritten to cover uncertainties and disturbances as

$$s\dot{s} = s(k_1 \dot{e} + k_2 e + k_3 \ddot{e})$$

$$s\dot{s} = s\{k_1 \dot{e} + k_2 e + k_3 A \dot{\omega}_r + k_3 \Delta A \dot{\omega}_m + k_3 B \omega_m + k_3 \Delta B \omega_m + k_3 F - s k_3 (C + \Delta C) \times [(k_3 C)^{-1} (k_1 \dot{e} + k_2 e + k_3 \ddot{\omega}_r + k_3 A \dot{\omega}_m + k_3 B \omega_m) + u_{sw}]\} \quad (17)$$

Simplifying above eq.

$$s\dot{s} = s\{k_3 [(\Delta A - C^{-1} A \Delta C) \dot{\omega}_m + (\Delta B - C^{-1} B \Delta C) \omega_m + F] - C^{-1} \Delta C (k_1 \dot{e} + k_2 e + k_3 \ddot{\omega}_r)\} - s k_3 (C + \Delta C) u_{sw} \leq |s| \{k_3 [|\Delta A - C^{-1} A \Delta C| + |(\Delta B - C^{-1} B \Delta C)| |\omega_m| + |F|] + |C^{-1} \Delta C| (k_1 |\dot{e}| + k_2 |e| + k_3 |\ddot{\omega}_r|)\} - s k_3 (C + \Delta C) u_{sw} < 0 \quad (18)$$

To ensure Eq. (18) is less than zero, the hitting control should be selected as

$$u_{sw} = \text{sgn}(s) [k_3 (C + \Delta C)]^{-1} [X_1 |\dot{\omega}_m| + X_2 |\omega_m| + k_3 |F| + X_3 |\dot{e}| + k_2 |e| + k_3 |\ddot{\omega}_r|] \quad (19)$$

Obviously, substituting Eq. (19) into Eq. (18)

we can find that $\dot{V}(t) < 0$, i.e., the hitting control actually achieves a stable sliding mode control system. However, a serious problem in Eq. (19) is that the hitting control is large for most of cases. Furthermore, the sign of u_{sw} is changed while the trajectories cross the sliding surface so that a heavily chattering phenomenon arises, and this large hitting control causes high-frequency unmodeled dynamics. In practical applications, the presence of the sign function in the control law generates strong communications, which could hurt seriously the actuator and the direct application on the system of such a control is not convenient. Therefore minimizing the hitting control should be considered in implementations. In addition, knowledge of the bounds of each uncertainty, ΔA , ΔB , and ΔC , and external load disturbance, nonlinear friction, and unmodeled dynamics, $F(t)$ in the model is needed.

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This is not always possible in practical applications, especially for complex and open-loop unstable control systems.

The continuous sliding mode control has been selected commonly in SMC problems to avoid chattering of the control force and to achieve the exponential stability. A thin boundary layer can be introduced around the sliding surface for the hitting control to be

$$u_{sw} = k \text{sat} \left(\frac{s}{\Omega} \right) \tag{20}$$

where k and Ω are positive constants.

The system robustness is a function of the width of the boundary layer. A variation of the above hitting control is to use a hyperbolic tangent function instead of a saturation function to improve the hitting control effort and it is given as

$$u_{sw} = k \tanh \left(\frac{s}{\Omega} \right) \tag{21}$$

IV. EXPERIMENTAL SET-UP AND PRELIMINARIES

Control diagram of the experimental set-up is shown in Fig. 3

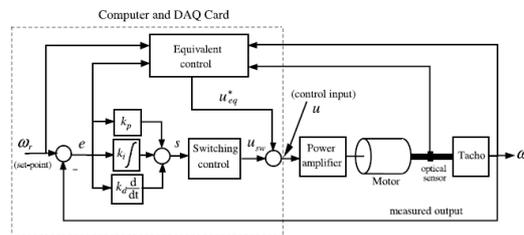


Fig. 3 Experimental Diagram of Sliding Mode control

such that the plant, a dc motor connected to a load via a long shaft, is used in experiments, ω_r is the command signal, ω_l is the output measured shaft speed in radians per second and u is the control input (or armature voltage). A computer (Pentium IV, 2.8 GHz in speed, 1.24 GB RAM) is used to implement the proposed second order sliding mode controller. Output shaft speed is measured from an optical sensor (as rev/sec) and a tachogenerator (as volts) connected to the motor shaft. The slotted opto-sensor consists of a gallium-arsenide infra-red L.E.D and a silicon photo transistor mounted in a special plastic case which is transparent to light of the wavelength. A series of pulses is generated when the slotted disk, which is mounted on the motor shaft, is rotated. When the shaft of the dc motor is turned, a voltage is induced at the tachogenerator terminals and it is directly proportional to the shaft speed. The dc motor operates with a maximum output shaft speed of 2400 rpm. The motor also drives a shaft that carries disks that operate various transducers, and a tachogenerator. A low pass filter, with a corner frequency of 250 rad/s, is used to filter the output speed signal from high frequency noise components. Speed of the dc motor corresponding to the different input armature voltages is measured to obtain the tachogenerator characteristics. It is determined that the tachogenerator has linear characteristics and gain of the tachogenerator is calculated as 2.15 V/rad/s. A data acquisition card (DAQ-Advantech, Model: PCI-1716, 250 kHz in speed and 0.03% of accuracy, 16 bit) is used to communicate between the plant and the computer. Operating range of the card is 10 V for input data and control outputs. Control input is the motor armature voltage that is limited to be minimum of -10 V and maximum of +10 V. The proposed second-order sliding mode controller is implemented in Simulink of Matlab software.

The produced control input (armature voltage) is sent to the power amplifier. The sampling period is taken to be 3 ms for all

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experimental tests. It is known that mathematical model of a plant based on physical laws describes dynamic behaviors. However, parameters in the mathematical model of a plant cannot be obtained precisely. Therefore, as a preliminary work, the present plant should be tested to calculate nominal plant parameters, A_n , B_n and C_n . This process is needed before the closed-loop operation is allowed. First-order plus dead-time model is one of the effective model types to approximate real plants, if the open-loop response to an applied deterministic signal does not possess any overshoot. The approximate plant model in transfer function form, based on the process reaction curve method, can be given

$$G(s) \cong \frac{Ke^{-T_d s}}{T_s + 1} \cong \frac{K}{(1 + T_d s)(1 + T_s s)} \quad (22)$$

where K , T_d and T are the steady-state gain, time delay and time constant, respectively. These should be obtained using the experimental test results.

V. EXPERIMENTAL RESULTS

Some experimental results are provided here to demonstrate the effectiveness of the proposed sliding mode controller. The speed responses and the associated control efforts for the proposed controller and conventional PID controller for a step command (0–1500-rpm speed change) are illustrated in Fig 4. The performance of the proposed sliding mode controller is much better than that achieved by the conventional PID control such that no overshoot, smaller rise time, and smaller settling time in magnitude were obtained from the proposed controller.

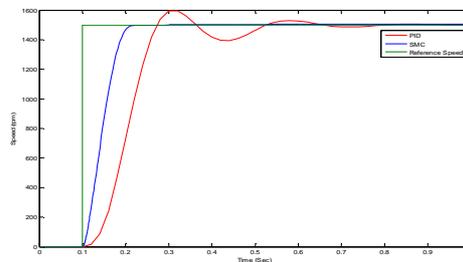


Fig. 4 Responses to a step command speed change(0-1500-rpm speed change)

To test the tracking of the system, a square wave command trajectory that corresponds to 1500 ± 53.34 rpm is applied to the system and the On the other hand, conventional PID controller did not meet the needs of precise control, since these resulted in large overshoots and settling times in magnitude. The variations of the control efforts were shown in Fig. 6 such that the sliding mode control effort is smaller in magnitude responses are shown in Figs. 5-6, for the sliding mode PID controller, respectively.

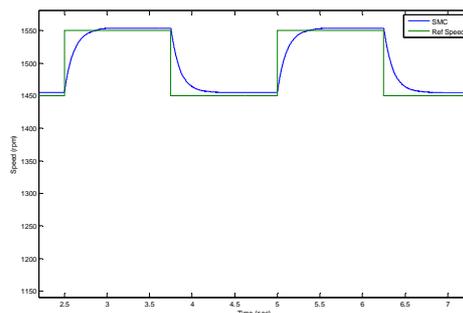


Fig. 5 command tracking with the sliding mode control

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Vol. 5, Issue 6, June 2016

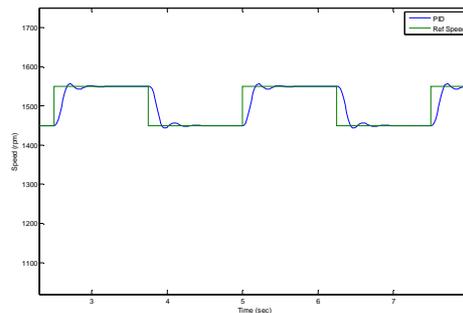


Fig. 6 Command tracking with PID controller

These figures confirm the fact that the system with the sliding mode controller has a better tracking performance than the system with PID controller.

VI. CONCLUSION

In this study, a sliding mode control with PID sliding surface has been adopted to control the speed of a computer-controlled electromechanical plant while the nominal system is assumed to be known. An approximated second-order plant model is used in the present design, since many of the industrial plants can be modeled using a second-order model. The practical application is associated with the sliding mode controller as a computational-intelligence approach to the engineering problems. Experimental application was carried out to test the effectiveness of the present sliding mode controller. From the experimental results the proposed sliding mode controller is more suitable to be applied to control the dc motor speed due to the uncertain handling capabilities and disturbance rejection of the SMC design method. In order to avoid the chattering phenomena, a hyperbolic function has been used. The proposed controller ensures the invariance property against parameter uncertainties, compared with traditional PID controller, without sacrificing the tracking accuracy. The closed-loop system is in the sliding mode at all times and the tracking error converges to zero exponentially under the existence of parameter uncertainties and disturbances. The closed-loop system has been shown to be globally exponentially stable in the sense of Lyapunov theorem.

The control performance of the electromechanical plant was significantly improved with the present sliding mode controller compared with the conventional PID control. Experimental results also confirm the fact that the sliding mode controllers are reasonable candidates to use in industrial applications and these can be considered to be an alternative to usual PID controllers, since it is simple to use and easy to understand with its straightforward solution algorithm, and the computational task is not a problem many more because of high-speed computers and application tools to use in industrial applications.

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ISSN(Online): 2319-8753
ISSN (Print): 2347-6710

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