

# Repetitive Sliding Mode Control for Nondecouplable Multivariable Systems: Periodic Disturbances Rejection

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**Abstract**—Disturbances rejection is an important field of control theory. In this context, our paper is proposed to deal with asymptotic rejection of periodic disturbances affecting discrete multivariable systems with an interactor matrix. A multivariable repetitive sliding mode control is proposed to cancel the disturbances when the system is nondecouplable. To synthesis this control an interactor matrix is used. A numerical example shows that the proposed strategy gives good performance in terms of rejecting periodic disturbances for nondecouplable multivariable systems.

**Index Terms**—Multivariable control systems, Interactor matrix, Sliding mode control, Repetitive control, Rejection of periodic disturbances.

## I. INTRODUCTION

The problem of rejecting periodic disturbances appears in a variety of industrial processes such as rotating machine tools, optical and magnetic disk drives and robots, etc. In the literature, there are several main approaches dealing with periodic disturbance cancellation. The most common approach is based on the internal model principle (IMP) [1] which consists in simply incorporating the poles of the disturbance model into the regulator pole configuration. Another approach is the adaptive feedforward cancellation method (AFC) [2] where a disturbance at the input of the plant can be canceled by constantly adding the negative of its value. Other researchers have proposed different approaches to deal with periodic disturbances such as repetitive control (RC) [3], [4], iterative learning control (ILC) [5], [6], [7] and Q-parametrization [8].

Many of industrial processes suffering of periodic disturbances are multivariable such as: airplane, helicopter, robotic system, mechanical and electrical systems. The design of a robust control for MIMO systems is very difficult due to the coupling problem between inputs and outputs, to the nonlinearity of the dynamics, to the uncertainty of the parameters and/or to the presence of external disturbances. Multivariable linear systems are characterized by an interactor matrix which is a generalization of the delay structure of single input-single output systems. The interactor matrix has a lower triangular polynomial matrix form.

Many methods are developed to determine the interactor matrix which plays an important role in multivariable control

[9], [10], [11]. In [12] the authors present a procedure based on the Markov parameters of the system to estimate the interactor matrix. An alternative algorithm to estimate the interactor matrix was proposed by Kase [13]. An idea for overcoming periodic disturbances involves appealing to sliding mode control.

Sliding mode control (SMC) is a robust nonlinear control which was firstly studied in the Soviet Union [14], [15]. This approach was used in many different fields of applications due to its robustness and invariance properties to matched uncertainties [16]. The main idea behind SMC is to drive state trajectories towards desired sliding surface in finite time and maintain them on it.

Faced with the development of computer and applications of digital control, discrete sliding mode control (DSMC) has become more important in academia and industries. However, the DSMC does not possess the same properties as continuous sliding mode control. Indeed, the presence of periodic disturbances can easily affect and degrade the performance of the system. To improve control performance, several techniques based on the combination of SMC with a feedforward control (such as internal model control (IMC) [17], [18], RC [19], [20] and iterative learning control [21], [22], etc.) has been proposed. For discrete multivariable systems without an interactor matrix, we have proposed the use of a repetitive sliding mode control to reject periodic disturbances [23], [24].

This work proposes a new sliding mode control for discrete time multivariable systems with an interactor matrix subjected to periodic disturbances. This approach is designed to force the system to track the reference trajectories and to reject periodic disturbances.

This paper is organized as follows. Section II describes the classical discrete sliding mode control for nondecouplable multivariable systems. Section III presents a new discrete repetitive sliding mode control for multivariable systems with an interactor matrix. Simulation results are given in section IV. Then, we finish with a conclusion.

## II. DISCRETE SLIDING MODE CONTROL FOR NONDECOUPLABLE MULTIVARIABLE SYSTEMS

Consider a class of multi-input multi-output (MIMO) discrete-time system described by the following model:

$$A(q^{-1})Y(k) = B(q^{-1})U(k-1) + V(k) \quad (1)$$

where  $Y(k)$ ,  $U(k)$  and  $V(k)$  are respectively the output, input and disturbances vectors:

$$Y(k) = [y_1(k) \quad \dots \quad y_p(k)]^T$$

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$$U(k) = [u_1(k) \quad \dots \quad u_p(k)]^T$$

$$V(k) = [v_1(k) \quad \dots \quad v_p(k)]^T$$

$A(q^{-1})$  and  $B(q^{-1})$  are two polynomial matrices defined as follows:

$$\begin{cases} A(q^{-1}) = I_p + A_1q^{-1} + A_2q^{-2} + \dots + A_{n_A}q^{-n_A}; \\ \dim A_{\tau_1} = (p, p); \tau_1 \in [1, n_A] \\ B(q^{-1}) = B_0 + B_1q^{-1} + B_2q^{-2} + \dots + B_{n_B}q^{-n_B}; \\ \dim B_{\tau_2} = (p, p); \tau_2 \in [0, n_B] \end{cases}$$

The model described by (1) can be written as follows:

$$Y(k) = A^{-1}(q^{-1})B^*(q^{-1})U(k) + A^{-1}(q^{-1})V(k) \quad (2)$$

where

$$B^*(q^{-1}) = q^{-1}B(q^{-1}) = B_0q^{-1} + B_1q^{-2} + \dots + B_{n_B}q^{-n_B-1}$$

The transfer matrix of the multivariable system is then defined by:

$$T(q^{-1}) = A^{-1}(q^{-1})B^*(q^{-1}) \quad (3)$$

Suppose that the transfer matrix is strictly proper and full rank [25], there exists a  $p \times p$  polynomial matrix,  $\xi(q)$ , which satisfies the following equation:

$$\lim_{q \rightarrow \infty} \xi(q)T(q^{-1}) = K \quad (4)$$

The polynomial matrix  $\xi(q)$  is called an interactor matrix of  $T(q^{-1})$ .  $K$  is a full rank matrix. If  $K = I_p$ ,  $\xi(q)$  is called an identity interactor.

In the general case, the interactor matrix is a lower triangular matrix:

$$\xi(q) = (I_p - H(q))D(q) \quad (5)$$

where:

$$D(q) = \begin{bmatrix} q^{f_1} & 0 & \dots & 0 \\ 0 & q^{f_2} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & q^{f_p} \end{bmatrix}$$

$f_i \geq d_i = \min_{1 \leq j \leq p} \{d_{ij}\}$ .  $d_{ij}$  is the delay between the  $j$ -th input and the  $i$ -th output.

The matrix  $H(q)$  has the following form:

$$H(q) = H_1q + \dots + H_vq^v$$

with  $v \leq f$ , and  $f = \sum_{i=1}^p f_i$

$H_i, 1 \leq i \leq v$  are a lower triangular matrices which diagonal elements are zero.

Suppose

$$d = \max_{1 \leq i \leq p} \{f_i\} + v$$

then, the interactor matrix can be written as follows:

$$\xi(q) = \sum_{i=1}^d \xi_i q^i$$

$d$  is the maximum degree of  $\xi(q)$ .

**Remark:** If  $\xi(q) = q^d I_p$ , the multivariable system is decouplable and it is mainly studied in [23].

The tracking error vector  $E(k)$  is defined as:

$$E(k) = Y(k) - Y_r(k) = [e_1(k) \quad \dots \quad e_p(k)]^T$$

where  $Y_r(k)$  is the desired trajectory to be tracked.

In the case of a nondecouplable multivariable system, the sliding functions vector is chosen in this form [26]:

$$S(k+d) = C(q^{-1})\xi(q)E(k) = [s_1(k) \quad \dots \quad s_p(k)]^T \quad (6)$$

taking account the interactor matrix.

where  $C(q^{-1})$  is a polynomial matrix defined as follows:

$$C(q^{-1}) = I_p + C_1q^{-1} + C_2q^{-2} + \dots + C_{n_C}q^{-n_C};$$

$$\dim C_{\tau_3} = (p, p); \tau_3 \in [1, n_C]$$

The sliding surface vector is defined by:

$$S(k) = 0 \quad (7)$$

Consider  $M(q)$  and  $R(q^{-1})$  the two polynomial matrices solutions of the diophantine polynomial matrix equation:

$$C(q^{-1})\xi(q) = M(q)\Delta(q^{-1})A(q^{-1}) + R(q^{-1}) \quad (8)$$

where:

$$\begin{cases} M(q) = M_1q + M_2q^2 + \dots + M_dq^d \\ R(q^{-1}) = R_0 + R_1q^{-1} + \dots + R_{n_R}q^{-n_R} \\ \dim R_{\tau_4} = (p, p); \tau_4 \in [0, n_R]; n_R = n_A \end{cases}$$

with  $\Delta(q^{-1}) = (1 - q^{-1})I_p$  is a differential operator.

Suppose:

$$G(q^{-1}) = M(q)B^*(q^{-1}) = G_0 + G_1q^{-1} + \dots + G_{n_B-1}q^{-(n_B)}$$

The equivalent control law is obtained for:

$$S(k+d+1) = 0 \quad (9)$$

Using the last equation and the equations (2), (6) and (8), we obtain:

$$S(k+d+1) = G(q^{-1})\Delta(q^{-1})U(k+1) + R(q^{-1})Y(k+1) + M(q)\Delta(q^{-1})V(k+1) - C(q^{-1})\xi(q)Y_r(k+1) = 0$$

To obtain the equivalent control, we suppose that the external disturbances are null:

$$\Delta(q^{-1})V(k) = 0$$

Then, the equivalent control law can be calculated as :

$$U(k) = U(k-1) - (G(q^{-1}))^{-1}R(q^{-1})Y(k) + (G(q^{-1}))^{-1}C(q^{-1})\xi(q)Y_r(k)$$

The robustness is ensured by the addition of a discontinuous term and the sliding mode control for nondecouplable multivariable systems can be expressed as:

$$U(k) = U(k-1) - (G(q^{-1}))^{-1}R(q^{-1})Y(k) + (G(q^{-1}))^{-1}C(q^{-1})\xi(q)Y_r(k) - \begin{bmatrix} m_1 \text{sign}(s_1(k)) \\ \vdots \\ m_p \text{sign}(s_p(k)) \end{bmatrix} \quad (10)$$

with sign is defined as:

$$\text{sign}(s_i(k)) = \begin{cases} -1 & \text{if } s_i(k) < 0 \\ 1 & \text{if } s_i(k) > 0 \end{cases}; \quad i \in [1 \ p]$$

This control law can reject the constant disturbances. However, in practice the disturbances may be periodic. To reduce the effect of periodic disturbances, we propose a discrete repetitive sliding mode control for a multivariable systems with an interactor matrix.

### III. DISCRETE REPETITIVE SLIDING MODE CONTROL FOR MULTIVARIABLE SYSTEMS WITH AN INTERACTOR MATRIX

Generally, the classical discrete sliding mode control is a robust control with respect to certain class of non stationarity and disturbances. However, there are many systems which are affected by a periodic disturbances. These disturbances might excite unmodeled dynamics and involve instability. Thus, the system performance cannot be ensured and the use of this method would not be considered acceptable for nondecouplable multivariable systems subject to harmonic disturbances.

To overcome this problem, a new repetitive sliding mode control for nondecouplable multivariable systems is proposed.

The basic idea consists to incorporate the periodic disturbances internal model formulation into the control law.

The components  $v_i(k)$ ,  $i \in [1, p]$  of the disturbances vector  $V(k)$  are assumed to be periodic with the period  $N$ :

$$v_i(k) = v_i(k-N), \quad i \in [1, p] \quad (11)$$

To reject periodic disturbances for multivariable systems with an interactor matrix, a new discrete sliding mode control is developed. To obtain this control, we propose to modify the diophantine polynomial matrix equation by including repetitive properties.

Consider  $L(q)$  and  $P(q^{-1})$  the two polynomial matrices solutions of the new diophantine polynomial matrix equation:

$$C(q^{-1})\xi(q) = L(q)\Delta_R(q^{-1})A(q^{-1}) + P(q^{-1}) \quad (12)$$

where:

$$\begin{cases} L(q) = L_1q + L_2q^2 + \dots + L_dq^d \\ P(q^{-1}) = P_0 + P_1q^{-1} + \dots + P_{n_p}q^{-n_p} \\ \dim P_{\tau_5} = (p, p); \tau_5 \in [0, n_p]; n_p = n_A + N - 1 \end{cases}$$

$\Delta_R(q^{-1}) = (1 - q^{-N})I_p$  is a repetitive operator.

Suppose:

$$Q(q^{-1}) = L(q)B^*(q^{-1}) = Q_0 + Q_1q^{-1} + \dots + Q_{n_B-1}q^{-(n_B)}$$

The equivalent control law is obtained for:

$$S(k+d+1) = 0 \quad (13)$$

By using the equations (2), (6), (12) and (13), the sliding function vector at the instant  $k+d+1$  can be calculated as:

$$S(k+d+1) = Q(q^{-1})\Delta_R(q^{-1})U(k+1) + P(q^{-1})Y(k+1) + L(q)\Delta_R(q^{-1})V(k+1) - C(q^{-1})\xi(q)Y_r(k+1) = 0$$

Or, the disturbances  $V(k)$  are periodic with the period  $N$ :

$$\Delta_R(q^{-1})V(k+1) = 0$$

Then, the equivalent control law can be written as:

$$U(k) = U(k-N) - (Q(q^{-1}))^{-1}P(q^{-1})Y(k) + (Q(q^{-1}))^{-1}C(q^{-1})\xi(q)Y_r(k)$$

Robustness is ensured by the addition of a discontinuous term. Then, the repetitive sliding mode control for nondecouplable multivariable systems is defined as:

$$U(k) = U(k-N) - (Q(q^{-1}))^{-1}P(q^{-1})Y(k) + (Q(q^{-1}))^{-1}C(q^{-1})\xi(q)Y_r(k) - \begin{bmatrix} m_1 \text{sign}(s_1(k)) \\ \vdots \\ m_p \text{sign}(s_p(k)) \end{bmatrix} \quad (14)$$

### IV. SIMULATION EXAMPLE

Consider a multivariable system described as follows:

$$A(q^{-1})Y(k) = B(q^{-1})U(k) + V(k)$$

with:

$$\begin{cases} A(q^{-1}) = I_2 + A_1q^{-1} + A_2q^{-2} \\ B(q^{-1}) = B_1q^{-1} + B_2q^{-2} \end{cases}$$

and

$$A_1 = I_2; \quad A_2 = I_2 \\ B_1 = \begin{pmatrix} 1 & 1 \\ 2 & 2 \end{pmatrix}; \quad B_2 = \begin{pmatrix} 0.5 & 0.5 \\ 0 & 1 \end{pmatrix}$$

$$Y(k) = \begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix}; \quad U(k) = \begin{bmatrix} u_1(k) \\ u_2(k) \end{bmatrix};$$

$$Y_r(k) = \begin{bmatrix} y_{r1}(k) \\ y_{r2}(k) \end{bmatrix}; \quad V(k) = \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}$$

The polynomial matrix  $C(q^{-1})$  is chosen as:

$$C(q^{-1}) = I_2 + I_2q^{-1} + 0.25I_2q^{-2}$$

The interactor matrix is:

$$\xi(q) = \begin{bmatrix} 1 & 0 \\ -2q & 1 \end{bmatrix} \begin{bmatrix} q & 0 \\ 0 & q^2 \end{bmatrix}$$

We suppose that the disturbances are given by:

$$\begin{cases} v_1(k) = 0.2 \\ v_2(k) = 0.25 \end{cases}; \quad k \leq 200$$

and

$$\begin{cases} v_1(k) = 0.2 + 0.4 \sin\left(\frac{2\pi k}{N}\right) + 0.25 \cos\left(\frac{2\pi k}{N}\right) \\ v_2(k) = 0.25 + 0.7 \sin\left(\frac{2\pi k}{N}\right) + 0.3 \cos\left(\frac{2\pi k}{N}\right) \end{cases}; \quad k > 200$$

with  $N = 10$ .

The desired trajectories are defined as follows:

$$A_r(q^{-1})Y_r(k) = B_r(q^{-1})U_r(k-1) \\ \begin{cases} A_r(q^{-1}) = I_p + A_{r1}q^{-1} + A_{r2}q^{-2} \\ B_r(q^{-1}) = B_{r0} \\ A_{r1} = -I_p; A_{r2} = 0.05I_p; B_{r0} = 0.25I_p \end{cases}$$

The retained synthesis parameters are:

$$m_1 = m_2 = 0.001$$

The evolution of disturbances  $v_1(k)$  and  $v_2(k)$  is given in Fig. 1.

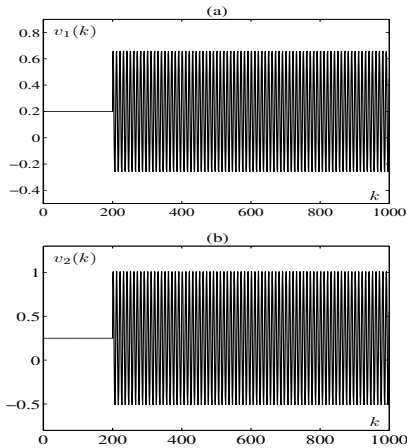


Fig. 1. (a). The evolution of the disturbance  $v_1(k)$ . -(b). The evolution of the disturbance  $v_2(k)$ .

The simulation results of the classical multivariable sliding mode control scheme are shown in Fig. 2, Fig. 3 and Fig. 4. Fig. 2 shows the evolutions of the desired reference trajectories  $Y_r(k)$  and the outputs of the system  $Y(k)$ . Fig. 3 presents the evolutions of the controller  $U(k)$ . The evolution of the sliding surfaces is presented in Fig. 4.

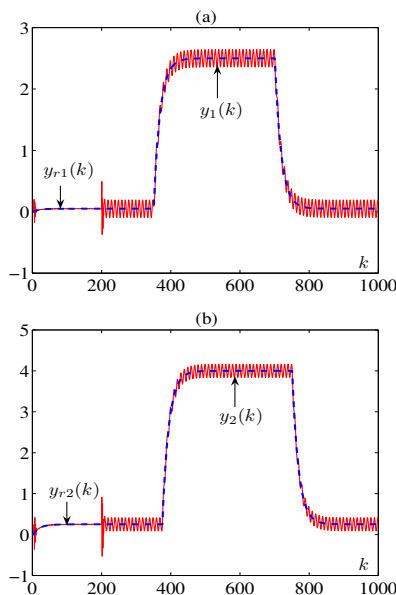


Fig. 2. (a). The evolutions of the desired reference trajectory  $y_{r1}(k)$  and the output system  $y_1(k)$ . -(b). The evolutions of the desired reference trajectory  $y_{r2}(k)$  and the output system  $y_2(k)$ .

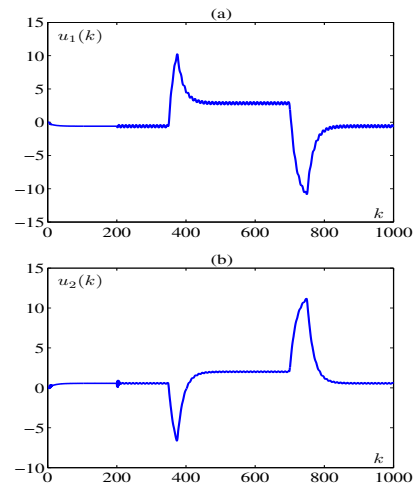


Fig. 3. (a). The evolution of the control  $u_1(k)$ . -(b). The evolution of the control  $u_2(k)$ .

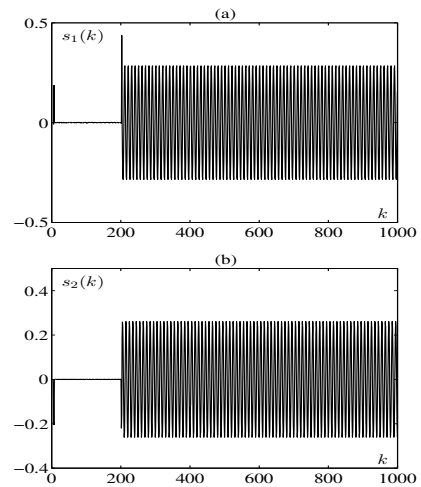


Fig. 4. (a). The evolution of the sliding function  $s_1(k)$ . -(b). The evolution of the sliding function  $s_2(k)$ .

These figures prove that the considered control law can reject perfectly the constant disturbances (for  $k \leq 200$ ) and force the outputs to track the reference trajectories. For  $k > 200$ , it can be seen, that the considered control signals are not able to reject periodic disturbances. In fact, the outputs  $y_1(k)$  and  $y_2(k)$  track the reference trajectories  $y_{r1}(k)$  and  $y_{r2}(k)$  with periodic errors.

To ameliorate the performances in term of rejecting periodic disturbances, we use the proposed control law (equation (14)).

Fig. 5, Fig. 6 and Fig. 7 illustrate respectively the evolutions of the outputs  $y_1(k)$  and  $y_2(k)$ , the inputs  $u_1(k)$  and  $u_2(k)$  and the sliding functions  $s_1(k)$  and  $s_2(k)$ . It can be seen that the inputs become periodic to cancel the considered disturbances. Then, the application of the new strategy for nondecouplable multivariable systems with periodic disturbances gives a very satisfactory performances in terms of tracking reference trajectories and rejecting periodic distur-

bances compared with the use of the classical discrete sliding mode control.

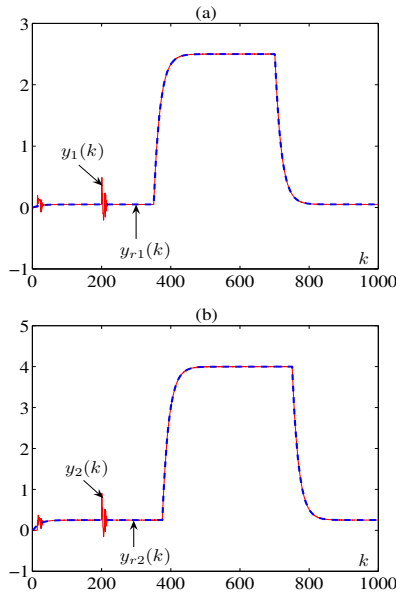


Fig. 5. (a). The evolutions of the desired reference trajectory  $y_{r1}(k)$  and the output system  $y_1(k)$ . -(b). The evolutions of the desired reference trajectory  $y_{r2}(k)$  and the output system  $y_2(k)$ .

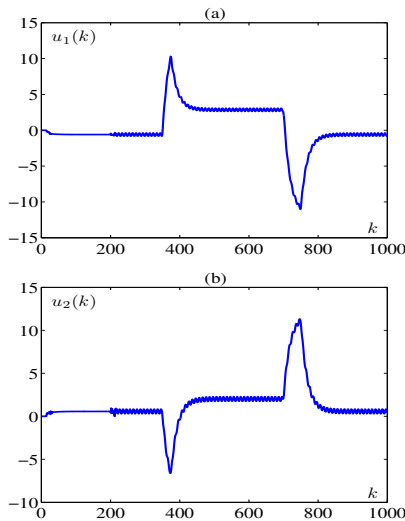


Fig. 6. (a). The evolution of the control  $u_1(k)$ . -(b). The evolution of the control  $u_2(k)$ .

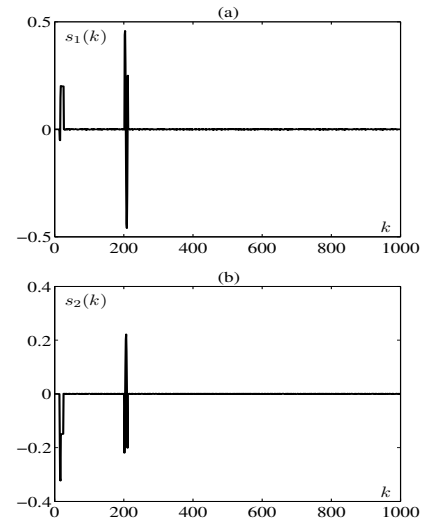


Fig. 7. (a). The evolution of the sliding function  $s_1(k)$ . -(b). The evolution of the sliding function  $s_2(k)$ .

## V. CONCLUSION

This paper deals with control and rejection of periodic disturbances problems for discrete nondecouplable multivariable systems. We have proposed a multivariable repetitive sliding mode control. The sliding function vector depends on the interactor matrix. The proposed control is based on the resolution of a new diophantine matrix equation. This new equation incorporate a repetitive operator which is able to cancel the periodic disturbances. The obtained simulation results show a perfect tracking of reference trajectories and a good rejection of periodic disturbances for nondecouplable multivariable systems in spite of the presence of periodic disturbances.

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