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Indirect Periodic Disturbance Compensator using Feedforward Control for Image Noises

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Abstract

This paper introduces a periodic disturbance compensator that uses feedforward control to reduce noise indirectly in the system. This technology reduces the influence of periodic disturbances in a multi-input system by applying a different physical quantity input to a different source from that of the disturbance source. The control object is modeled to compensate for the periodic disturbances caused by the noise source by applying a different physical quantity. The control signal is generated from the aforementioned model and measurement results of the influence of the disturbance, and it is input to the different source on a feedforward basis. We applied our proposed periodic disturbance compensator for the electrophotographic process (EP), thereby determining that the periodic disturbance (image noise) caused by eccentric rotation is effectively reduced by modulating the laser power without correction for the noise source.

Introduction

Periodic disturbances cause many problems such as sympathetic vibration, sound noise, and oscillation in products that consist of a drive mechanism. This noise must be suppressed to raise the product quality. Generally, the part accuracy in the drive mechanism is responsible for the majority of noise. Such noise can be reduced by improving the accuracy; however, this is very expensive.

Various disturbance compensators have been developed to solve these problems. Active noise control (ANC) is a well known compensator that reduces the disturbances (audio noise) in real time and is widely used to reduce audio noise in audio devices [1], [2], [3]. It cancels audio noise by using the antiphase sound signal from an audio source. This disturbance compensator technology is applied not only to acoustic engineering but also to vibration suppression in mechanical engineering. In an optical disc drive system, for example, the motion of the optical pickup is controlled to reduce the influence of eccentric rotation of the optical disc [4], [5]. Another disturbance compensator technology, adaptive feedforward cancellation (AFC), is also used to reduce the occurrence of periodic disturbances [6], [7]. The AFC technology reduces the periodic disturbances added after the output of the control object by adding the control signal to the output of the feedback controller, which is determined by estimating the gain and phase of the periodic disturbances using an adaptable algorithm.

As just described, in the general disturbance compensator including ANC, the control signal is designed as an antiphase signal of a disturbance source enabling disturbances to be cancelled, and it is applied directly to the disturbance source in the same physical quantity shown in Figure 1 (e.g., sound disturbances are compensated by sound, and position disturbances are compensated by position). To apply the ANC to the electrophotographic process (EP) to reduce image disturbances (image noise), we need to move the rotators to cancel the fluctuation in the developing gap; however, the moments of inertia in the rotators are too large to respond sufficiently.

Because of this situation, new control technology needs to be developed to improve the product quality by reducing the number of disturbances without increasing cost. Therefore, we developed a control technology to reduce the image density unevenness by applying control signals of different physical quantities from the disturbance source [8]. A previous report stated that periodic fluctuations in the developing electric field caused by rotational inaccuracy of the photoconductor drum and development roller are controlled using the modulation of the developing bias and charging bias instead of adjusting the distance of the developing gap. The developing bias and charging bias are input to stabilize the electric field on a feedforward basis. This method enables reducing the periodic image density unevenness caused by periodic disturbances (fluctuations) in the photoconductor drum and development roller.

In this paper, we report on our extension of the control technology in the previous report done by extracting it so that it can be applied to a general system. Also, we applied the proposed technology for the EP, determining that the periodic disturbances (image noise) caused by rotational inaccuracy of the photoconductor drum were improved effectively by modulating the laser power without correction for the noise source.

Indirect Periodic Disturbance Compensator

The control signal in the previous disturbance compensator adjusts for the influence of the periodic disturbances by applying the disturbance source directly in the same physical quantity. In contrast, the proposed periodic disturbance compensator indirectly adjusts for the periodic disturbances by applying a different physical quantity.

Figure 2 shows a conceptual diagram of the proposed periodic disturbance compensator. We applied this technology considering multiple-input and single-output systems (n input). In this system, $u_{1\text{-}n}$ is the input, u_d is the control signal from the controller, the physical quantities of u_1 and u_n are different from each other, and a periodic disturbance $d(t)$ is input to u_1 as shown in Equation 1.

$$d(t) = \sum D_j \cdot \sin(j \cdot \omega \cdot t + \varphi_j) \quad (1)$$

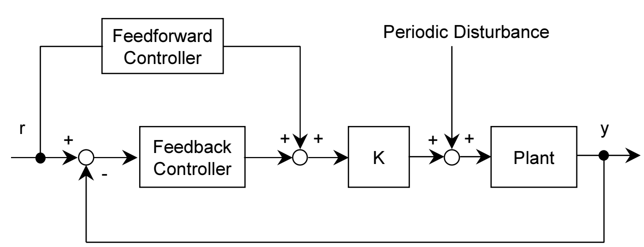

Figure 1. General control system for periodic disturbances

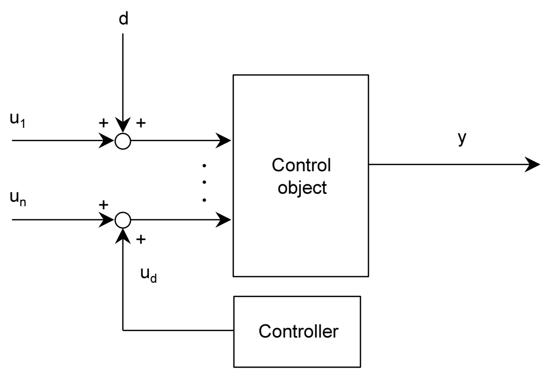

Figure 2. Conceptual diagram of the proposed periodic disturbance compensator

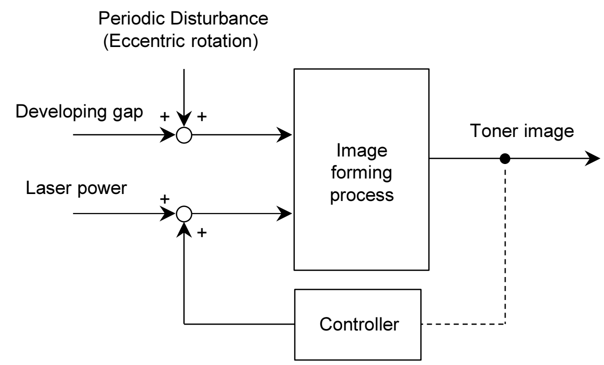

Figure 3. Conceptual diagram of the proposed periodic disturbance compensator applied to the EP

where D_j / φ_j are the amplitude and phase of disturbance, ω is the angular velocity of the disturbance, and j is the order. For simplicity, we assumed that the frequency source of the disturbance was one type and that all frequencies occurred at integer multiples of ω, however, the proposed technology can be applied even if the disturbance is composed of a plurality of frequencies.

In this case, the output y including the periodic disturbance $d(t)$ is expressed as

$$y(t) = \sum \alpha_j \cdot \sin(j \cdot \omega \cdot t + \phi_j) \tag{2}$$

where α_j / ϕ_j are the amplitude and phase of output. As shown in the Equation 2, y oscillates at a frequency equal to the periodic disturbance $j\omega$ due to the influence of the periodic disturbance from u_1.

When applying the general disturbance compensator to such a the system, the control signal u_d is input to u_1 to cancel disturbance $d(t)$. However, when the control signal u_d is limited because of actuator output and the like, we cannot obtain the control effect sufficiently. In such a case, a problem subject to actuator output restrictions often occurs in the mechatronics system.

Therefore, the control signal u_d in the proposed technology is input to un as shown in Equation 3 to cancel the periodic disturbance indirectly on a feedforward basis.

$$u_d(t) = \sum A_j \cdot \sin(j \cdot \omega \cdot t + \theta_j) \tag{3}$$

where A_j / θ_j are the amplitude and phase of control signal. The A_j / θ_j are calculated from pre-measured periodic disturbance $d(t)$ or output y, however, the model to convert the physical quantity is required to cancel the periodic disturbance $d(t)$ because the u_d has a different physical quantity from control signal u_1 to which the disturbance is input.

Therefore, assuming model Q from un to y, the influence of disturbance can be compensated by considering the inverse characteristic Q^{-1} of the model in the controller. Model Q may be created using a general method. According to this method, saturation of the control signal can be avoided by selecting an appropriate u_n, and we can improve the final output quality because the periodic disturbance occurring at u_1 can be indirectly compensated by converting it to another physical quantity.

Control Object

This paper describes the application of the proposed periodic disturbance compensator to the periodic image density unevenness in the EP system.

The periodic image density unevenness in the EP system is caused by the rotational inaccuracy of the photoconductor drum and development roller. The rotational inaccuracy cases the developing electric field to fluctuate, finally, unevenness in the periodic image density occurs. In this case of applying the general disturbance compensator to such an EP system, the control signal is input to the motors driving a photoconductor drum and a developing roller by using the actuator to cancel the periodic rotational inaccuracy. However, controlling them is difficult because the moments of inertia of the rotators are too large to respond. Thus, the periodic disturbances are suppressed by another means to improve the image density uniformity using control technology. In a previous report, we introduced a control technology that can improve the periodic image density unevenness in the EP by modulating the developing bias and charging bias. This paper describes an improvement in the unevenness in the periodic image density by modulating the laser power instead of the developing bias and charging bias.

Figure 3 shows a conceptual diagram of the proposed periodic disturbance compensator applied to the EP. For the image forming process as the control object, the developing gap and laser power are the input, and the toner image is the output. The rotational inaccuracy is input to the developing gap as the periodic disturbance. Actually, the plural parameters are input to the image forming process; however, here is a simplified description. In this study, we selected the laser power as the mean of the control signal to cancel the periodic disturbances. The control signal is generated using the model from laser power to toner image, and the toner image includes the influence of the periodic disturbances, which are extracted from the toner image pre-measured using the toner detection sensor, and compensates for the influence of the periodic disturbances by adding a control signal to the pre-determined laser power on a feedforward basis.

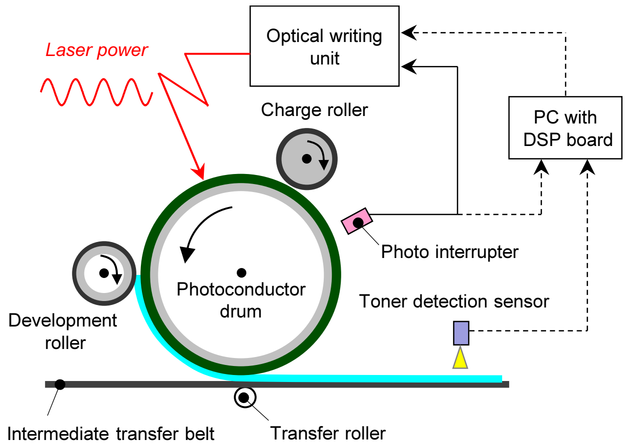

Figure 4. Configuration of experimental setup

Experimental Setup

Figure 4 shows the experimental setup, which consisted of a general image forming apparatus using a two-component development process. The setup included a photoconductor drum, development roller, charge roller, optical writing unit, toner detection sensor, transfer roller, and intermediate transfer belt. A photo interrupter and personal computer (PC) were added to it, as well. The photo interrupter was located close to the rotation axis of the photoconductor drum. The toner detection sensor was rotated above the intermediate transfer belt to detect the toner pattern. The PC recorded the outputs from the toner detection sensor and photo interrupter synchronously, and it calculated the control table. The control table was written in the storage area of the optical writing unit. The optical writing unit, which exposes a photoconductor drum on the basis of the image input, was handled by the control table. Thus, the laser power was modulated on the basis of the photo interrupter output and the control table in real time.

The sampling time in the measurement was 1 ms, and the laser power was modulated every scan. All measurements and controls were carried out on the basis of the photo interrupter output.

Modeling and Design of Controller

In this section, we introduce the method of creating a model and the design for a disturbance compensator. The proposed disturbance compensator obtains the influence of the disturbance by measuring the toner pattern. Therefore, the characteristics between the laser power and amount of toner adhesion need to be modeled.

The relationship between laser power and surface potential of the photoconductor drum was investigated to create the model of the laser power to toner adhesion amount. Figure 5 shows the experimental results of the relationship between laser power and surface potential, the x-axis represents the laser power, and the y-axis represents the toner adhesion amount on the intermediate transfer belt. This figure shows that the relationship between laser power and toner adhesion amount is linear. In this paper, this relationship is approximated using a linear equation as model Q and considered in the controller as inverse model Q^{-1}.

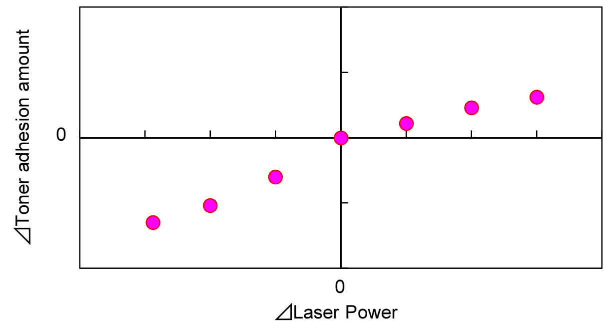

Figure 5. Characteristic between laser power and toner adhesion amount

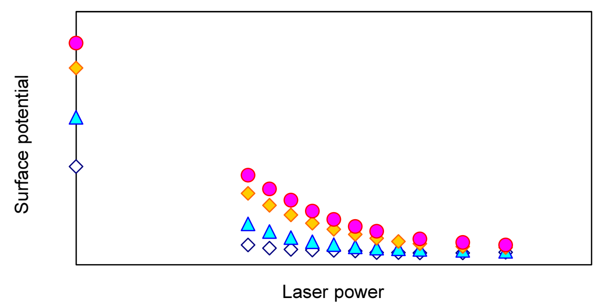

Figure 6. Relationship between laser power and surface potential

Additionally, laser power is influenced by a photo-induced discharge of the photoconductor drum and frequency characteristics. Thus, this paper also includes the aforementioned characteristics as part of our goal to improve the control accuracy. Figure 6 shows the photo-induced discharge (PIDC curve). In an actual experiment, the control signal was calculated by superimposing an appropriate gain according to the surface potential on the photoconductor drum, and periodic components of periodic disturbance based on these characteristics were extracted.

The control table $\Delta LDP(t)$ is determined systematically. First, the toner pattern was formed while supplying a constant developing bias and charging bias, and the toner pattern on the intermediate transfer belt was measured using a toner detection sensor. Next, a periodic component in the toner detection results was extracted using a Fourier transform and determined on the basis of the photo interrupter output to suppress the unevenness in the periodic image density, and it was approximated using a superposition of sine curves. Finally, the control signal $\Delta LDP(t)$ was calculated and expressed as

$$\Delta LDP(t) = \sum G_j \cdot \sin(j \cdot \omega \cdot t + P_j) \tag{2}$$

where G_j / P_j are the amplitude and phase of the laser power as the control signal, which was calculated from model Q and detected results of the toner pattern. The influence of the periodic disturbance was compensated by adding the $\Delta LDP(t)$ as the control signal on a feedforward basis calculated using the aforementioned procedure to the laser power in synchronization with the rotation of the photoconductor drum.

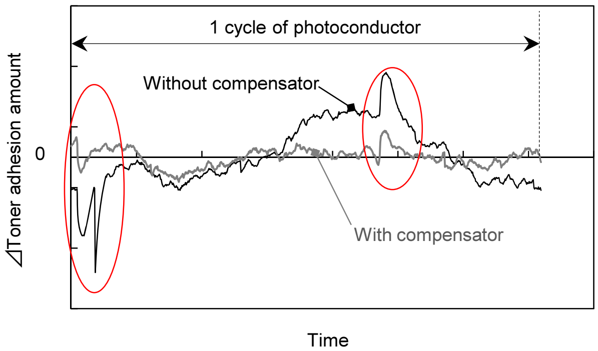

Figure 7. Comparison of control results with periodic disturbance

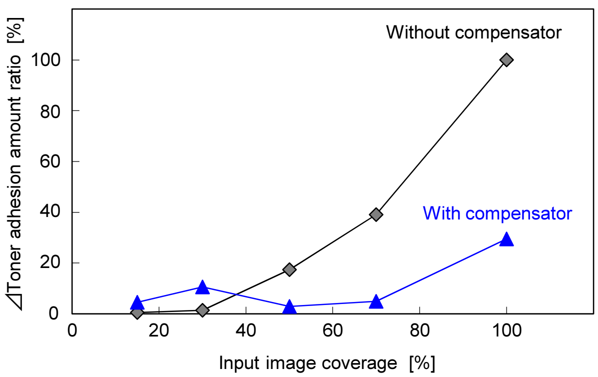

Figure 8. Experimental results under various levels of image coverage

Experimental Results

With our proposed compensator for reducing the periodic disturbance, the constant image forming parameters were determined using general process control. All the experiments were repeated several times to determine the measurement repeatability. Periodic image density unevenness was formed at 70% image coverage, evaluated using the toner detection sensor output. Also, j was chosen to be 3 to express the unevenness profile of the photoconductor drum.

Figure 7 shows a comparison of the control results for periodic disturbance. The image coverage is 70%, the x-axis represents the time, and the y-axis represents the amount of toner adhesion. In this figure, the toner adhesion was averaged using the photoconductor rotation period based on the output of the photo interrupter. The figure shows that the adhesion amount was effectively reduced when the compensator was used. Additionally, although sudden fluctuation occurred in a specific area (in the red circle), the proposed periodic disturbance compensator could effectively reduce such fluctuation, including the high frequency component.

Figure 8 shows a comparison of the experimental results under various levels of image coverage. The x-axis represents the input image coverage, and the y-axis represents the toner adhesion amount ratio extracted as the photoconductor rotation period. These results show that the compensator effectively adjusted for periodic image disturbances over a wide range of image coverage.

At a range under 30%, the toner adhesion amount increased with the compensator, but this had little or no impact on the visible image quality.

These results demonstrated that our proposed periodic disturbance compensator effectively and indirectly reduced the periodic fluctuations in the toner pattern by modulating the laser power without compensating for rotational inaccuracy.

Conclusions

In this paper, we described a periodic disturbance compensator that extends the previous noise reduction technology. This compensator indirectly adjusts for the influence of disturbances by inputting a control signal at a different physical quantity from the disturbance source and at a position different from the disturbance source on a feedforward basis.

We applied the proposed technology for the EP, determining that the periodic disturbances (image noise) caused by eccentric rotation was reduced by modulating the laser power effectively without any correction for the noise source.

This periodic compensator can be applied to various systems in which the previous noise reduction technology cannot be applied.

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Author Biography

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