Low noise drive methods for pulse motors in facsimile machines

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Experimental analyses of low noise driving mechanisms for pulse motors used for paper transport and cutter mechanisms in facsimile machines are presented in two parts. The first study focuses on the noise generation mechanism from one-way clutch gear used for torque transmission switching between document paper transport mechanisms and a recording paper cutter, called “chattering noise.” Unexpected movement of the clutch due to internal friction and subsequent collisions of the gears is found to be the cause for this type of noise. The chattering noise is controlled with a spring-friction damper placed between two clutch gears. The second study focuses on the noise generation mechanism observed for particular pulse intervals when the pulse motor for recording paper transport is driven with a double pulse train. It is found to be the rotational oscillation resonance noise from the pulse motors, and it can be controlled using proper double pulse combination timing.

Keywords: Pulse motor, Facsimile, Noise control, Noise generation mechanism, Experimental analyses

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1. INTRODUCTION

The number of facsimile machines in offices is rapidly increasing due to the recent development of consumer electronics for producing facsimile machines with expanded capability at considerably lower cost. However, facsimile machines with higher speed, lower cost, and/or smaller size may result in higher noise levels, if it is not controlled properly. New low noise driving mechanisms must therefore be developed.

The noise from the facsimile machines can be divided into two major types: the paper transport noise from pulse motors in the transmitter section and the printer noise in the receiver section. For the printer noise, paper sticking noise in thermal printers has been studied both theoretically and experimentally and control methods to minimize the noise of this type is well understood.1) Studies on the pulse motor characteristics have been published widely. Pickup et al.,2) and Lawrenson et al.,3) studied the control of resonance using electrical damping. Gotoh,4) Nishimura and Uryu,5) and Kojima et al.,6) analyzed dynamic characteristics of motor rotor shafts with single or double driving pulse inputs. Detailed theoretical studies are, however, difficult to perform due to the non-linearity of the equation of motion governing the rotor shaft.
dynamics, and the unsteadiness of the input pulse rate during facsimile machine operation. Experimental analysis is therefore widely used in this field of studies.

Studies presented here show experimental analyses of low noise driving mechanisms for pulse motors used for paper transport and cutter mechanisms in G3 class facsimile machines. Dynamic characteristics of the motor-gear-clutch system is investigated in detail in the first part.

Document paper is driven, in general, either with single or double pulses for reading one line, 0.13 mm wide in facsimiles. In the second part, noise generation mechanism and its control technique are described in detail for the case of double pulse driving. It was found that a particular timing between two adjacent pulses caused resonance noise of the motor. Noise of this type was controlled by careful choice of the time interval between the two pulses.

2. BASIC STRUCTURE OF FACSIMILE MACHINES

2.1 Structure of Facsimile Machines

Two basic functions of a facsimile machine are to transmit and receive graphical information of a document through telephone lines as shown in Fig. 1. The transmitter reads a document, line by line, with a photo sensor and converts the graphical information from the document into binary code, then encodes, modulates and finally sends it out through the telephone line. The receiver demodulates and decodes the received information from the telephone line and finally prints it out usually with a thermal printer on a recording paper. A schematic diagram of a facsimile machine is shown in Fig. 2. Paper transport mechanisms in a facsimile machine consist of various gears, belts and clutches with loose coupling, driven by pulse motors, giving a rather high possibility of generating annoying mechanical noise.

2.2 Paper Transport Mechanism in the Transmitter

The transmitter section consists of a document paper transport mechanism and an optical device for reading the document. The optical device reads the information on the document, line by line (one line is 0.13 mm wide) with a lens-mirror assembly and converts it to an electric signal using a Charge Coupled Device, CCD, with 2,048 photo sensors. The light source is an ordinary fluorescent lamp. The amount of information varies considerably from line to line depending on the print density of the document. In order to send out the encoded transmitter signal with constant speed, paper transport speed must be matched with the amount of the information on the document, which requires a wide range of the paper speeds.

The document paper transport mechanism and the recording paper cutter are driven with one pulse motor through two one-way clutches, (A) and (B), as shown in Fig. 3. When the motor rotates counter-clockwise, the motor torque is transmitted to the paper transport mechanism through clutch
(a) Clutch is engaged with counter clockwise rotation of the shaft.
(b) Clutch is disengaged with the clockwise rotation.

Fig. 4 One-way clutch mechanism.

(A), while clutch (B) disconnects the motor from the recording paper cutter. With the clockwise rotation of the motor, only the paper cutter is driven through clutch (B). The details of the one way clutch mechanism are shown in Fig. 4.

The clutch consists of an outer ring with a "cam surface," rollers, roller holders, and springs. When the driving shaft is rotating counter-clockwise, the rollers are moved toward the "cam surface" and are held there, and the torque is transmitted to the outer ring as shown in Fig. 4(a). When the shaft is rotating clockwise, however, the rollers are detached from the "cam surface" and the outer ring is disconnected from the shaft, as shown in Fig. 4(b). Movement of the clutches is one of the noise sources in a facsimile machine.

2.3 Pulse Motor Characteristics and Chattering Noise Generation

Pulse motors are commonly used in facsimile machines as drivers due to the following reasons: (1) the shaft rotates a pre-determined angular displacement with each pulse input, (2) the rotation speed and direction can be controlled easily with the input pulse rate, (3) rotation speed can be adjusted according to the recording density of the document, and (4) it is suitable for open loop digital control because the rotational positioning error does not accumulate during operation, resulting in a smaller and less expensive driving mechanism than DC motors, including driving circuit.

The angular displacement of the pulse motor is controlled by the number of input pulses, and the rotational speed is determined by the number of input pulses per second (pps). On the other hand, rotational movement of the pulse motors is not smooth like induction motors and is a source of mechanical noise. It consists of a repetitive cycle of starting, acceleration, deceleration, and stopping with each pulse. After a pulse is applied, the shaft rotational angle repeatedly overshoots and undershoots around the equilibrium point, showing a rotational oscillation before converging to the equilibrium point. The oscillation of the shaft may be amplified, instead of damped, however, if the next driving pulse is applied while the shaft angle is decreasing from the overshooting point. This kind of amplified shaft oscillation is one of the major noise sources in the transmitter section.

The shaft oscillation mentioned above causes the chattering noise due to the collision of the gear teeth in the paper transport mechanism as described in detail below. Degree of the noise generation depends on the pulse rate, and it is most noticeable around 450 pps. The noise generation mechanism at this motor speed was analyzed experimentally in detail. The motor used was a four phased hybrid type pulse motor with alternative single and double phase excitation mode and 0.9 degree of rotation per pulse.

3. NOISE GENERATION MECHANISM DUE TO CLUTCH GEAR CHATTERING AND ITS CONTROL

3.1 Experimental Technique

The experiments were performed in two steps. First, the basic dynamic characteristics of the motor and the gears at a constant speed of 450 pps were studied. Second, the transient characteristics at variable pulse rate in actual facsimile machine transmission were evaluated with the Facsimile Test Chart No. 2. The paper transport speed varied from section to section in the test chart due to the variation of print density. Consequently, the noise level was not constant during the transport of the chart. The A-weighted noise level was measured using a sound level meter with a time constant of two seconds and the highest level for the entire chart was defined as the noise level in this operation.

Rotational displacements of the motor and the gears were measured using a non-contact type photo displacement sensor. Reflected light from the motor shaft end and the side surface of the gear was measured by the photo sensor and the phase was compared with the motor driving signal. Collision of the gears was detected with a strain gage 0.2 mm
long attached to the side surface of the cutter gear. A schematic diagram of the experimental setup is shown in Fig. 5.

3.2 Experimental Results and Discussions
The dynamic behavior of the motor shaft and the clutch gear (B) during the document paper transport, at the pulse rate of 450 pps is shown in Fig. 6. Gear chattering noise is most noticeable at this speed. The Fig. 6(b) shows the motor-gear-clutch assembly schematically. Counter-clockwise rotation, shown as CCW, is taken positive in the figure. The top part of Fig. 6(a) shows the motor shaft rotation angle, the middle part shows circumferential displacement of the clutch gear, and the bottom part shows the strain on the teeth surface of the clutch gear, vs. time. Figure 6(a) indicates that the motor shaft rotates with overshooting, shown as “a” in the figure, and undershooting, “b,” oscillations.

The clutch (B) is disengaged and the clutch gear (B) is supposed to stand still during this operation. Figure 6(a) shows, however, that the clutch gear (B) is oscillating back and forth synchronized with the motor shaft oscillation. This phenomenon can be explained as follows.
While the motor shaft is rotating CCW direction, the clutch (B) is not completely disengaged, but the clutch seems to rotate CCW direction, shown as “c,” due to friction of the rollers in the clutch. When the motor shaft rotates clockwise after overshooting, the clutch (B) is engaged and the clutch gear (B) also rotates clockwise due to the motor torque. This rotation is stopped by the collision with the cutter gear, shown as “d” and “e” in the figure. This collision is supposed to be the source of the chattering noise around 450 pps.

On the other hand, the motor shaft does not show overshootings at pulse rates when the chattering noise is not heard. Such a case is shown in Fig. 7, with the pulse rate of 1,000 pps. After the motor shaft started to rotate with one pulse input, next driving pulse comes in before the undershooting movement occurs, thus keeping the motor rotation angle monotonously increasing. Circumferential movement of the clutch gear is hardly observable and the collision with the cutter gear does not seem to occur in this case.

3.3 Noise Control Method for Chattering Noise
A friction damper placed between two clutch gears was found to be effective for controlling the
chattering noise mentioned above. Pure frictional materials such as a felt were used successfully for this purpose in our experiment. These materials are, however, not sufficiently wear resistant for long term use. After several materials had been tried, a coil spring was chosen as a spring-friction damper. Figure 8 shows the motor-gear-clutch with the spring-friction damper assembly schematically.

Movement of the motor shaft and the clutch gear (B) and the gear surface strain after adopting the spring-friction damper is shown in Fig. 9. The motor shaft oscillation seems to be critically damped and the clutch gear oscillation amplitude was reduced to be about 1/3 of the original. There is no sign of gear teeth collision in the strain gage record and no chattering noise was audible.

The noise level of a facsimile machine with this treatment was measured using the Facsimile Test Chart No. 2 in order to evaluate effectiveness of the noise control method quantitatively. One third octave noise spectra for facsimile machines before and after the adoption of the coil spring are shown in Fig. 10. The noise level was reduced over a wide range of frequency, and the overall noise level decreased by 1.5 dB. Moreover, disappearance of the annoying chattering noise improved the quality of sound considerably. Durability against wear and reduction of motor torque margin by the use of the coil spring were proved to be satisfactory based on the several test runs.
4. CHARACTERISTICS AND CONTROL OF RESONANCE NOISE WITH DOUBLE PULSE DRIVING

4.1 Experimental Technique

The double pulse train is defined as \( T_2 \) being the line interval, or basic double pulse period, and \( T_1 \) being the interval of two pulses within one line, as shown in Fig. 11. The interval \( T_2 \) determines the paper transport speed and is dependent on the information density of the document. The minimum value of \( T_2 \) must be twice of the period corresponding to the maximum motor speed, in this case, 2.3 ms. The interval \( T_1 \) is not, however, directly related to the paper transport speed and can be chosen arbitrarily within certain range; i.e., \( T_1 \geq 2.3 \) ms and \( T_2 - T_1 \geq 2.3 \) ms.

A single pulse train with interval \( T_2 \) was generated with a commercially available pulse generator. The range of \( T_1 \) and \( T_2 \) were chosen as \( 2.3 \leq T_1 \leq 10 \) ms and \( 4.6 \leq T_2 \leq 20 \) ms. Six facsimile machines and 9 pulse motors were used to evaluate noise characteristics, in order to observe the scatter of measured data. A facsimile machine was placed at the center of an anechoic room and noise level was measured at 1 m from the driving motor and the paper transport mechanism in the direction of the highest noise level. Background noise level of the anechoic room was less than 20 dB. A block diagram for the measurement of the dynamic characteristics of the motor shaft is shown in Fig. 12. In this case a potentiometer was used for measuring the rotation angle of the motor shaft instead of the optical system described in the first part. Indicial and double pulse input responses of the motor shaft and rotational oscillation of the motor stator were measured with this apparatus.

4.2 Experimental Results and Discussions

4.2.1 Noise level vs. \( T_1 \) and \( T_2 \)

The results of noise measurements for six facsimile machines are shown in Fig. 13. The abscissa shows the line interval \( T_2 \) and the ordinate shows the double pulse interval \( T_1 \). The line \( T_2 = 2T_1 \) shows the special case of equal pulse intervals. Since the basic double pulse period is \( T_2 \), the measured results will be, in principle, symmetric with the line \( T_2 = 2T_1 \). The \( T_1 - T_2 \) region is divided with 5 dB interval zones, and the highest level among the six facsimile machines was taken for conservative evaluation of the noise level in each zone. In certain range of \( T_1 \) and \( T_2 \), operation is impossible due to the restriction for \( T_1 \) and \( T_2 \) described above, although some data are shown in the figure in that range. The \( T_1 - T_2 \) region in Fig. 13 is clearly divided into spotty area of noisy zone of 50 dB or more and rather wide area of quiet zone of less than 40 B.

One noisy zone is centered around the line of equally spaced pulse intervals, \( T_2 = 2T_1 \) at \( T_2 = 14 \) ms. Other noisy zones are around the marginal
Fig. 14 Noise level vs. $T_2$ for equal interval pulse ($T_2 = 2T_1$).

Fig. 15 Noise level vs. $T_2$ for $T_1 = 2.5$ ms.

Fig. 16 Noise level vs. $T_1$ for $T_2 = 8.3$ ms.

The facsimile machines are operated only with the pulses of equal intervals for the entire range of $T_2$.

Along the line of $T_1 = \text{constant}$ near the marginal operation case of $T_1 = 2.3$ ms, two noisy zones are shown in Fig. 13. This phenomenon is shown in more detail for the case of $T_1 = 2.5$ ms in Fig. 15. The noise level curves have two sharp peaks, and the noise levels are scattered and relatively high except for the zone $T_2 < 6.5$ ms. The case when the $T_2$ is kept constant at $T_2 = 8.3$ ms, is shown in Fig. 16. It shows drastic decrease of the noise level around $T_1 = 4$ ms. Scatter of the data is small in this zone.

4.2.2 Comparison of noise and motor vibration levels

The noise levels of six facsimiles and vibration levels of nine motors were measured separately and compared in order to verify the relation between noise and motor vibration. Number of occurrence of high noise and vibration levels are shown in Figs. 17 and 18, against $T_2$ for constant $T_1$. In these figures, the abscissa shows $T_2$ and the ordinate shows number of facsimiles or motors which gave high noise or vibration levels at that $T_2$. Since high noise or vibration levels occur in groups around particular values of $T_2$ only, average values and standard deviations of $T_2$ in each group are shown in these figures.

The time intervals $T_2$ with which noise and vibration levels become high are almost the same for three values of $T_2$ in both figures. Only exception is $T_2 \approx 24$ ms, where only motor vibration shows a high value. This phenomenon can be explained as follows. The number of driving pulses per unit time,
or energy input per unit time, decreases with increase of $T_2$. Thus, in Figs. 17(a) and 18(a), the number of facsimiles showing high noise level decreases with increase of $T_2$, and eventually resulting in disappearance of high noise level at $T_2 = 24$ ms. It became clear that the motor vibration was the major source of the facsimile noise which occurred at particular pulse time intervals of $T_2$.

4.2.3 Motor shaft response during oscillation

Rotational oscillation characteristics of a motor are shown in Fig. 19. The ordinate shows the rotational angle of the motor and the abscissa shows the time duration after the first pulse was received. The second pulse arrived at $t = 2.3$ ms in Fig. 19(a), and at $t = 7.0$ ms in Fig. 19(b). In other words, the second pulse arrived when the motor shaft angle was still increasing in case of (a), while in case of (b) the motor shaft was rotating backward in oscillation.

The motor shaft oscillates around a neutral point and the oscillation is damped gradually. However, the shaft oscillation is amplified and shows resonance if the second pulse comes in while the shaft is rotating backward, such as in Fig. 19(b). The instances when the motor shaft rotation passes the neutral point during backward rotation are read and indicated in Fig. 19. In this report, these
instances or times are referred to as "critical timing." The critical timings and corresponding $T_1$ which gave high vibration levels of the motors in Figs. 17 and 18 are listed in Tables 1 and 2. These two values agree with each other within less than 10% of difference. From these results we conclude that the facsimile resonance noise is caused by the motor shaft oscillation, due to the driving pulse input during the backward rotation of the motor shaft.

4.2.4 Damped oscillation response of the motor shaft

The motor shaft response for the case of the second pulse arrival at $T_1=3.5$ ms is shown in Fig. 20, although the pulse is not visible in this figure. The motor shaft oscillation is nearly critically damped in this case. This indicates that the resonance noise would be avoided if this condition of no motor shaft oscillation could be realized in actual facsimile operation.

Qualitative analysis for this no-oscillation response was made in order to understand the phenomenon and to realize it in actual facsimile operation. In Fig. 21(a), a part of the motor stators are indicated as $A^e$, $B^e$ and $C^e$, and these stators are excited consecutively with the driving pulses. Although the shape of the voltage applied to the stators is a square wave form, the current in the stator coils shows first-order system response as shown in Fig. 21(b). There is a possibility that the same driving current remains in the stator $B^e$, although in a diminishing quantity, when the next driving pulse is applied to the stator $C^e$. This remaining current in $B^e$ acts like a brake while the rotor is pulled to the stator $C^e$. The no-oscillation, or critically damped oscillation condition can be realized when these two forces from two stator are balanced. This damping effect increases with increase of the ratio $L/R$, where $L$ is the coil inductance and $R$ is the coil resistance.

Gotoh\(^4\) investigated the condition to realize this damping effect for double pulse inputs. According to his theoretical analysis, the optimum condition is shown as

$$T_1 = t_i + t_o/[2(1 - \xi)^{1/2}] \tag{1}$$

where $t_i$ is the initial delay time, $t_o$ is the oscillation period of the rotor determined by motor torque coefficient, $K$, and the moment of inertia of the rotor, $J$, or $t_o = 2\pi(J/K)^{1/2}$, and $\xi$ is the damping factor.

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**Table 1** Comparison of the motor response, $T_1=2.3$ ms.

| Critical timing shown from Fig. 19(a) | 8.1 | 14.4 | 20.2 |
| Timing to give maximum motor vibration | 7.9 | 13.4 | 19.2 |

**Table 2** Comparison of the motor response, $T_1=7.0$ ms.

| Critical timing shown from Fig. 19(b) | (6.1) | 12.8 | 18.9 | 24.7 |
| Timing to give maximum motor vibration | 8.0 | 13.4 | 19.4 | 24.4 |
The initial delay time $t_1 \approx 1$ ms, and the oscillation period $t_0 \approx 6$ ms were obtained from Fig. 19 and were substituted into Eq. (1) in order to obtain optimum condition for $T_1$ for facsimile motors as,

$$T_1 \approx 1 + 6/2 = 4 \text{ ms} \quad (2)$$

assuming $\xi \approx 0$.

In this analysis, the initial angular velocity of the rotor is assumed to be zero. In actual facsimile operations, driving pulses are applied in sequence and the angular velocity of the rotor could be non-zero, resulting in shorter initial delay time than that of the model case. However, the experimental results discussed above show that the noise level becomes a minimum around $T_1 \approx 4$ ms, and this result corresponds to the no-oscillation condition obtained from Eq. (2).

4.3 Effectiveness of the Resonance Noise Control in Facsimile Operations

It was shown in above discussion that the resonance noise in facsimiles can be avoided by choosing proper time intervals between the two pulses, in case of double pulse driving. The line interval, or basic double pulse period $T_2$, controls the paper transport speed which is dependent on the print density of the document. The time interval between the two pulses, $T_1$, can be chosen arbitrarily within a certain range. Therefore it would be possible to control the noise if a proper $T_1$ could be chosen for the entire range of $T_2$. With examination of Figs. 13 through 16, following timing control for $T_1$ was chosen as shown in Fig. 22(a). Facsimiles are not operational for the $T_2$ less than 4.6 ms. For the range 4.6 ms $\leq T_2 \leq 7.8$ ms, $T_1 = T_2/2$, or equal interval pulse trains were chosen. A constant $T_1$, $T_1 = 3.9$ ms was chosen for the range above $T_2 = 7.8$ ms. Or,

$$T_1 = T_2/2 \text{ for } T_2 \leq 7.8 \text{ ms};$$
$$T_1 = 3.9 \text{ ms for } T_2 \geq 7.8 \text{ ms} \quad (3)$$

Noise characteristics of the six facsimiles with these $T_1$ conditions, experimentally driven by the pulses generated by the external timing control unit shown in Fig. 12, were measured and the maximum noise level was plotted for entire range of $T_2$ in Fig. 22(b). The noise level measured is below 36 dB except at $T_2 = 5$ ms, the fastest paper transport speed.

Finally, the noise characteristics of two facsimile machines during actual operation were measured by using the test chart No. 2, one for transmission and the other for receiving. Double pulse train for paper transport was generated in the facsimile and the basic double pulse period $T_2$ was utilized as generated. The second pulse was then formed by the external timing control unit after the prescribed $T_1$ as described by Eq. (3).

Noise level change with time during the transmission is shown in Fig. 23. The noise level is $3 - 5$ dB lower than conventional facsimile machines without $T_1$ control. This experiment successfully shows the
effectiveness of the pulse timing control for noise reduction.

5. CONCLUSION

Experimental analyses of low noise driving mechanisms for pulse motors used for paper transport and cutter mechanisms in facsimile machines were performed. Chattering noise was observed in one way clutch gears used for torque transmission from the motor to the paper cutter. Unexpected movement of the clutch due to internal friction and subsequent collision of the gears was found to be the cause for this type of noise. The noise was controlled by placing a spring-friction damper between two clutch gears. Resonance noise from the motor rotor oscillation was observed for particular pulse intervals when driven with double pulse trains. The noise was controlled by choosing proper time intervals of two consecutive pulses.

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