A Design of the VCM Coil Diameter of a Rotary Actuator in a Computer Hard Disk Drive

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A design strategy of the rotary moving coil actuator is presented for a computer hard disk drive. This paper puts a focus on a coil diameter of the rotary moving coil actuator for the given mechanical properties and magnetic characteristics. To achieve the criteria for the coil diameter, the seek time and power consumption are expressed in terms of the coil conductor diameter. This study shows that the seek time decreases but the power consumption increases as the coil conductor diameter increases. Therefore, the coil design makes a compromise over the seek time and power consumption. An example of the coil diameter design is given to obtain the appropriate coil diameter satisfying the specifications on the seek time and power consumption.

Key Words: Rotary Moving Coil Actuator, Seek Time, Power Consumption, Hard Disk Drive

1. Introduction

A hard disk drive (HDD) is a very popular data storage device in a computer system. The direction of HDD development is toward high capacity, small form factor, fast data access time and more reliability. Nowadays, HDDs with 3.5″ disks are widely used in desk-top personal computers while HDDs with 1.5″ or 2.5″ disks are used in lap-top or notebook computers. Some companies are now introducing 3.5″ HDDs with about 500 MB capacity per platter. Their products have faster data read/write performance than previous ones.

Speed of data read/write performance relies on the data access time in a computer, which is summation of the seek time, data rate, data transfer rate and so on. The data rate represents amount of transferred data per time from disks to buffer and the data transfer rate is defined by amount of transferred data from buffer to host. They are closely related with the interface firmware. On the other hand, the overall mechanical performance of a HDD, including the servo control performance, is usually measured in terms of its seek time. The seek time is the average time it takes for a head to move from one track to another, which includes the time to settle over the track plus the latency that is the time for one revolution (Jorgensen, 1988). Conventionally, HDD industries regard the seek time as time during which an actuator passes one third of the total seek angle. The seek time is generally determined by magnetic properties of magnets in a voice coil motor (VCM), servo control algorithms and electrical and mechanical properties of an actuator. It is desirable that these four aspects of a moving coil actuator design are combined and optimized to obtain faster seek time and lower power consumption, because they have a close relationship and interact each other. In a practical design, however, it is not easy to combine and optimize them simultaneously. In fact, they have been improved independently for development of moving coil actuators. The proposed coil design strategy has an adventage to improve the seek time and power consumption without significant change of the mechanical form factor and properties of a HDD.

Magnetic properties of VCM magnets and servo control algorithms of an actuator are impor-

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tant to accelerate the seek time. Hiyane, et. al. (1972) and Inou, et. al. (1974) presented the design procedures of moving coil actuators with a linear geometry, which are the old types of actuators and are not used now. Some studies on the magnetics were carried out, which considered simple rules and procedure of the actuator magnet design to minimize the seek time using a servo control algorithm (Wagner, 1983 and 1992). Wagner also studied the effect of different steels on the seek time (Wagner, 1991), where it was found that for most of the commonly used steels, such as low carbon steel or new sintered iron steel. There is no significant difference in the seek time provided the designed-in steel is used. On the other hand, great efforts have been made to minimize the seek time in the viewpoint of servo control algorithms : *e. g.*, Oswald, 1980 ; Tal and Kahne, 1973 ; Tal, 1981 and Ananthanarayanan, 1982.

In this paper, a new design procedure for a rotary moving coil actuator is introduced : particulary, it has a focus on the optimum coil diameter which satisfies the specifications for the seek time and power consumption. This design is considered under given geometric configuration, magnetic properties, and servo control algorithm. The bang-bang control strategy algorithm (Ananthanarayanan, 1982 ; Burghes and Graham, 1980) is used as a servo control algorithm to calculate the seek time and power consumption, because it is simple to design the coil.

2. Seek Time and Power Consumption

Major mechanical parts of the HDD may be classified as the base, cover, spindle motor, VCM, actuator and disks. As seen in Fig. 1, the actuator consists of heads/suspensions, an arm and a coil while the VCM consists of a coil and a couple of magnets and yokes. The seek time is greatly influenced by mechanical properties such as the mass balance and moment of inertia of the actuator. In addition to mechanical properties, electrical properties such as resistance are also important to determine the seek tiem and power consumption.

A conventional moving coil actuator is shown in Fig. 2. The upper yoke and magnet are removed form Fig. 2(a) to make it easy to understand the structure of the VCM shown in Fig. 2(a). Figure 2(b) is the cross-section A-A′ of the VCM. Magnets have bipolarity on each side so that the magnetic flux direction in the left part of the VCM is opposite to that in the right part. If the magnets are placed as shown in Fig. 2(b) and the current direction is counterclockwise in the coil of Fig. 2(a), the force is applied to the left of the coil. Therefore, the resultant torque becomes clockwise. In the coil shown in Fig. 2(b), the cross sign indicates that the current goes into the coil and the dot means that the current comes out of the coil. When the current passes through the coil clockwise, the torque direction is counterclockwise.

The design objective is to obtain the optimum coil diameter of the actuator, which satisfies the

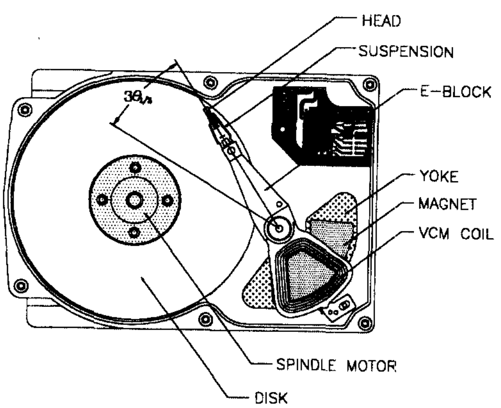

Fig. 1 Configuration of a computer hard disk drive

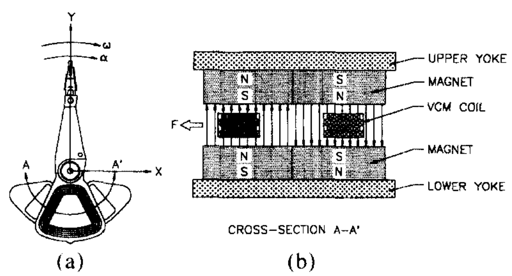

Fig. 2 Rotary moving coil actuator (a) and the voice coil motor (b)

fast seek time and low power consumption simultaneously, under the given mass moment of inertia of the actuator and configuration of the coil part. In fact, once the shape of the coil part is determined, choice of the coil diameter is closely related with the inductance, resistance and torque constant. Hence, the seek time and power consumption are dependent upon the coil diameter.

The governing equations (Kenjo and Nagamori, 1984) of a rotary moving coil actuator are

$$L\frac{di(t)}{dt}+Ri(t)+K_t\dot{\theta}(t)=V(t) \tag{1}$$

$$T(t)=J\ddot{\theta}(t) \tag{2}$$

$$T(t)=K_t i(t) \tag{3}$$

where $i(t)$, L and R are the current, inductance and resistance of the coil, respectively; K_t is a torque constant in the SI unit and it is determined by the number of coil turns, the effective coil length, the average moment radius of the coil, and the magnetic flux density in the gap between magnets; $V(t)$ is the resultant voltage drop which is given by $V(t)=V_o(t)-V_{ic}(t)$ where $V_o(t)$ and $V_{ic}(t)$ are the overall voltage drop and voltage drop in IC chips; $T(t)$ is the total torque with respect to the center of the pivot bearing; J is the mass moment of inertia of the actuator including the heads/suspensions, arm, coil and coil supporter; $\theta(t)$ is the angular displacement of the actuator; the superposed dots indicate the derivatives with respect to time. In the above equations, we neglect the torque biases, *e. g.*, flex cable force, reluctance force and non-linear bearing effects; in Eq. (2), the torque due to friction in a pivot bearing is also neglected because it is usually very small. Consideration of temperature effect to resistance gives us the following equation:

$$R(T)=R_0[1+\alpha_T(T-T_0)] \tag{4}$$

in which $R(T)$ and R_0 are the resistance at temperatures T and T_0, respectively; α_T is electric resistance temperature factor; T is the temperature at which the actuator is on a seek mode; T_0 is the reference temperature.

The bang-bang control assumes that the angular velocity of the actuator has a triangular profile as shown in Fig. 3 in which t_{TS} is the total seek time including the seek time t_s and settling time t_{st}; $\omega_{\max}$ is the maximum angular velocity of the actuator; r is the ratio of decelerating time to accelerating time called the angular velocity profile ratio. Assuming that it takes t_s for the actuator to pass one third of the seek angle, the angular velocity profile of Fig. 3 determines the angular velocity and acceleration as follows:

$$\dot{\theta}(t)=\begin{cases}(1+r)\omega_{\max}\dfrac{t}{t_s} & \text{for } 0\le t\le\dfrac{1}{1+r}t_s\\[2mm] \dfrac{1+r}{r}\omega_{\max}\left(1-\dfrac{t}{t_s}\right) & \text{for } \dfrac{1}{1+r}t_s\le t\le t_s\end{cases} \tag{5}$$

$$\ddot{\theta}(t)=\begin{cases}(1+r)\dfrac{\omega_{\max}}{t_s} & \text{for } 0\le t\le\dfrac{1}{1+r}t_s\\[2mm] -\dfrac{1+r}{r}\dfrac{\omega_{\max}}{t_s} & \text{for } \dfrac{1}{1+r}t_s\le t\le t_s\end{cases} \tag{6}$$

where

$$\omega_{\max}=2\frac{\theta_{1/3}}{t_s} \tag{7}$$

in which $\theta_{1/3}$ is one third of the seek angle (rad) in the data zone. It should be noted that the resultant voltage drop has different directions for accelerating and decelerating time, *i. e.*,

$$V(t)>0 \text{ for } 0\le t\le\frac{1}{1+r}t_s \tag{8}$$

$$V(t)<0 \text{ for } \frac{1}{1+r}t_s\le t\le t_s \tag{9}$$

Similarly, the overall voltage drop and voltage drop in IC chips have the same sign as the resultant voltage drop. Since the absolute value of the overall voltage drop in the actuator should be less than or equal to that of the power supply voltage,

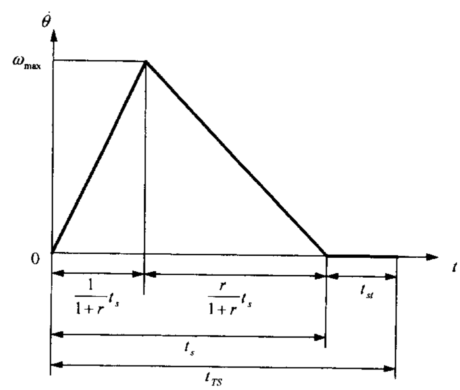

Fig. 3 Angular velocity profile of a rotary moving coil actuator

we have the following inequality constraint for the resultant voltage drop :

$$|V(t)| \leq |V_{ps}(t)| - |V_{ic}(t)| \quad (10)$$

where $V_{ps}(t)$ is the power supply voltage.

Solving Eqs. (2) and (3) for $i(t)$, the current $i(t)$ is expressed in terms of the moment of inertia, torque constant and angular acceleration :

$$i(t) = \frac{J}{K_t}\ddot{\theta}(t) \quad (11)$$

Since the current and angular acceleration are constant during the acceleration or decelerating time, substitution of Eq. (11) into Eq. (1) results in

$$\frac{RJ}{K_t}\ddot{\theta}(t) + K_t\dot{\theta}(t) = V(t) \quad (12)$$

which means that the voltage drop under the bang-bang control can be expressed in terms of the resistance, moment of inertia, torque constant, angular velocity and acceleration. The first term in the left-hand side of Eq. (12) is the voltage drop due to the resistance whereas the second term is the voltage drop due to the back emf (electromotive force). If the actuator is in deceleration, the back emf plays a positive role in the resultant voltage drop, that is, it adds the voltage to the system. Otherwise, it plays a negative role so it drops the voltage from the system. The reason is that the back emf term is always positive regardless of the direction of the angular acceleration but the other terms can be positive or negative depending upon the direction of the angular acceleration. Therefore, in view of voltage drop, we may consider only the acceleration region in the actuator coil design, because the magnitude of the resultant voltage drop in the accelerating time is always larger than that in the decelerating time. In other words, the accelerating time has more severe design condition than the decelerating time, considering the voltage drop.

Under the bang-bang control, the seek time can be expressed in terms of the torque constant, seek angle, average resultant voltage drop, mass moment of inertia, resistance, and angular velocity profile ratio. Substitution of Eqs. (5) and (6) into Eq. (12), using Eq. (7), yields

$$2(1+r)\frac{RJ\theta_{1/3}}{K_t}\frac{1}{t_s^2} + 2(1+r)K_t\theta_{1/3}\frac{t}{t_s^2} = V(t) \quad \text{for } 0 \leq t \leq \frac{1}{1+r}t_s \quad (13)$$

Integrating the both sides of Eq. (13) from 0 to $\frac{t_s}{1+r}$ with respect to t, we obtain the following equation :

$$K_t\bar{V}t_s^2 - K_t^2\theta_{1/3}t_s - 2(1+r)JR\theta_{1/3} = 0 \quad (14)$$

where $\bar{V}$ is the average resultant voltage drop and is given by

$$\bar{V} = \frac{1+r}{t_s}\int_0^{\frac{t_s}{1+r}} V(t)dt \quad (15)$$

$\bar{V}$ is also restricted by

$$|\bar{V}(t)| \leq |V_{ps}(t)| - |V_{ic}(t)| \quad (16)$$

Solving Eq. (14) for t_s, the seek time is given by

$$t_s = \frac{K_t\theta_{1/3}}{2\bar{V}}\left(1 + \sqrt{1 + \frac{8(1+r)JR\bar{V}}{K_t^3\theta_{1/3}}}\right) \quad (17)$$

As seen in Eq. (17), the seek time becomes longer as the average resultant voltage drop becomes smaller. The power supply voltage usually varies with 10% fluctuation of the nominal value, so the wrost case occurs when the power supply voltage is minimum, *i. e.*, when $\bar{V} = \min|V_{ps}(t)| - |V_{ic}(t)|$.

The torque constant can be expressed in terms of the number of coil turns, the geometry of the coil parts, and the magnetic flux density in the air gap between magnets. Suppose that a straight coil of length l is placed in a uniform magnetic field B, with its direction always normal to the field direction. If the current i passes through the coil, the force F can be written by

$$F = lBi \quad (18)$$

and the torque is given by

$$T = lrBi \quad (19)$$

where r is the average moment radius. Since the coil shown in Fig. 4 has two effective sides and N coil turns, comparing Eqs. (3) and (19) results in the torque constant given by

$$K_t = 2Nl_er_{ave}B_g \quad (20)$$

where N is the number of coil turns ; l_e is the effective length of the coil side which is inside the

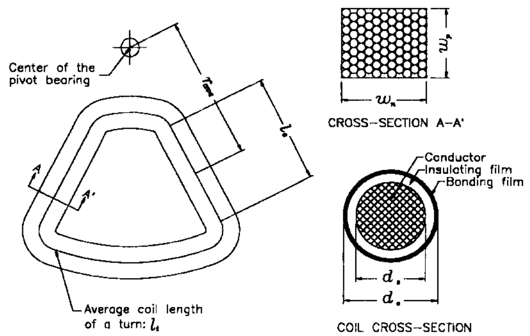

Fig. 4 Configuration of the coil part

magnetic flux ; r_{ave} is the average moment radius of the coil which is the distance from the pivot center to the mid-point of the effective coil side ; B_g is the magnetic flux density in the air gap between magnets.

On the other hand, since the resistance is proportional to the total length of the coil and reversibly proportional to the cross-sectional area of the coil, the reference resistance R_0 at the temperature T_0 may be written by

$$R_0 = k_R \frac{N l_t}{d_c^2} \tag{21}$$

where l_t is the average length of a turn of the coil, d_c is the coil conductor diameter shown in Fig. 4, and k_R is a resistance proportional factor. Substituting Eq. (21) into (4), the resistance at the temperature T is

$$R(T) = k_R[1 + \alpha_T(T - T_0)] \frac{N l_t}{d_c^2} \tag{22}$$

The winding style of a coil shown in Fig. 4 results in the following approximated relation between the number of turns and the dimensions of the coil part :

$$N = \frac{2}{\sqrt{3}} \left(\frac{w_n w_p}{d_o^2} - \frac{w_n}{d_o} \right) \tag{23}$$

where w_n and w_p are the widths of the coil part normal and parallel to the magnetic flux in the air gap, respectively ; d_o is the overall diameter which includes the conductor, insulating film, and bonding film.

From Eqs. (17), (20), (22) and (23), the seek time can be expressed as a function of the overall and conductor diameters, after all the basic design parameters are determined for the coil geometry, electrical properties for the coil, average resultant voltage drop, seek parameters and magnetic flux density.

Another important design objective in the actuator design is low power consumption which is related with the coil resistance, moment of inertia, torque constant, seek angle, and seek time. The excessive power consumption results in temperature rise of the coil ; the temperature rise increases the coil resistance and then the increase of the coil resistance has a role to make the seek time longer. The power consumption in the actuator is given by

$$P_i = Vi \tag{24}$$

Neglecting the voltage drop due to the inductance and combining Eqs. (1) and (24), the power consumption is rewritten as

$$P_i = Ri^2 + K_t \dot{\theta} i \tag{25}$$

Substitution of Eq. (11) into the second term in the right-hand side of Eq. (25) leads to

$$P_i = Ri^2 + \frac{d}{dt}\left(\frac{1}{2} J \dot{\theta}^2 \right) \tag{26}$$

where the first term represents the power loss due to the resistance and the second term represents a change in the kinetic energy of the actuator. Since the power consumption varies with time, it is necessary to average the power consumption during the one third seek mode. Furthermore, the directions of the voltage and current for the accelerating time are opposite to those for the decelerating time, so the average power consumption needs to be defined as

$$P = \frac{1}{t_s} \int_0^{t_s} P_i dt \tag{27}$$

which is reduced to

$$P = \frac{1}{t_s} \int_0^{t_s} Ri^2 dt \tag{28}$$

because the change in the kinetic energy averages zero. Substitution of Eq. (11) into (28), using Eqs. (6) and (7), results in

$$P = \frac{4(1+r)^2}{r} \frac{R J^2 \theta_{1/3}^2}{K_t^2 t_s^4} \tag{29}$$

As seen in Eq. (29), the power consumption increases with the angular velocity profile ratio, resistance, moment of inertia and seek angle while it decreases with the torque constant and seek time.

3. Design of a Moving Coil Actuator

Consider an example for the rotary moving coil actuator design whose objective is to obtain less than 9.5 msec total seek time and less than 6 Watt power consumption. In order to satisfy this design objective, we select the optimum coil diameter with a given geometry of the actuator.

The first design stage is to determine the basic shape of the actuator, because the mass balance of the actuator should be established with respect to the pivot center. At the same time it is necessary to reduce the mass moment of inertia of the actuator within the limit to guarantee the dynamic stability of the actuator. We circumvent the discussion about the dynamic stability of the actuator here for simplicity. However, it is noted that the dynamic stability requires sufficient stiffiness of the actuator arm. Since the sufficient stiffiness and small mass moment of inertia are desirable, magnesium is used as the actuator material rather than aluminum. Magnesium has Young's modulus close to aluminum while it has less mass density than aluminum. The dimensions of the coil part shown in Fig. 4 are determined by considering mass balance and mass moment of inertia : the widths of the coil cross-section normal and parallel to the magnetic flux in the air gap are 4.5 mm and 2.0 mm, respectively ; the effective length of the coil side is 17.0 mm ; the average moment radius of the coil is 20.0 mm ; the average length of a turn of the coil is 80.0 mm. A copper-clad aluminum Class 2 wire (Totoku, 1993) is used for the actuator coil instead of a copper wire in order to reduce the mass of the coil part. By using the draft software program "AUTOCAD" (Autodesk, 1993), the mass moment of inertia of the actuator shown in Fig. 2 is calculated as 5×10^{-6} Kg m.

The seek angle shown in Fig. 1 is determined by the so-called "zone map" which specifies the data zone on the disk : the seek angle is 24.06° so the one third seek angle is 0.14 rad. On the other hand, the velocity profile ratio is given by 1 : 1.5. The velocity profile in a real servo control is not triangular, because a real servo control does not use the bang-bang control strategy. However, the real angular velocity profile is hardly used for the coil design because of its complexity. Hence, the triangular angular velocity profile of the bang-bang control is generally adopted for the coil design.

Electrical properties of the coil depends on the coil material. The electric resistance temperature factor is 0.004/℃ for the copper-clad aluminum Class 2 wire and the resistance propertional factor is needed to calculate the resistance of a given coil. The data on the first two columns of Table 1 are obtained from the coil catalogue, "Magnet Wires" (Totoku, 1993). The first column of the Table 1 is for the coil conductor diameters and the second column is for the coil resistance per 1 Km at 20℃. Based on Eq. (21), the resistance proportional factor can be calculated as seen in Table 1 : the resistance proportional factor is determined as $3.248\times10^{-5}\ \Omega$mm.

The other constraints in the actuator coil design are the environmental temperature, resultant voltage drop in the actuator and magnetic flux density in the air gap. The temperature and power supplied voltage are considered for the worst case to provide margins to the design. The environmental temperature is chosen as 70℃ while the reference temperature is 20℃. Although the nominal power voltage is 12 V, it is usually fluctuating with 10% of the nominal value. Considering the voltage drop in the IC chips which is given by 1.3 V, the minimum of the resultant voltage drop in the actuator becomes $\bar{V}=(0.9)(12)-1.3=9.5$ V. The magnetic flux density in the air gap between magnets is designed as 0.6 Tesla by using the Shin-Etsu magnet N45 (Shin-Etsu, 1993). The design parameters are summarized in Table 2.

With the basic design parameters shown in Table 2, the seek time and power consumption are calculated. The first two columns of the Table 3 are obtained from the coil catalogue (Totoku, 1993) while the other columns are calculated by

Table 1 Calculation of the resistance proportional factor of the coil

Conductor diameter, d_c(mm)	Resistance per 1 Km at 20℃, $R_0(\Omega)$	Resistance proportional factor, $k_R(\Omega mm)$
0.16	1270	3.251×10^{-5}
0.17	1120	3.237×10^{-5}
0.18	1000	3.240×10^{-5}
0.19	900	3.249×10^{-5}
0.20	812	3.248×10^{-5}
0.21	737	3.250×10^{-5}
0.22	672	3.252×10^{-5}
0.23	613	3.243×10^{-5}
0.24	564	3.249×10^{-5}
0.25	520	3.250×10^{-5}
0.26	482	3.258×10^{-5}
0.27	446	3.251×10^{-5}
Average		3.248×10^{-5}

Table 2 Input design parameters of the rotary moving coil actuator

Input design parameter	Value	Input design parameter	Value
w_n	4.5 mm	r	1.5
w_p	2.0 mm	α_T	0.004/℃
l_e	17.0 mm	k_R	3.248×10^{-5} Ωmm
r_{ave}	20.0 mm	T_0	20℃
l_t	80.0 mm	T	70℃
J	5×10^{-6} Kg m^2	$\overline{V}$	9.5 V
$\theta_{1/3}$	0.14 rad	B_g	0.6 Tesla

the formulas given in the previous section. The following is the calculation procedure of the seek time and power consumption:

(1) Calculate the number of coil turns (N) within the given coil part cross-section by using Eq. (23).

(2) Calculate the torque constant (K_t) of the actuator from Eq. (20).

(3) Calculate the coil resistance (R) at 70℃ as the worst case by Eq. (22).

(4) Calculate the seek time (t_s) from Eq. (17), which does not include the settling time (t_{st}). In this design, the settling time is selected as 1 msec, so the total seek time (t_{TS}) is obtained by adding 1 msec to the seek time.

(5) Calculate the power consumption by using Eq. (29).

As seen in Table 3, as the conductor diameter increases, the number of coil turns, coil resistance at 70℃, torque constant and total seek time also

Table 3 Number of coil turns, coil resistance at 70℃, torque constant, total seek time and power consumption with different conductor and overall diameters

Conductor diameter, d_c(mm)	Overall diameter, d_o(mm)	Number of turns, N	Resistance at 70℃, R(Ω)	Torque constant, K_t(N m/A)	Total seek time, t_{ST}(msec)	Power consumption, P(W)
0.16	0.189	263	32.1	0.1075	12.3	1.39
0.17	0.199	236	25.5	0.0964	11.6	1.77
0.18	0.211	209	20.1	0.0852	11.0	2.29
0.19	0.221	189	16.3	0.0772	10.4	2.84
0.20	0.231	172	13.4	0.0703	9.9	3.50
0.21	0.241	157	11.1	0.0642	9.5	4.27
0.22	0.252	143	9.2	0.0584	9.1	5.21
0.23	0.264	129	7.6	0.0528	8.7	6.37
0.24	0.274	119	6.5	0.0487	8.4	7.58
0.25	0.284	111	5.5	0.0451	8.1	8.95
0.26	0.294	103	4.7	0.0418	7.8	10.51
0.27	0.304	95	4.1	0.0389	7.5	12.27

decrease. However, the power consumption increases with the conductor diameter. To select the appropriate coil diameter satisfying the design objective, *i, e.,* less than 9.5 msec total seek time and less than 6 Watt power consumption, the total seek time and power consumption are plotted in Fig. 5, which shows that the conductor diameter should be larger than 0.211 mm to obtain less than 9.5 msec seek time while it should be less than 0.227 mm to satisfy less than 6 Watt power consumption. The coil design to meet the above design target is summarized as

$$0.211 \text{ mm} < d_c < 0.227 \text{ mm} \tag{30}$$

Consequently, the optimum conductor diameter of the actuator coil of this design is 0.22 mm.

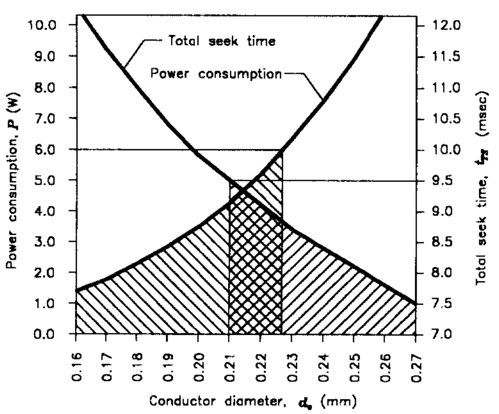

Fig. 5 Total seek time and power consumption with the coil conductor diameter

4. Conclusions

In this paper, a new design procedure is presented for a rotary moving coil actuator. The seek time and power consumption of an actuator are expressed in terms of the coil conductor diameter for the given actuator geometry and bang-bang control strategy. It is shown that the seek time is shorten and the power consumption of the coil rises as the conductor diameter increases with a constant cross-sectional area of the coil part. Therefore, a designer should make a compromise over seek time and power consumption. As seen in the design, the seek time provides the upper bound of the coil diameter while the power consumption provides the lower bound. The proposed design procedure can be applied to different types of moving coil actuators in order to achieve desired seek time and power consumption.

In future work, the mass moment of inertia and mass balance need to be considered for more complete design optimization. When a coil diameter is changed, the mass moment of inertia and mass center for a coil are slightly changed. Therefore, after change of the coil, the mass balance and mass moment of inertia of an actuator should be recalculated to give feedback for design optimization. Moreover, since an actuator shape is related with dynamic stability of a servo control system, the additional structural design consideration should be included in a future design of the rotary moving coil actuator.

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