M51971L/FP

MOTOR SPEED CONTROL

DESCRIPTION

The M51971 is a semiconductor integrated circuit designed to control the motor rotating speed.
The built-in FG amplifier with high gain enables to use a wide range of rotating speed detector (FG detector).
Use of less external parts enables DC motors to be controlled with high precision.

FEATURES

- Wide range of supply voltage .... 4 – 17.5V
- Variation coefficient of supply voltage ..... ±0.005%/V (standard)
- Load variation coefficient ..... ±0.01% (standard, full load range)
- Temperature coefficient of rotating speed .... 7ppm/°C (standard)
- Built-in high performance FG amplifier

APPLICATION

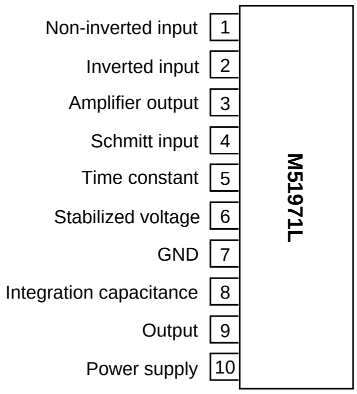
Motor rotating speed control in floppy disk driver, player, tape recorder, car stereo, etc.

RECOMMENDED OPERATING CONDITIONS

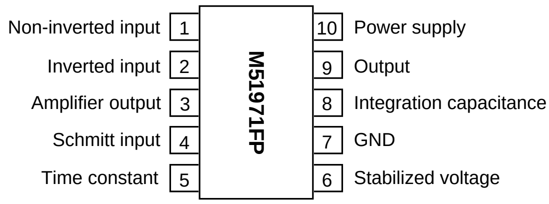
Supply voltage range .... 4 – 17.5V
Rated supply voltage 9V
Input voltage range at pin ① .... -0.4 – Vcc Note 1
Input voltage range at pin ④ .... -0.4 – Vcc
Highest setup tacho-generator frequency 2.5kHz
Minimum trigger pulse width (input pulse at pin ④)
.... 40µs Note 2

Note 1: The linear operation range is -0.4 to +0.4V.
Note 2: This condition applies to both periods: from pulse rising to pulse falling and pulse falling to pulse rising.

PIN CONFIGURATION (TOP VIEW)

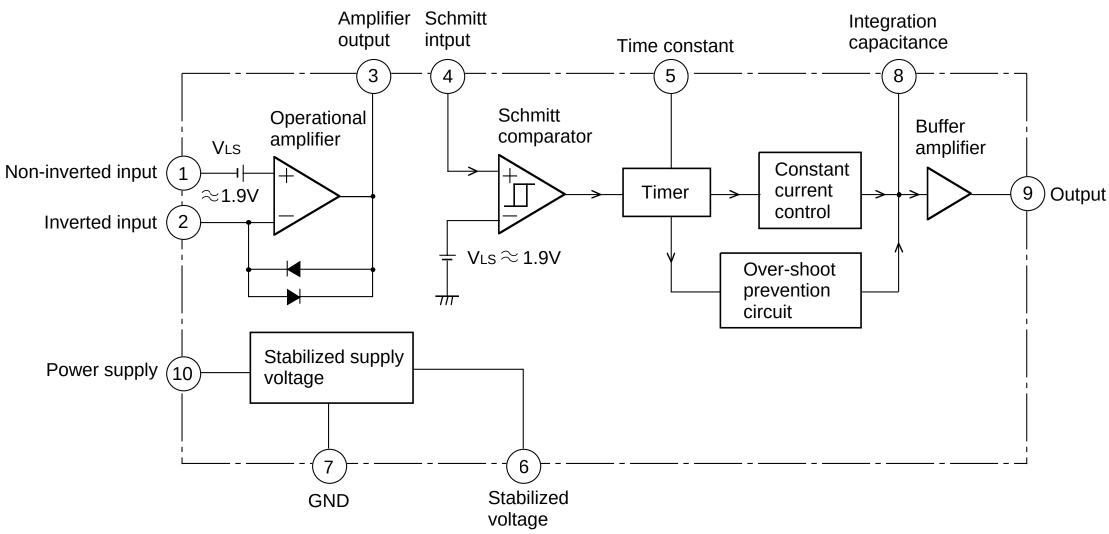


Outline 10P5



Outline 10P2-C

BLOCK DIAGRAM



ABSOLUTE MAXIMUM RATINGS (Ta=25°C unless otherwise noted)

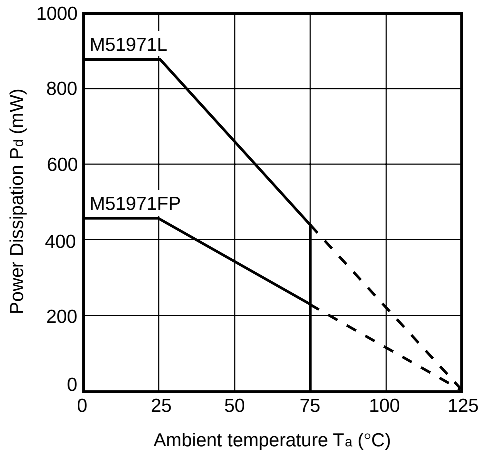
Symbol	Parameter	Conditions	Ratings	Unit
Vcc	Supply voltage		18	V
V①	Apply voltage at pin①		-3 – Vcc	V
I③	Source current at pin③		-5	mA
I⑥	Source current at pin⑥		-5	mA
V④	Apply voltage at pin④		0 – Vcc	V
I⑨	Source current at pin⑨		-20	mA
PdF	Power dissipation		880 (M51971L) 450 (M51971FP)	mW
KθF	Thermal derating	Ta≥25°C	8.8 (M51971L) 4.5 (M51971FP)	mW / °C
Topr	Operating temperature		-20 – +75	°C
Tstg	Storage temperature		-40 – +125	°C

ELECTRICAL CHARACTERISTICS (Ta=25°C, Vcc=9V unless otherwise noted)

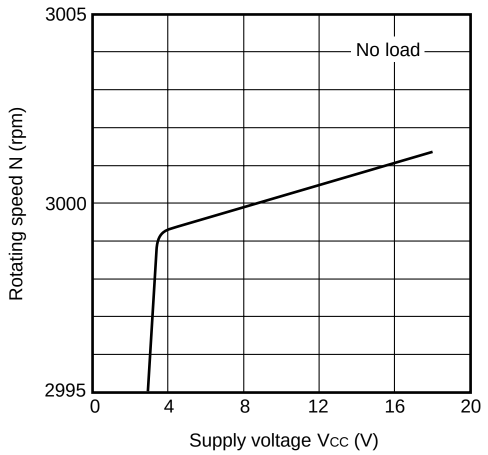
Symbol	Parameter	Test conditions	Limits			Unit
			Min.	Typ.	Max.	
VCC	Supply voltage range		4.0		17.5	V
ICC	Circuit current			3.2	6.0	mA
VS	Stabilized supply voltage	Voltage at pin⑥	2.44	2.71	2.98	V
I①	Input current at pin①	V① = 0V	-3.0	-0.5		µA
I②	Input current at pin②	V① = 0V	-180	-30		nA
V①LS	Level shift voltage at pin①	V① = 0V	1.51	1.89	2.27	V
AV	FG amplifier voltage gain	V①=0.2mVrms, f=500Hz, External set gain=60dB	54	59	64	dB
I④	Input current at pin④	V④ = 2.5V		0.4	2.0	µA
V④TH	Threshold voltage at pin④	Uses level shift voltage at pin① as the reference.	0	16	40	mV
V④HY	Hysteresis width at pin④		20	37	55	mV
V⑤S	Saturation voltage at pin⑤	Rτ = 75kΩ		3	20	mV
Tτ	One-shot pulse width	Rτ = 75kΩ, Cτ = 4700pF	375	395	415	µsec
I⑧C	Charging current at pin⑧	V⑧ = 1V	-260	-190	-140	µA
rCD	Ratio of charging to discharging current at pin⑧	V⑧ = 1V	-14.5	-11.6	-9.0	–
R⑨	Output protection resistance at pin⑨	I⑨ = -20mA	65	100	150	Ω
V⑨max	Maximum voltage at pin⑨		2.9	3.2		V
V⑨min	Minimum voltage at pin⑨			50	200	mV
VBO	Buffer amplifier offset voltage	V⑧ = 1V, V⑧ - V⑨	0	100	200	mV

TYPICAL CHARACTERISTICS

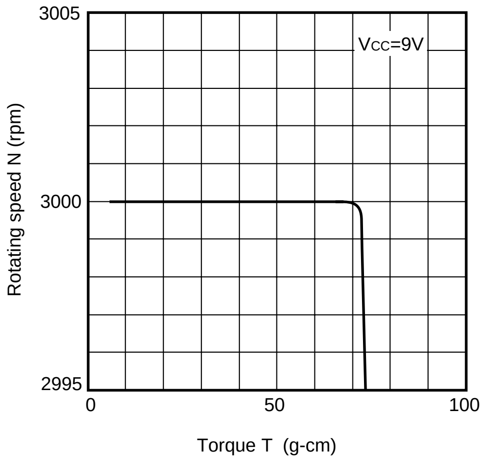
Thermal Derating (Maximum Rating)



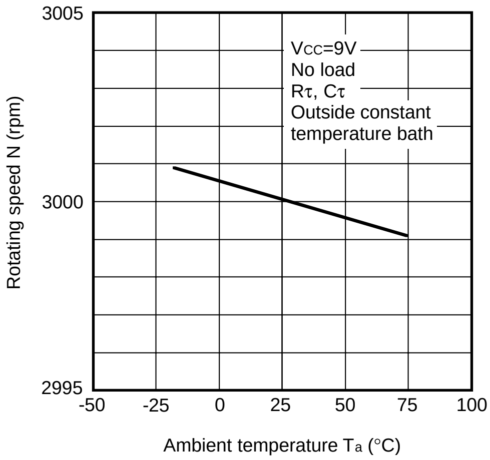
Rotating speed–Supply voltage characteristics



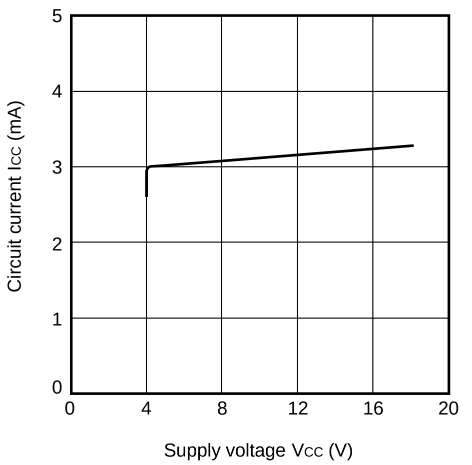
Rotating speed–Motor torque characteristics



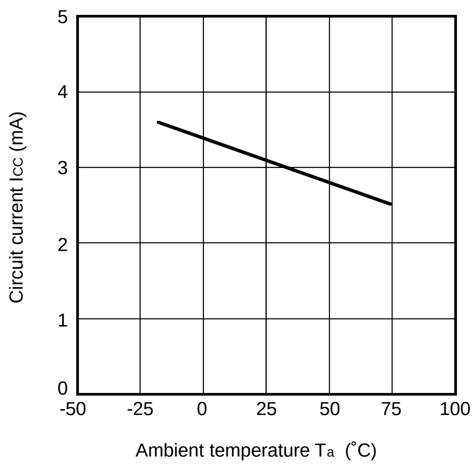
Rotating speed–Ambient temperature characteristics



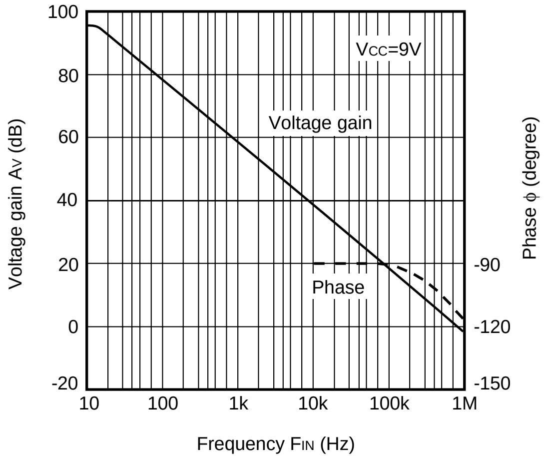
Circuit current–Supply voltage characteristics



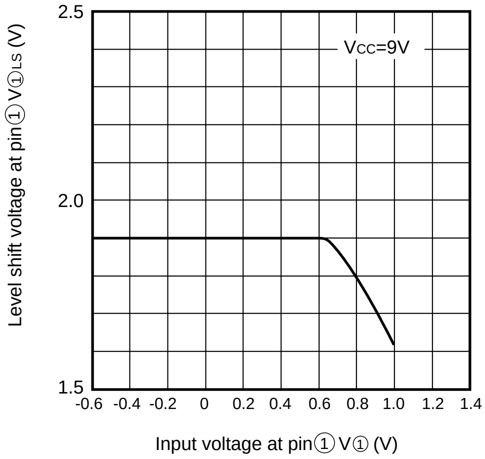
Circuit current–Ambient temperature characteristics



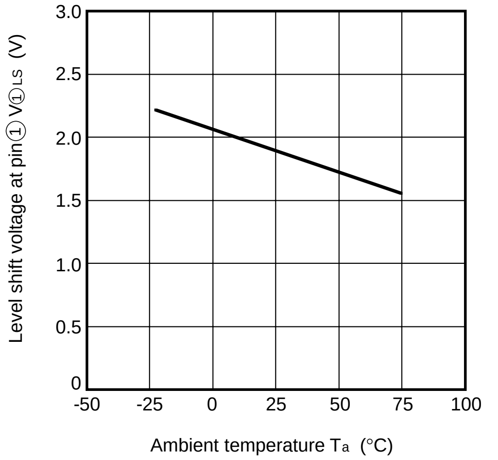
FG amplifier open loop voltage gain, phase transition characteristics



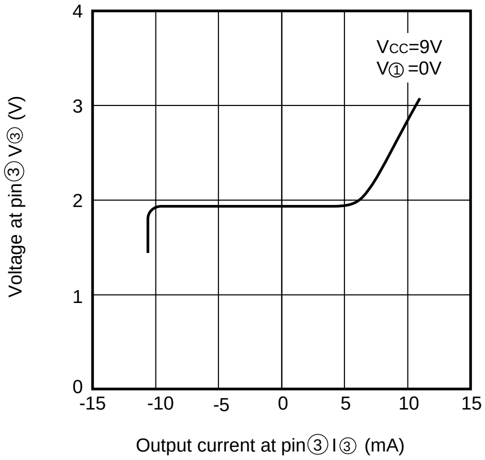
Revel shift voltage at pin① – Input voltage characteristics at pin①



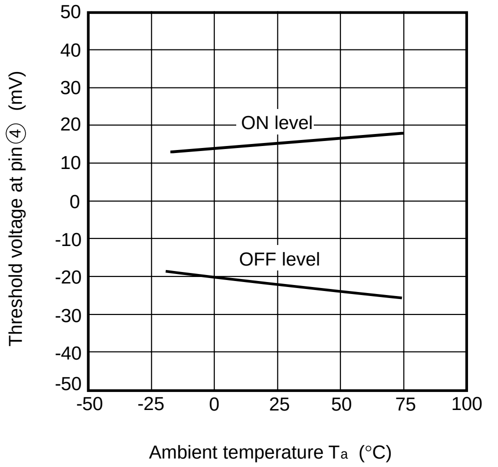
Level shift voltage at pin① – Ambient temperature characteristics



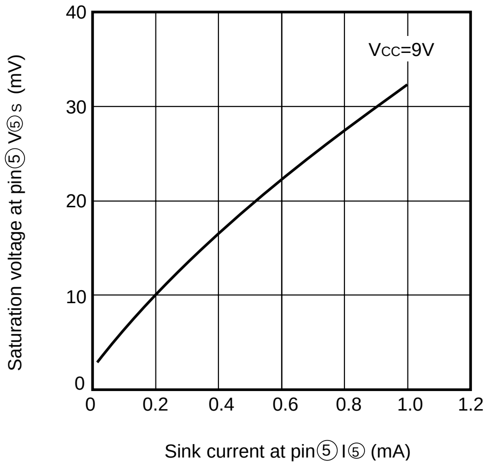
Voltage at pin③ – Output current characteristics of pin③



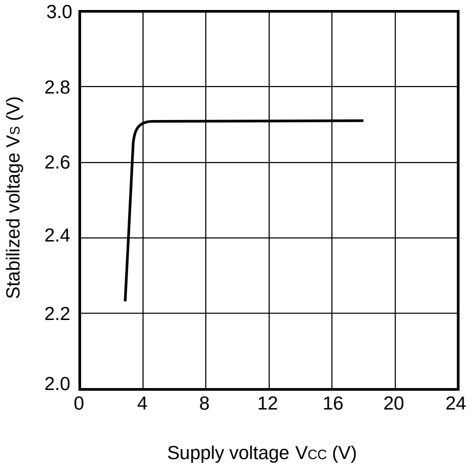
Threshold voltage at pin④ – Ambient temperature characteristics



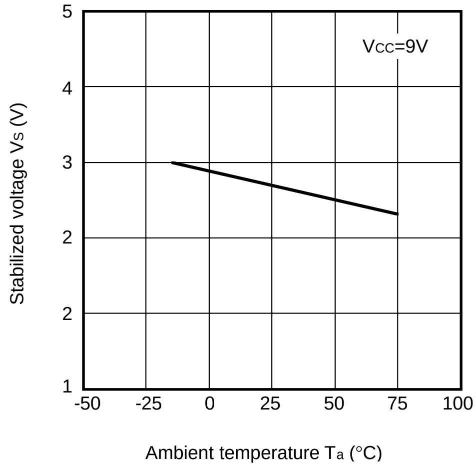
Saturetion voltage at pin⑤ –Sink current characteristics at pin⑤



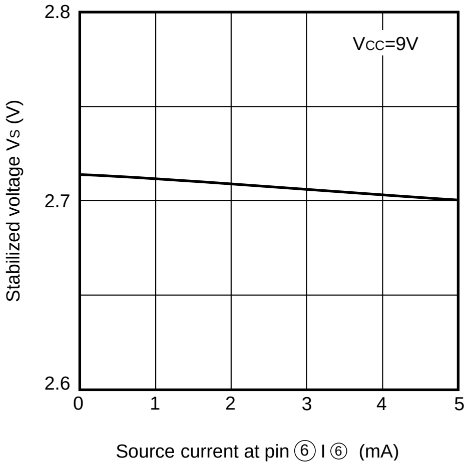
Stabilized voltage–Supply voltage characteristics



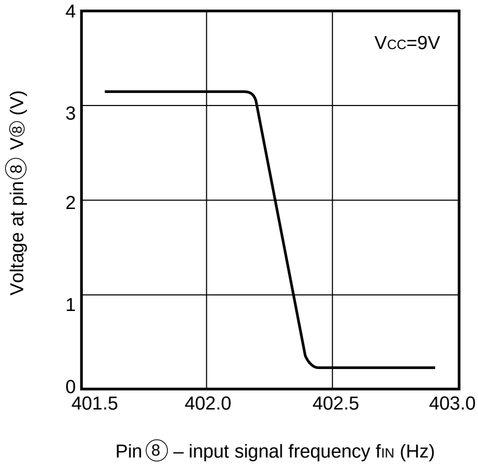
Stabilized voltage–ambient temperature characteristics



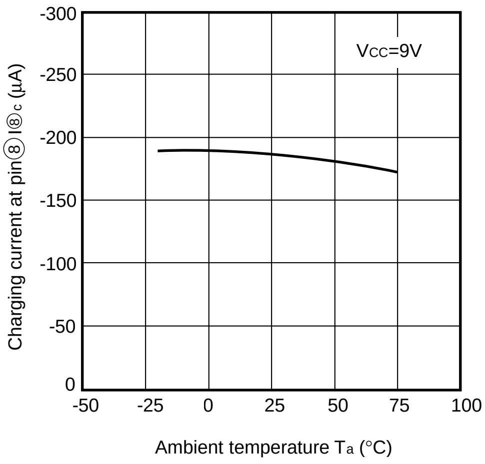
Stabilized voltage–Source current characteristics of pin⑥



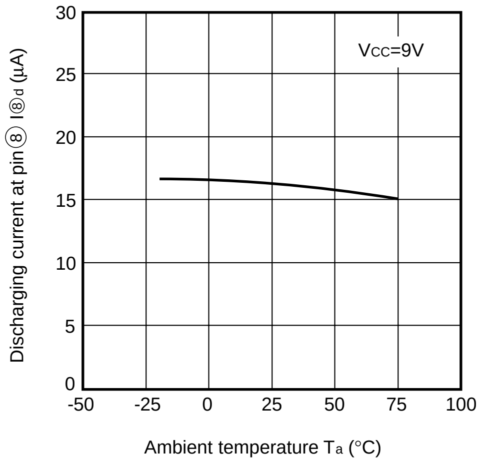
Voltage at pin⑧ – Input signal frequency characteristics



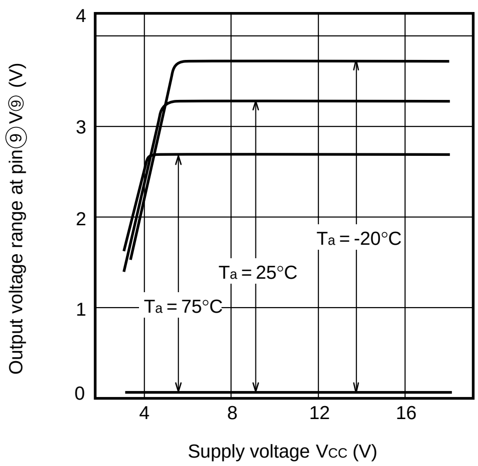
Charging current at pin⑧ – Ambient temperature characteristics



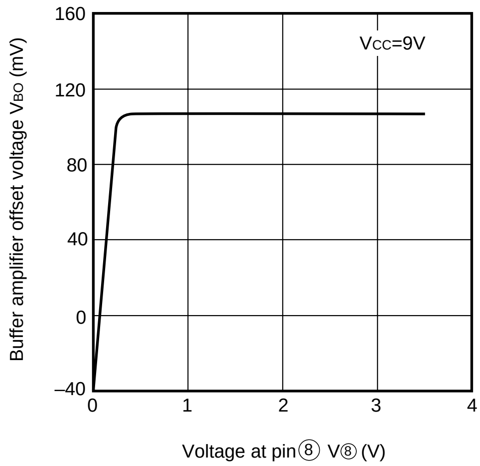
Discharging current at pin⑧– Ambient temperature characteristics



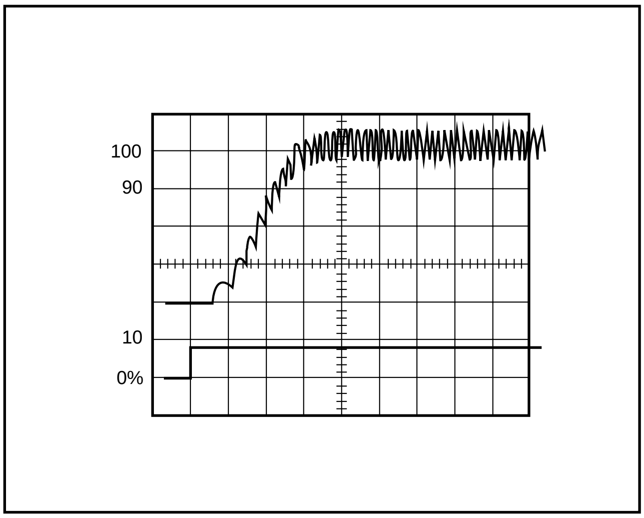
Output voltage range at pin⑨ – Supply voltage characteristics



Buffer amplifier offset voltage – Voltage characteristics at pin⑧



Application Characteristics Example



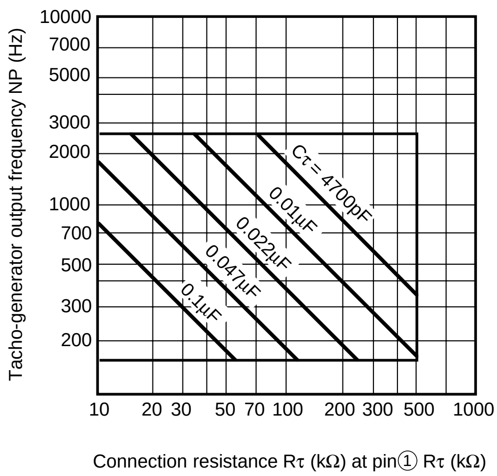
Upper side : Motor speed (FV conversion waveform of tacho-generator frequency)
Lower side : Supply voltage
Horizontal axis : 20 ms/div
Time constant of motor ≈ 100 ms

How to determine Rτ and Cτ

These constants determine the motor rotating speed. If the motor rotating speed and the number of poles of tacho-generator are assumed to be N and P, respectively, the following relational expression is generally established. According to the required rotating speed, select the constant in such a way that Rτ can be put in the range of 10kΩ – 500kΩ. When using a high resistance, take care for leak current that may flow on the surface of the printed circuit board.

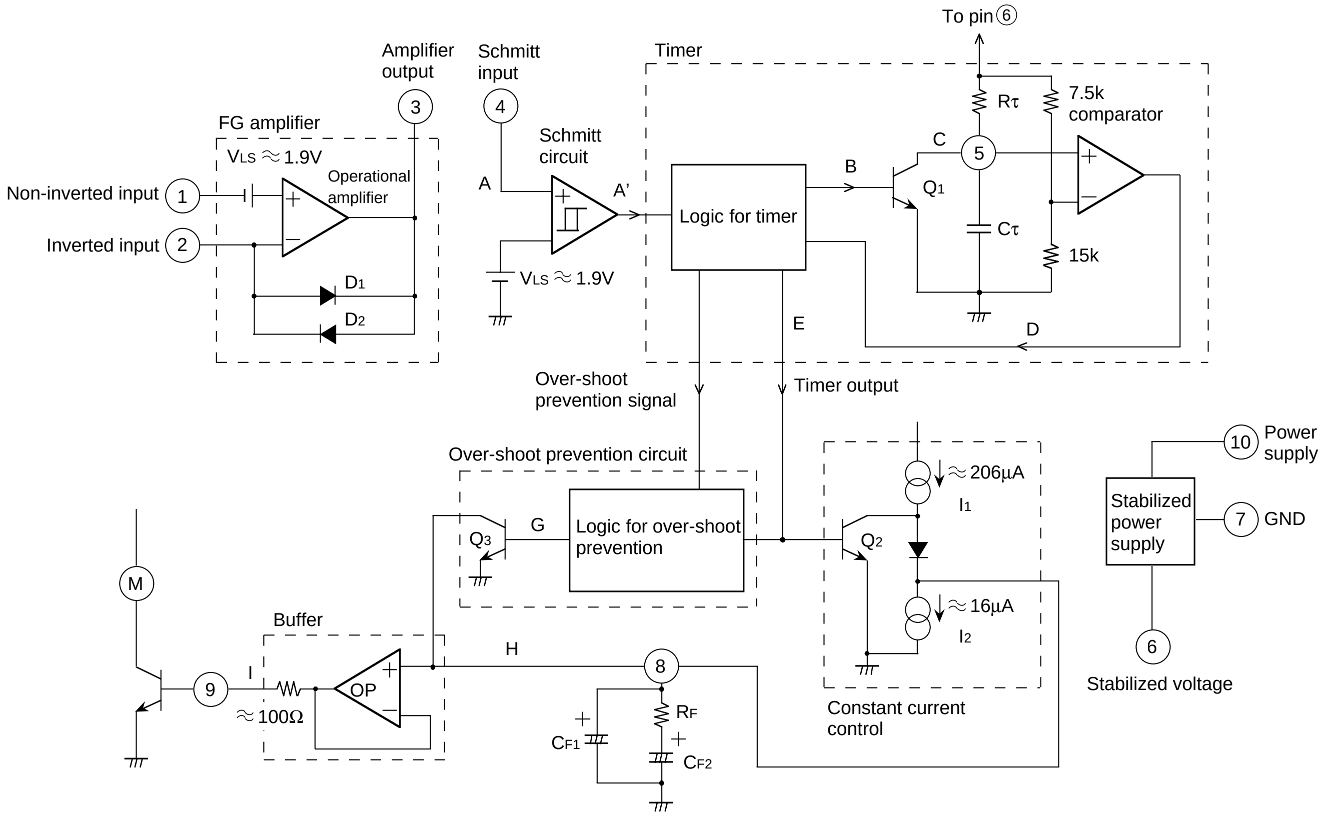
$$NP \approx \frac{1}{1.20 \cdot R\tau \cdot C\tau}$$

Tacho-generator output frequency – Connection resistance characteristics at pin①



Brief Description on M51971 Operation

Block Description



FG amplifier

The FG amplifier consists of an operational amplifier, revel shift circuit and diode for waveform clip.
When a DC block capacitor is connected to pin②, output DC voltage at pin③ becomes higher than DC voltage at pin① by V_{LS} (≈1.9V≈3V_{BE}).
AC signals centering around the GND can be therefore amplified easily. The clipper diode limits the output signal amplitude to ±0.7V (V_{BE}) max. and rapidly charges DC block capacitor with power supply turned ON.

Schmitt circuit

The Schmitt circuit is a comparator with histeresis, and has ON level of V_{LS} + 20mV and OFF level of V_{LS} - 20mV.

Timer

The timer generates basic time necessary for controlling the speed.
This timer is a one-shot circuit triggered with input signals and generates pulse of 1.1 $C_\tau R_\tau$ in pulse width.

Constant current control circuit

The constant current control circuit is controlled with output of timer circuit. The circuit generates, at pin⑧, source current of $I_1 - I_2$ (≈190μA) for the period without one-shot pulse and generates sink current of I_2 (≈16μA) for the period with one-shot pulse.
The ratio of I_1 to I_2 is characteristic to the IC. The frequency of the tacho-generator to be set is determined by the one-short pulse width and this current ratio (I_1 / I_2 ≈12.6).

$$T_G = T_\tau \times \frac{I_1}{I_1 - I_2} \approx 1.09 \times T_\tau$$

Where:
T_G : Tacho-generator signal frequency (set value)
T_τ : One-short pulse width

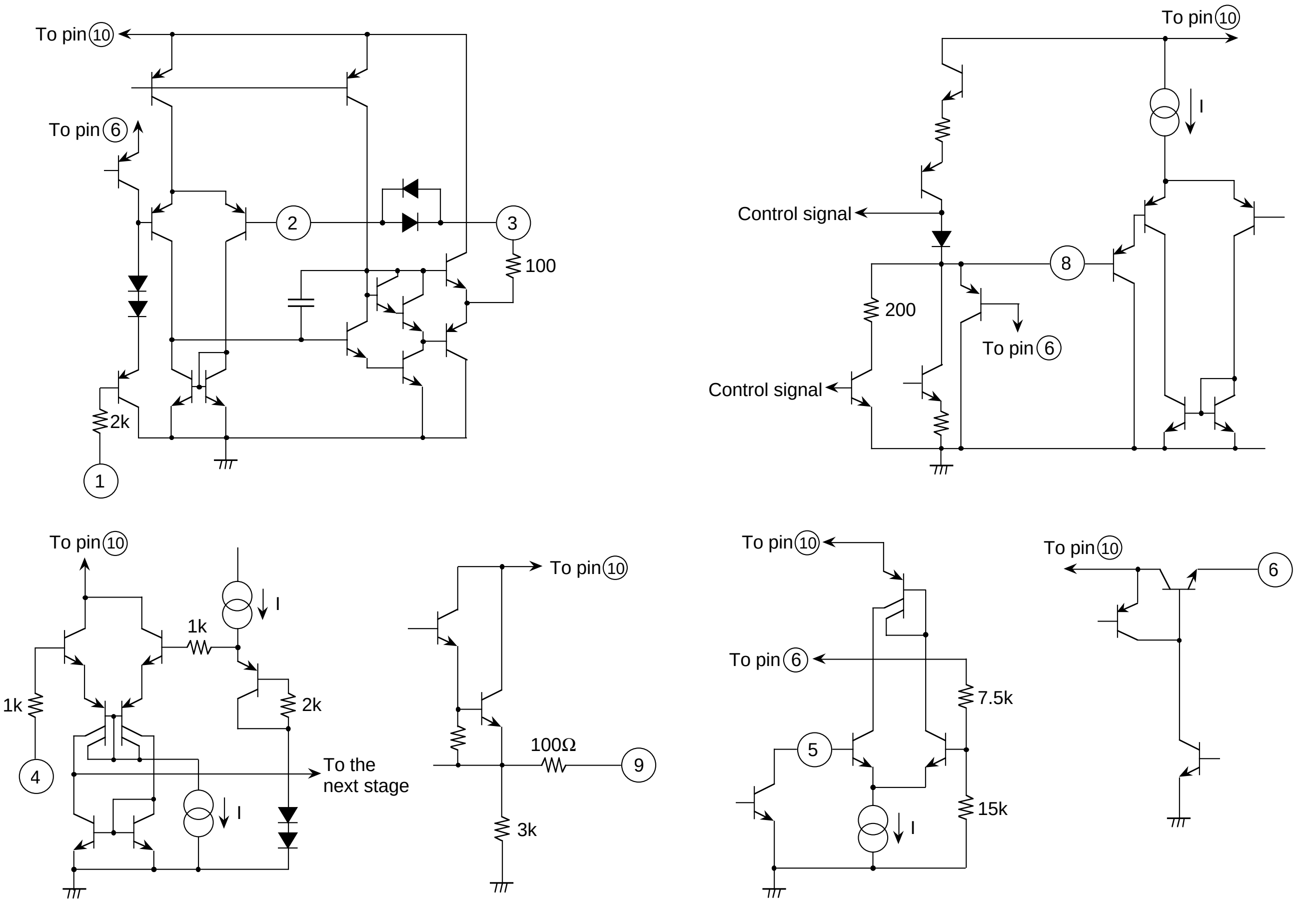
Over-shoot prevention circuit

The over-shoot prevention circuit operates when over-shoot is large in particular, e.g. the motor is suddenly released from lock status.
Q_3 is set to ON for the period of one-short pulse width (T_τ) when the signal period of the tacho-generator in a motor is shorter than the one-shot pulse. Generally, electric charge of C_{F1} is discharged for this period due to $R_F \cdot C_{F2} >> T_\tau$.

Buffer amplifier

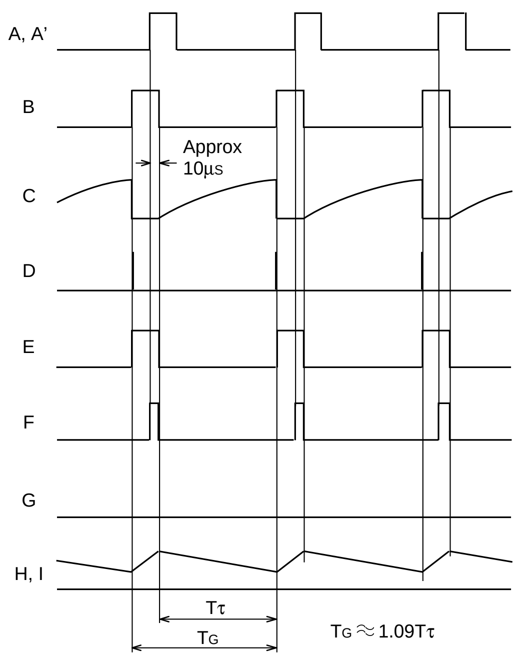
The buffer circuit is a voltage follower circuit using an operational amplifier. The input current is very small (10nA max.) and the circuit can drive the output current of 20mA.

Input/Output Circuit Drawing

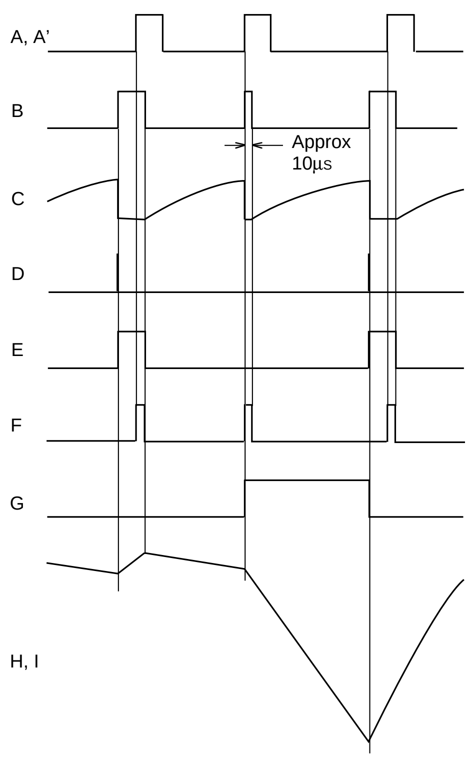


Timing Chart

I. In normal operation

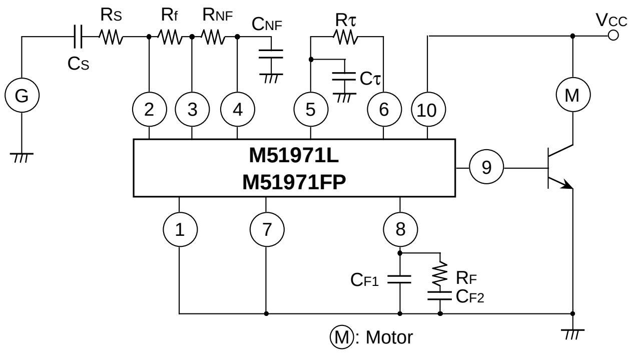


II. Normal operation to rapid discharging operation



Application Circuit Examples

I. When the output impedance of the tacho-generator is low;



Ⓜ: Motor
Ⓖ: Tacho-generator

C_S : Coupling capacitor for AC amplification
R_S, R_f : FG amplifier gain set resistance
R_{NF}, C_{NF} : Filter for noise removal
R_τ, C_τ : Time constant for motor speed setup
C_{F1}, C_{F2}, R_F : Phase compensation capacitance and resistance to stabilize integration and speed control systems

Notes:

1. The signal amplitude of the tacho-generator for set motor rotating speed must be set to 1 mV_{P-P} or more.
2. FG amplifier gain $\approx \sqrt{\dfrac{1+\omega^2{}_G C_S{}^2(R_S+R_f)^2}{1+\omega^2{}_G C_S{}^2 R_S{}^2}}$

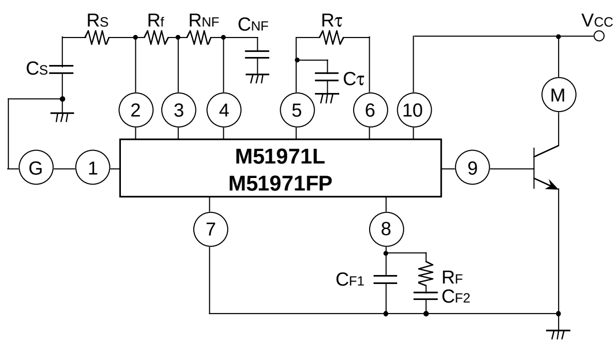
   ω_G : Angle frequency of tacho-generator signal
3. The C_S, R_S, R_{NF} and C_{NF} values are desirable to be selected as follows:
   (Values omitted)

$$C_S \leq 4.7\mu F$$

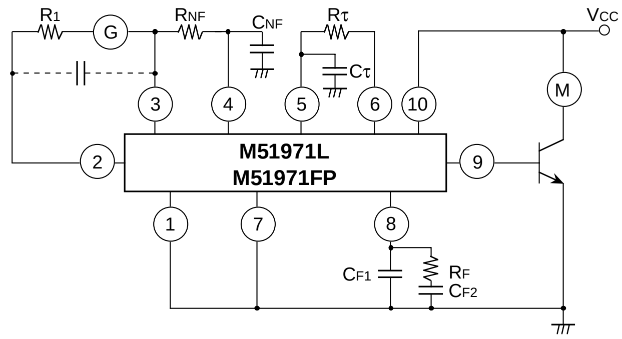
$$\frac{2}{\omega_G} \geq C_S R_S \geq \frac{1}{\omega_G}$$

$$R_{NF} \cdot C_{NF} \leq \frac{1}{\omega_G}$$

II. When the output impedance of the tacho-generator is high and the signal amplitude is small;

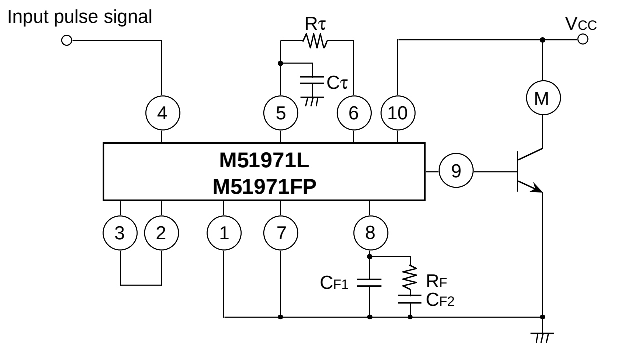


III. When the signal amplitude of the tacho-generator is large;



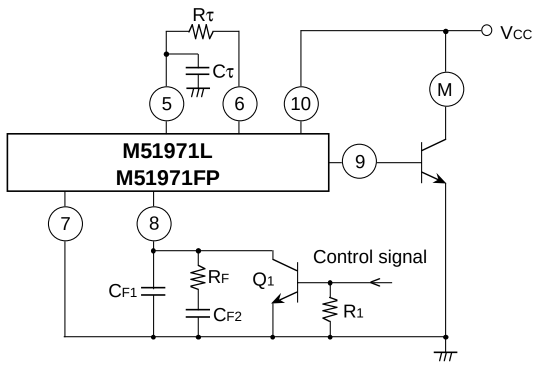
In the above three examples, the portion over V_f (0.7V) of the output waveform at pin③ is clipped in the built-in waveform clip diode.

IV. When the input waveform is pulse shape



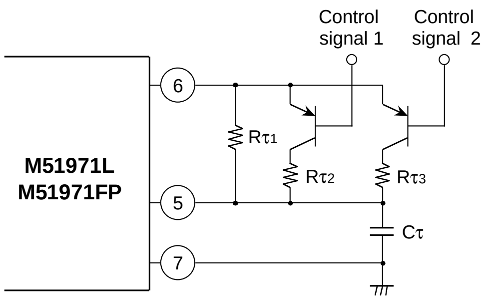
Note: The threshold voltage at pin④ to GND is approx. 1.9V.

V. When turning the motor ON/OFF with control signals;

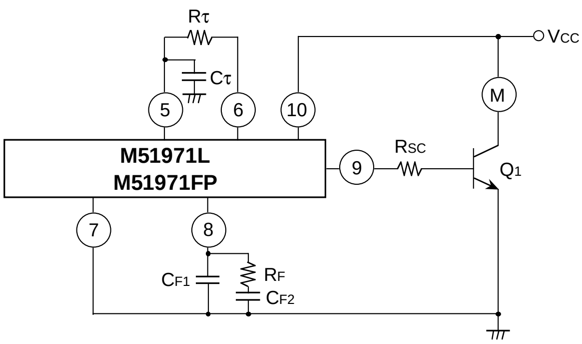


When Q_1 is set to ON : Stops the motor.
When Q_1 is set to OFF : Controls the motor rotating speed.

VI. To switch the set rotating speed in stages with control signals



VII. Limiting output current at pin⑨ to prevent the IC from heating

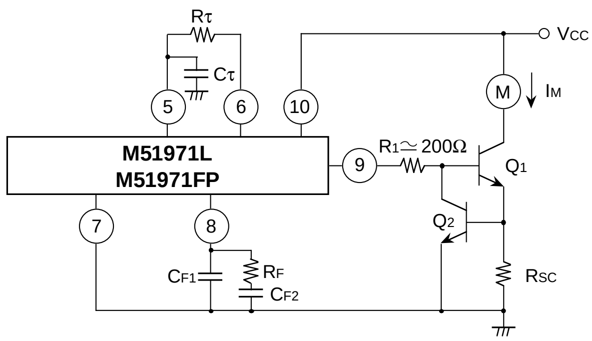


$$I_{⑨}max = \frac{V_{⑨}max}{R_{⑨} + R_{SC}} \; : V_{⑨}max \approx 3.2V, \; R_{⑨} \approx 100\Omega$$

(See the Electrical Characteristics and Typical Characteristics.)

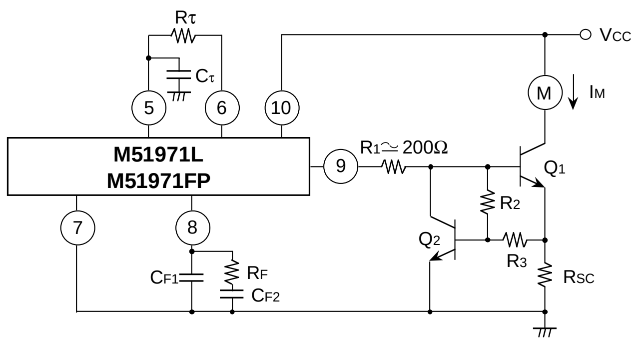
VIII. To limit drive current to the motor

1)



$$I_{Mmax} = \frac{V_{BE2}}{R_{SC}} \approx \frac{0.7V}{R_{SC}}$$

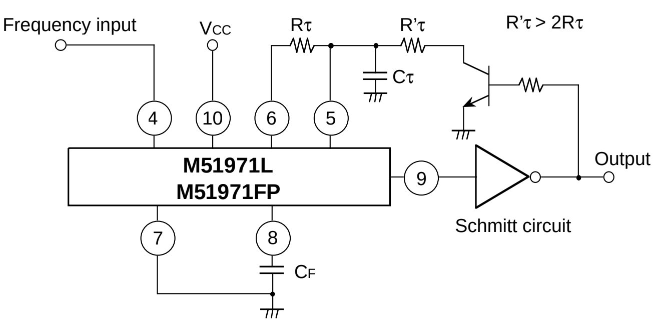
2) To reduce power loss due to a current limiting resistance



$$I_{Mmax} = (V_{BE2} - V_{BE1} \times \frac{R_3}{R_2 + R_3}) / R_{SC}$$

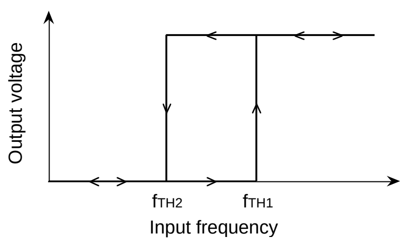
$$\approx \frac{0.7V \times R_2}{(R_2 + R_3) \cdot R_{SC}}$$

IX. Frequency comparator



Note: The selected Hysteresis of the Schmitt circuit must be more than or equal to the ripple current at pin⑧ (to prevent chattering).

Input/output transmission characteristics



$$f_{TH1} \approx \frac{1}{1.20 \times R\tau \cdot C\tau}$$

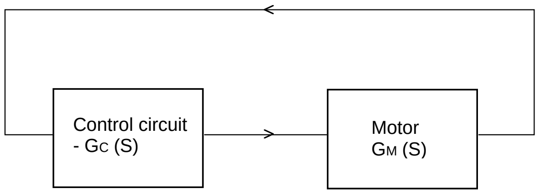
$$f_{TH2} \approx \frac{1}{1.09 \times R\tau // R'\tau \times C\tau \times \ln\left\{\frac{3(R\tau + R'\tau)}{R'\tau - 2R\tau}\right\}}$$

Hint for designing a stabilized speed control system

(Method for determining the filter constants (C_{F1}, C_{F2} and R_F) at pin⑧)

The filter constants at pin⑧ must be determined to satisfy the system stability.

1. Transfer Function of the Motor Speed Control System



Motor speed control system

The motor speed control system is a negative feedback system including a control circuit and a motor.
As the condition necessary for stable negative feedback, the phase must be generally 180° or less in the frequency area where the gain of open-loop transfer function ($G_C(S) \cdot G_M(S)$) is 1 or more.

2. Transfer Function of Motor

If the motor armature current and angular velocity are assumed to be Ia and ωv, respectively, the following equation is established.

$$\Delta T_g = K_T \cdot \Delta I_a = (SJ+D) \cdot \Delta\omega v \quad \cdots\cdots (1)$$

Where: T_g : Torque generated in the motor
K_T : Proportional constant between the torque generated in the motor and the armature current
J : Inertia moment of Motor and load
D : Coefficient of viscosity friction

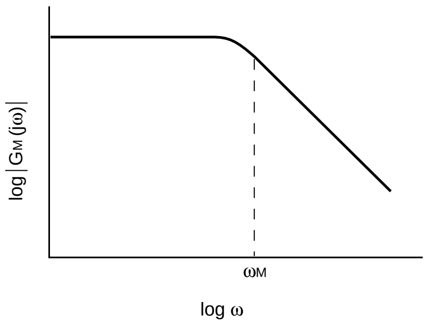
If the number of poles in the tacho-generator is assumed to be P, the relation of $\omega = P \cdot \omega v$ exists between tacho-generator angular frequency ω and motor angular velocity ωv and, therefore, the motor transfer function (transfer function including motor and tacho-generator) $G_M(S)$ takes a single-pole transfer function as follows:

$$G_M(S) = \frac{\Delta\omega}{\Delta I_a} = \frac{P \cdot K_T}{D \cdot (1 + S \cdot \frac{J}{D})} \quad \cdots\cdots (2)$$

$$= \frac{K_M}{1 + \frac{S}{\omega_M}} \quad \cdots\cdots (3)$$

Where: $K_M = \frac{P \cdot K_T}{D} \quad \cdots\cdots (4)$

$$\omega_M = \frac{D}{J} \quad \cdots\cdots (5)$$



Approximate motor transfer function

3. Transfer Function of Control Circuit Using the M51971

If input information is assumed to be given continuously (the tacho-generator frequency is assumed to be infinitely high), the transfer function from the input at pin④ to the output at pin⑨ is as follows:

$$G_{C(M51971)}(S) \equiv \frac{\Delta \text{ (output voltage at pin⑨)}}{\Delta \text{ (input frequency at pin④)}}$$

$$= \frac{T\tau\,(|I_{⑧c}| + |I_{⑧d}|)}{C_{F1} + C_{F2}} \times \frac{1 + S/\omega_{F1}}{S(1 + S/\omega_{F2})} \quad \cdots\cdots (6)$$

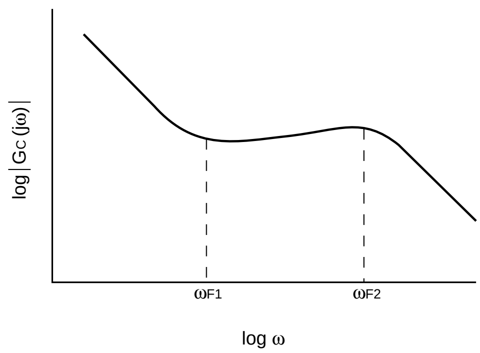
Where : $T\tau$: Timer pulse width $\approx$ 1.10 x $R\tau$ x $C\tau$
$I_{⑧c}$: Charging current at pin⑧
$I_{⑧d}$: Discharging current at pin⑧

$$\omega_{F1} \equiv \frac{1}{R_F \cdot C_{F2}}$$

$$\omega_{F2} \equiv \frac{C_{F1} + C_{F2}}{R_F \cdot C_{F1} \cdot C_{F2}}$$

If the gain of the circuit connected to the back of pin⑨ of the M51971 is assumed to be K_{CP}, transfer function $G_C(S)$ for the entire circuit is as follows:

$$G_C(S) = K_{CP} \times \frac{T\tau\,(|I_{⑧c}| + |I_{⑧d}|)}{C_{F1} + C_{F2}} \times \frac{1 + S/\omega_{F1}}{S(1 + S/\omega_{F2})} \quad \cdots\cdots (7)$$



Approximate transfer function of control circuit

4. Necessity for stable control

Stable control requires the gain of $G_C(S) \cdot G_M(S)$ to be the phase characteristics of 180˚ or less in a frequency area of 1 or more.
The relation of the phase and the gain is determined according to the Baud's theorem when all poles and zero points of the transfer function are placed at the left side of the complex sphere.
If $G_C(j\omega) \cdot G_M(j\omega)$ follows the Baud's theorem, in a frequency area of $|\ G_C(j\omega) \cdot G_M(j\omega)\ | \geq 1$ the inclination of gain of $G_C(j\omega) \cdot G_M(j\omega)$ must be -12dB/oct or more for stable control.
For the reason above, when the circuit constant is selected to achieve $\omega_{F1} \approx \omega_M$, and the inclination of the gain of each of $G_C(j\omega)$ and $G_M(j\omega)$ is -6dB/oct, that is, the following formula must be established with respect to the frequency of ω_{F2} where the inclination of the gain of $G_C(j\omega) \cdot G_M(j\omega)$ begins to be -12dB/oct.

$$|\ G_C(j\omega_{F2}) \cdot G_M(j\omega_{F2})\ | < 1 \cdots\cdots (8)$$

To make a precise control, the gain of open-loop transfer function must be large in the entire area of frequency.
The variation of the motor rotating speed attenuates due to disturbance at an inclination of -6dB/oct with the frequency of ω_M or more.
The capability of rotating speed control in the frequency area from ω_{F1} to ω_{F2} is determined by the gain of open-loop transfer function at $\omega_{F1}(\approx\omega_M)$. The following formula is established with $|\ G_C(j\omega_{F2}) \cdot G_M(j\omega_{F2})\ | < 1$ and when the inclination of the gain of $G_C(j\omega) \cdot G_M(j\omega)$ is almost equal to -6dB/oct with the frequency of ω_{F2} or less.

$$|\ G_C(j\omega_M) \cdot G_M(j\omega_M)\ | < \frac{\omega_{F2}}{\omega_{F1}} \approx \frac{\omega_{F2}}{\omega_M} \cdots\cdots (9)$$

Improvement of control precision in the frequency area from ω_{F1} to ω_{F2} requires the following conditions.

$$\omega_{F1} \approx \omega_M \cdots\cdots (10)$$

$$\frac{\omega_{F2}}{\omega_{F1}} >> 1 \cdots\cdots (11)$$

The K_{CP} or $C_{F1} + C_{F2}$ value must be set to satisfy formulae (4) and (5).

5. Influence on the Stability of Tacho-generator Frequency

The control system that is controlled with tacho-generator frequency, i.e. period, is a kind of sample hold system controlled with discrete information in the time axis.
Addition of extra phase delay to sample hold operation makes the system more unstable.
More precise transfer function $H^*(j\omega)\ (G_C{}^*(j\omega) \cdot G_M{}^*(j\omega))$ taking the above operation into account is as follows, when $H(j\omega)(G_C(j\omega) \cdot G_M(j\omega))$ is assumed to be the transfer function where this operation is not taken into account:

$$H^*(j\omega) = \frac{\sin\pi(\omega/\omega_G)}{\pi(\omega/\omega_G)}\, e^{-j\frac{2\pi\omega}{\omega_G}} \sum_{n=-\infty}^{\infty} H(j\omega + jn\omega_G) \cdots\cdots (12)$$

Where:
ω_G: Set value of tacho-generator frequency
That is, extra phase delay of $2\pi\omega/\omega_G$ (radian) must be taken into account.
That is, if the angular frequency satisfying $|\ G_C{}^*(j\omega) \cdot G_M{}^*(j\omega)\ | = 1$ is assumed to be ω_{0dB}, the following relation must be established.

$$\omega_G > 4 \cdot \omega_{0dB} \cdots\cdots (13)$$

When this determines ω_G, the possible gain of open-loop transfer function with ω_M can be obtained.

$$|\ G_C(j\omega_M) \cdot G_M(j\omega_M)\ | < 0.357 \times \frac{\omega_G}{\omega_M} \cdots\cdots (14)$$

This formula (14) must be satisfied in the control system using the frequency of the tacho-generator regardless of the control system and indicates that the upper limit value of the control gain with ω_M is inevitably determined when the motor and tacho-generator are determined.
Improvement of the control precision in the rotating speed requires $|\ G_C(j\omega_M) \cdot G_M(j\omega_M)\ | >> 1$. The following formula must be therefore established.

$$0.357 \cdot \frac{\omega_G}{\omega_M} >> 1 \cdots\cdots (15)$$

6. Conclusion

According to the theoretical consideration above, the design of speed control system making the best use of the characteristics of the motor is described as follows:

$$(1)\quad \omega_{F1} \equiv \frac{1}{R_F \cdot C_{F2}} \approx \omega_M \cdots\cdots (16)$$

If ω_M sharply changes with motor load changed, a circuit constant is desirable to be set around minimum ω_M.

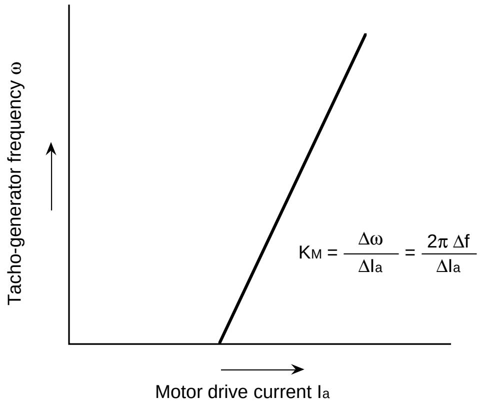
$$(2)\quad \omega_{F2} \equiv \frac{C_{F1} + C_{F2}}{R_F \cdot C_{F1} \cdot C_{F2}} \geq \frac{1}{4}\,\omega_G \cdots\cdots (17)$$

As C_{F1} is smaller, influence by ω_{F2} becomes smaller, but the peak-to-peak value of the output pin waveform becomes larger and the drive waveform becomes closer to pulse shape.
In most of design cases, both sides are therefore desirable to be equal.

(3) Selection of gain constant
Keeping the relation satisfying formulae (16) and (17) above, obtain a value for stable control by changing the K_{CP} or $C_{F1}+C_{F2}$ value.
If the motor set speed is divided into several stages, stage of lower speed is less stable. In this case, experiment must be made at lower speeds.

How to find rough value of motor transfer function

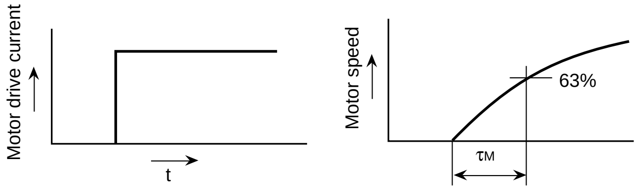
(1) Finding K_M



Plot the relation between the motor drive current and tacho-generator frequency to obtain the inclination.

(2) Finding ω_M

Though ω_M is found by measuring the motor frequency response, this method generally takes a lot of time and labor. Measurement of step response can find rough values easily.



Supply step-shape current to the motor in static status, measure time τ_M until the motor speed reaches 63% of the final speed and then find ω_M by the following formula.

$$\omega_M = \frac{1}{\tau_M} \quad \cdots\cdots\cdots (18)$$