

MEMS mirrors

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1. Overview

Our MEMS mirrors are miniature electromagnetic mirrors that incorporate MEMS technology. Within a magnetic field generated by the magnet, electrical current flowing in the coil surrounding the mirror produces a Lorentz force based on Fleming's left-hand rule, and this force drives the mirror. MEMS mirrors feature a wide optical deflection angle and high mirror reflectivity as well as low power consumption.

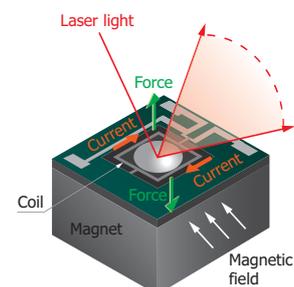
» Description

- ▶ Battery operation capability (5 V or less)
- ▶ Low power consumption
- ▶ Wide optical deflection angle of mirror
- ▶ Compact
- ▶ Evaluation circuit (USB interface) available (sold separately)

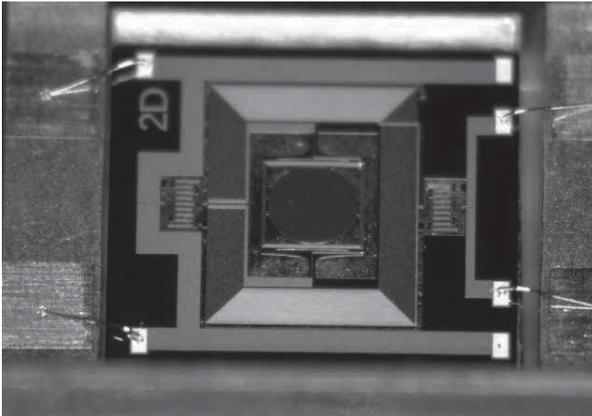
1-1 Structure

MEMS mirrors consist of a mirror chip and a magnet. The mirror chip includes a mirror, coil and torsion bars [Figure 1-1]. The mirror chip [Figure 1-2] is formed as a thin film in a portion of a silicon substrate using MEMS technology. Whereas electromagnetic mirrors are usually configured with a magnet surrounding the mirror chip, our MEMS mirrors use a small, powerful magnet positioned under the mirror chip, a design that achieves an ultra-compact size. The magnet is designed to provide an optimal magnetic field to the coil around the mirror. There are two types of MEMS mirrors: a single-axis one-dimensional type and a dual-axis two-dimensional type.

[Figure 1-1] Structure



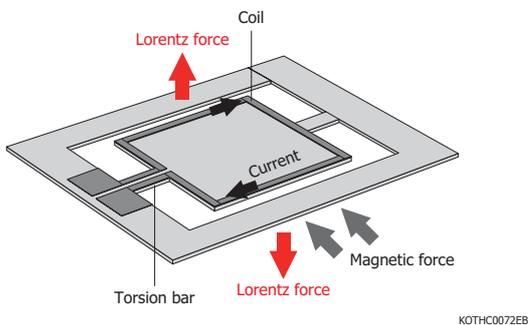
[Figure 1-2] Mirror chip



1 - 2 Operating principle

The basic operating principle for controlling the angle of the mirror is based on the Fleming's left-hand rule [Figure 1-3]. When a coil is placed perpendicular to a magnetic field, and current flows in the coil, force is exerted on the coil. This force is called the Lorentz force, and its magnitude is proportional to the strength of the current and magnetic field.

[Figure 1-3] Operating principle



The mirror is supported by beams called torsion bars. The torsion bar serves as the axis of rotation and also as a torsion spring for suppressing mirror rotation. When current flows through the coil around the mirror, a torque that rotates the mirror (Lorentz force) is produced, and an elastic force of the torsion bar spring is exerted in the opposite direction. The rotation of the mirror stops when these two forces balance each other. The angle of the mirror can be changed by varying the magnitude of the current flowing through the coil to control the torque.

MEMS mirrors resonate at their characteristic oscillation frequencies, which are determined by their mass, structure, and spring constant. Using resonance makes it possible to obtain large mirror deflection angles very quickly using only a small current. Since when resonating, mirror movements are represented as sine waves and complex movements are not possible,

resonance is used for applications where constant reciprocating motion suffices.

The operation mode that uses resonance is called resonant mode, and the mode that does not use resonance is called non-resonant mode. Because non-resonant mode is used for linear operation that takes advantage of the excellent linearity between the drive current and optical deflection angle, it is also called linear mode. Note that resonant mode is also called non-linear mode.

1 - 3 Drive method

There are several general MEMS mirror drive methods [Table 1-1]. Our MEMS mirrors are electromagnetic. This method requires only a low voltage to drive both resonant mode or non-resonant mode and offers excellent balance. Electromagnetic MEMS mirrors can be used in a wide variety of applications, such as in portable battery-powered devices.

[Table 1-1] General MEMS mirror drive methods

Drive method	Electrostatic method	Piezoelectric method	Electromagnetic method (used by Hamamatsu)
Rotational torque	Low	High	Medium
Drive voltage	50 V to 150 V	20 V to 50 V	-
Drive current	-	-	Approx. 20 mA
Power consumption	<< 1 mW (Approx. 0 mA)	High (Approx. 20 mA)	Approx. 100 mW (Approx. 5 V)
Optical deflection angle (Non-linear mode)	$\pm 10^\circ$	$\pm 25^\circ$	$\pm 25^\circ$
Optical deflection angle (Linear mode)	$\pm 5^\circ$	Difficult control	$\pm 15^\circ$

2. Operation mode

As mentioned in 2-1, “Operating principle,” there are two operation modes for MEMS mirrors: linear mode (non-resonant mode) and non-linear mode (resonant mode).

2 - 1 Linear mode

Linear mode is used to accurately control the optical deflection angle of the mirror by means of the drive current. The relationship between the drive current and optical deflection angle of the mirror exhibits excellent linearity, and the angle reproducibility relative to the drive current is high. Note that linear mode is not suitable for high-speed operation. The mirror must be driven at a frequency lower than the specific resonant frequency of the mirror to prevent resonance. Normally, a frequency in the range of 1/10 the resonant frequency or less to 1/5 the resonant frequency or less is recommended.

2 - 2 Non-linear mode

Non-linear mode is a resonance operation mode at the resonant frequency of the mirror. High-speed operation is possible, but the optical deflection angle of the mirror cannot be controlled highly accurately. Non-linear mode is used to drive a non-linear mode dedicated MEMS mirror or to drive a non-linear mode dedicated axis. Driving a mirror in non-linear mode requires the application of either a sine-wave or square-wave current signal at the same frequency as the resonant frequency of the mirror.

In non-linear mode, even if a square wave is applied, the deflection angle of the mirror operates as a sine wave. Further, a phase lag occurs in the optical deflection angle relative to the drive current.

2 - 3 Mirror types and operation modes

There are two types of MEMS mirrors: a single-axis one-dimensional type and a dual-axis two-dimensional type. The two-dimensional type has types with different modes for each axis [Table 2-1].

Currently, Hamamatsu provides a portion of the MEMS mirrors in Table 2-1. Contact us for future product release plans.

[Table 2-1] MEMS mirror types

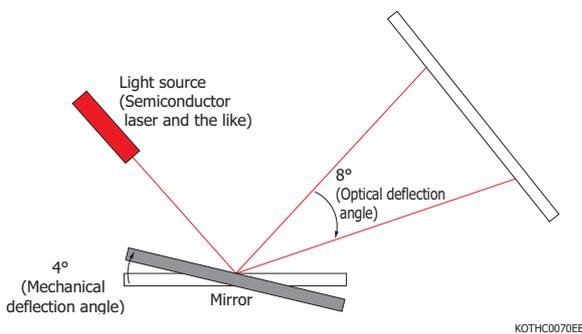
Type	Operation mode		Main application
	Slow axis	Fast axis	
One-dimensional (single axis)	Linear mode	-	Measurement
	-	Non-linear mode	High-speed measurement
Two-dimensional (dual axis)	Linear mode	Linear mode	Measurement
	Linear mode	Non-linear mode	Image display
	Non-linear mode	Non-linear mode	High-speed image display

3. Specifications

3 - 1 Definition of optical deflection angle

Hamamatsu defines the MEMS mirror deflection angle using optical deflection angle, not mechanical deflection angle. The optical deflection angle is an angle formed between the incident light and reflected light when a light beam from a light source is directed at a mirror. It is twice the mechanical deflection angle, which is the tilt angle of the mirror [Figure 3-1].

[Figure 3-1] Optical deflection angle



3 - 2 Absolute maximum ratings

Table 3-1 shows an example of the absolute maximum ratings of a MEMS mirror (S12237-03P: linear mode dedicated one-dimensional MEMS mirror). MEMS mirrors must be used within the absolute maximum ratings.

[Table 3-1] Absolute maximum ratings (S12237-03P)

Parameter	Symbol	Value	Unit
Drive current	I_s max	± 20	mA
Maximum optical deflection angle	θ_s max	± 18	degrees
Operating temperature	T_{opr}	0 to +60	°C
Storage temperature	T_{stg}	-10 to +80	°C

The maximum optical deflection angle is defined as the angle that if the mirror deflection angle were to be increased further the mirror would be damaged as a result of the mirror making contact with the magnet or the other parts.

The drive current is defined as the current that may melt the coil wires. When the drive current is increased,

the maximum optical deflection angle is reached before the drive current reaches its absolute maximum rating. The drive current must not be increased to its absolute maximum rating. The magnitude of the drive current must be observed carefully so that the maximum optical deflection angle is not exceeded. Particularly in high-speed operation, even when the mirror is driven with the same current, the maximum optical deflection angle may be exceeded as the resonant frequency is approached, causing damage to the mirror. Deflection angle especially at the resonant frequency is several ten times or higher than that at low frequencies, which makes it difficult to control. As such, do not drive the mirror at resonant frequency for linear mode dedicated MEMS mirrors and axes.

Non-linear mode dedicated MEMS mirrors and axes must be driven at the resonant frequency. Note that in non-linear mode, the optical deflection angle when the mirror is driven at the resonant frequency differs significantly from the optical deflection angle at other frequencies. Driving the mirror at frequencies other than the resonant frequency may produce unexpected optical deflection angles even when the drive current is adjusted to obtain the optical deflection angle under the recommended operating conditions and may damage the mirror.

When driving a non-linear mode dedicated MEMS mirror or axis, use drive signals produced by a reference signal generator with excellent temperature stability.

3 - 3 Recommended operating conditions

The recommended operating conditions are for guaranteeing section 3-4, "Electrical and optical characteristics." Note that even if the recommended operating conditions are exceeded slightly, as long as the absolute maximum ratings are not exceeded, the MEMS mirror will not be damaged.

Table 3-2 shows the recommended operating conditions for the S12237-03P. The recommended operating condition for the optical deflection angle is ± 15 degrees, but the absolute maximum rating is ± 18 degrees, so there is about a 3-degree margin. Further, the recommended operating condition for the drive frequency is DC to 100 Hz. For frequencies higher than 100 Hz, the MEMS mirror operates in non-linear mode and may be damaged, so we recommend that you use it within the recommended operating condition range.

[Table 3-2] Recommended operating conditions (S12237-03P)

Parameter	Min.	Typ.	Max.	Unit
Operation mode	Linear mode			-
Optical deflection angle	-15	-	+15	degrees
Drive frequency	DC	-	100	Hz

3 - 4 Electrical and optical characteristics

Table 3-3 shows the electrical and optical characteristics of the S12237-03P.

[Table 3-3] Electrical and optical characteristics (S12237-03P)

(Recommended operating conditions unless otherwise noted)

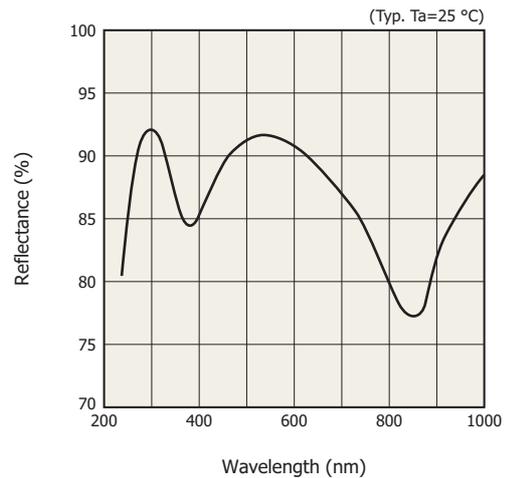
Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit	
Mirror size	A		φ2.59	φ2.60	φ2.61	mm	
Drive current	Is	Ta=25 °C fs=DC	θs=-15°	-18	-15	-12	mA
			θs=+15°	+12	+15	+17	
Resonant frequency	fs-R	Is=0.6 mA p-p	500	530	560	Hz	
Reflectance	Or	λ=450 to 650 nm	85	-	-	%	
Coil resistance	Rs	Ta=25 °C, Is=0.2 mA	145	165	185	Ω	

» Mirror reflectivity

Aluminum metal is deposited on the mirror surface of the MEMS mirror providing high reflectance in the visible region. Figure 3-2 shows the relationship between wavelength and reflectance. For the three primary colors of red, blue, and green, reflectance is 85% or higher.

Note that reflection from the chip surface outside than the mirror area is not zero, so if the beam size irradiated from the light source is greater than the mirror size, the reflection appears as stray light on the target. Design the optical system so that the beam size is smaller than the mirror size.

[Figure 3-2] Mirror reflectivity



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» Drive current

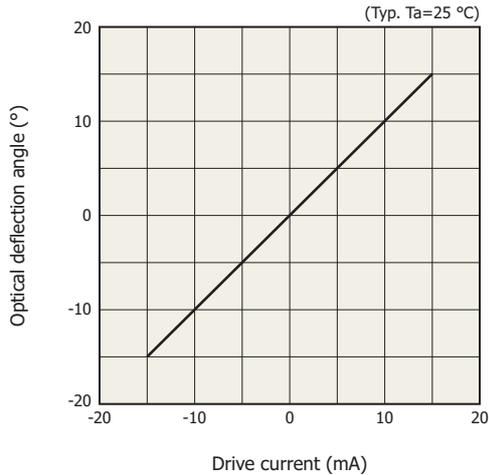
Drive current is an important parameter that defines the optical deflection angle. Drive current, in linear mode and non-linear mode, is defined as values that can achieve the minimum and maximum values of the optical deflection angle under recommended operating conditions.

Figure 3-3 shows the optical deflection angle versus drive current characteristics of the S12237-03P. The relationship between the optical deflection angle and drive current can be approximated by a straight line. From the graph that connects the minimum and maximum drive currents with a straight line, the current for a given deflection angle can be calculated. This method enables the mirror to be controlled to any optical deflection angle with an accuracy of 1° or less (if you want to control the mirror with even higher accuracy, see chapter 5, “High accuracy control.”)

In Figure 3-3, the polarity of the drive current represents the direction of the drive current flowing through the MEMS mirror coil. The direction of the drive current can be used to change the direction of the optical deflection angle. In Figure 3-3, the drive current in one direction produces 15° of optical deflection angle and in both positive and negative directions produce a total of 30°.

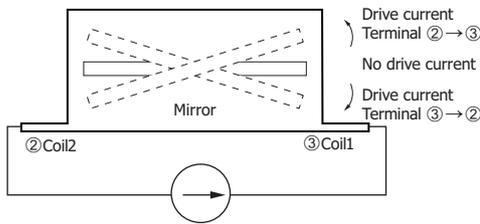
Note that the optical deflection angle characteristics of linear mode dedicated MEMS mirrors are measured using DC operation.

[Figure 3-3] Optical deflection angle vs. drive current (S12237-03P)



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[Figure 3-4] Drive current and optical deflection angle directions (S12237-03P)

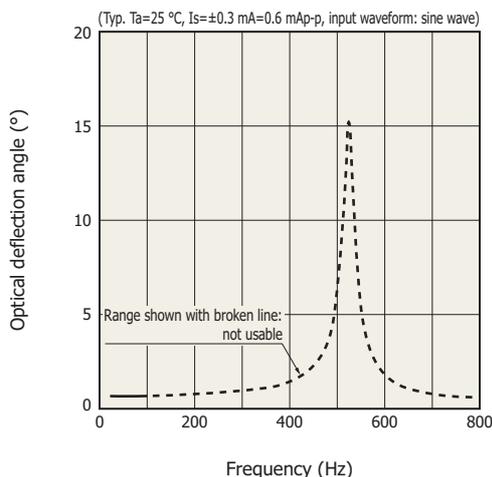


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» Resonant frequency

Resonant frequency in linear mode serves as a guide for determining the range of drive frequencies. Figure 3-5 shows the frequency characteristics of the S12237-03P. At the resonant frequency, an extremely small drive current of 0.6 mA produces a large optical deflection angle. A small shift in the drive current can cause the absolute maximum rating of the optical deflection angle to be exceeded and may damage the mirror. Never drive the mirror at a frequency near the resonant frequency in linear mode.

[Figure 3-5] Frequency characteristics (S12237-03P)

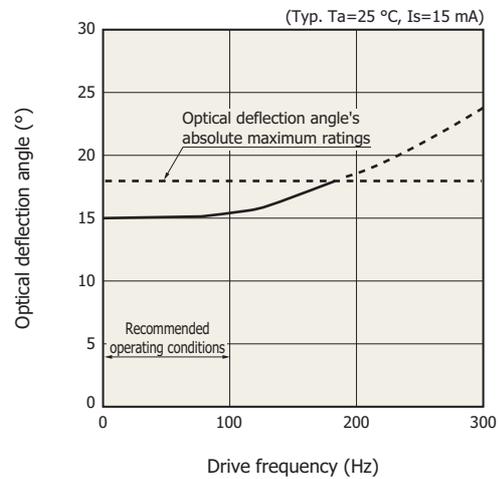


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» Drive frequency

Figure 3-6 shows the frequency characteristics of the optical deflection angle in the low frequency region. Here, a sine wave with a 15 mA current amplitude is driving the mirror. At the recommended drive frequencies of 100 Hz or less, the graph shows nearly flat frequency characteristics, but as the drive frequency is increased, the optical deflection angle increases. At around 180 Hz, the optical deflection angle's absolute maximum rating of 18° is reached, and the possibility of damaging the mirror increases. You must drive the MEMS mirror under the recommended operating conditions (drive frequency: DC to 100 Hz).

[Figure 3-6] Optical deflection angle vs. drive frequency (S12237-03P)



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» Coil resistance

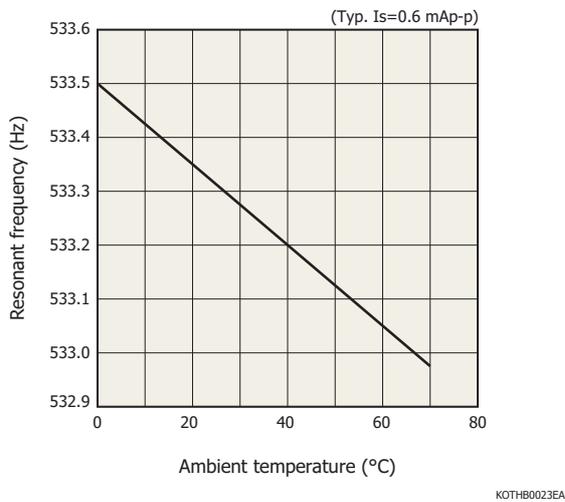
The inductive component due to the coil wiring around the MEMS mirror is extremely small. It is less than several microhenries for linear mode dedicated MEMS mirrors and 0.1 μ H or less for non-linear mode MEMS mirrors. As such, at the linear mode frequency region around several hundred hertz and at non-linear mode frequency region around several megahertz, the coil impedance is 0.1 Ω or less, and this can be ignored when compared to the pure resistivity of the coil. In most cases, the coil resistance can be assumed to be its pure resistance. Note that the coil resistance indicated in the electrical and optical characteristics is for 25 °C.

» Temperature characteristics

In MEMS mirrors, the coil resistance, the magnetic force of the magnet, the resonant frequency, and the like have temperature characteristics. To control the mirror's optical deflection angle with high accuracy over a wide temperature range, you must pay attention to the temperature characteristics.

Figure 3-7 shows the temperature characteristics of resonant frequency for the S12237-03P.

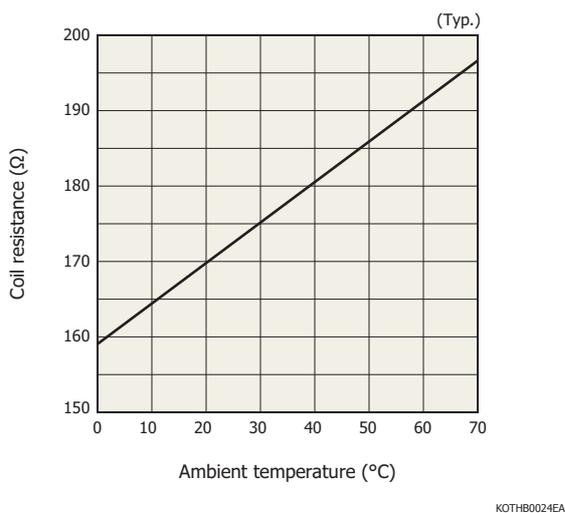
[Figure 3-7] Temperature characteristics of resonant frequency (S12237-03P)



In the operating temperature range, the resonant frequency varies by about 0.1 to 0.2%, and the effect on the characteristics can be ignored.

Figure 3-8 shows the temperature characteristics of coil resistance for the S12237-03P. When the MEMS mirror is driven by a voltage source, the temperature characteristics of the coil resistance cannot be ignored. When the MEMS mirror is driven by a current source, the temperature characteristics of the coil resistance can be ignored. Therefore, we recommend that the MEMS mirror be driven by a current source.

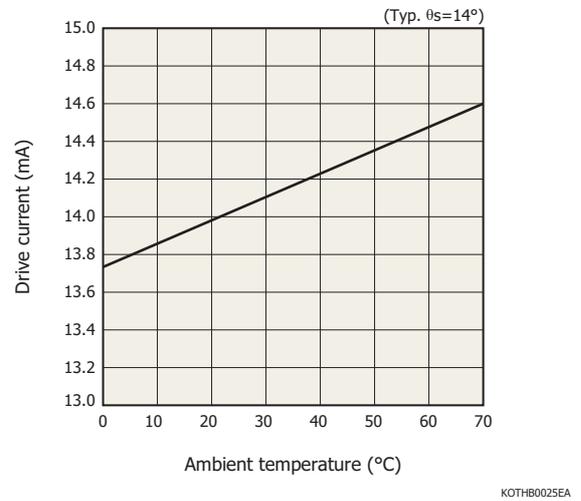
[Figure 3-8] Temperature characteristics of coil resistance (S12237-03P)



The temperature characteristics of the magnetic force of the magnet are not easy to measure. As such, the changes in the magnetic force due to the magnet temperature is estimated from the changes in the drive current used to keep the optical deflection angle

constant. Figure 3-9 shows the changes in the drive current used to keep the optical deflection angle constant when the temperature changes.

[Figure 3-9] Temperature characteristics of drive current (S12237-03P)



In the measurement of Figure 3-9, a current source was used. Current is not affected by coil resistance changes due to temperature. Therefore, it can be assumed that the drive current is changing due to the changes in the magnetic force due to temperature.

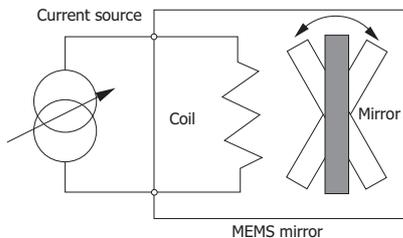
In Figure 3-9, we can see that the changes in the magnetic force due to temperature is causing a deflection angle error of about 1°. Because the coil resistance changes according to temperature, the chip temperature can be monitored by reading the coil resistance. And this makes temperature correction possible.

4. How to use

4 - 1 Drive method

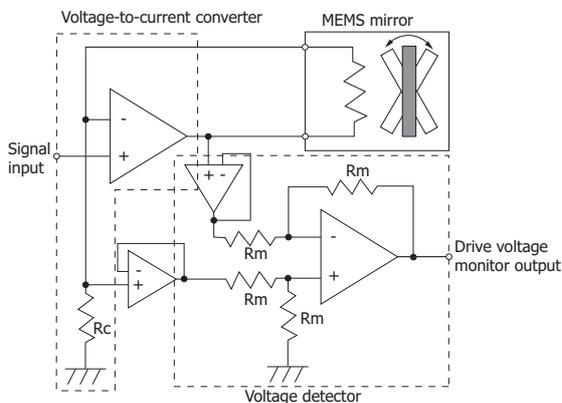
If a voltage source is used to control the drive current, the drive current is determined by the applied voltage and coil resistance. Coil resistance changes due to the heat generated by the drive current and ambient temperature. As such, to make a given current flow through the coil using a voltage source, you must monitor the coil resistance and adjust the voltage. To vary the optical deflection angle continuously, you must also take back electromotive force into consideration. When the MEMS mirror is operated in linear mode, the drive frequency is relatively low, so the back electromotive force is extremely small and can be ignored in some cases, but when operated in non-linear mode, it cannot be ignored in most cases. When a voltage source is used, the actual voltage applied to the coil is the voltage obtained by subtracting the back electromotive force from the applied voltage, and this makes controlling the drive current difficult. Therefore, a current source is used to drive the MEMS mirror in order to control the current flowing through the coil [Figure 4-1]. Figure 4-2 shows an example of a driver circuit.

[Figure 4-1] Drive example



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[Figure 4-2] Example of driver circuit



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Driving a MEMS mirror only requires a voltage-to-current converter. Adding further a voltage detector enables the detection of back electromotive force and coil resistance. Drive current of the MEMS mirror in Figure 4-2 is expressed by equation (4-1) using input voltage v_s .

$$I_s = \frac{V_s}{R_c} \dots\dots\dots (4-1)$$

Drive current: I_s
Current detection resistor: R_c

Using a metal film resistor with a small temperature coefficient as a current detection resistor allows the drive current to be controlled down to 0.1% or less in the operating temperature range. The voltage detector section detects the potential difference that is actually applied across the coil terminals of the MEMS mirror and outputs it to the drive voltage monitor output terminal. The coil resistance can be determined by dividing this voltage by the drive current given by equation (4-1).

4 - 2 Mirror size and beam size

For the light source used with the MEMS mirror, we recommend a semiconductor laser (except when a specific light source is required). The optical system must be designed so that the beam size of the light source is sufficiently smaller than the mirror size. Semiconductor lasers are suited to achieve small beam sizes.

The MEMS mirror is designed so that its mirror size is maximum within the range that provides the required optical deflection angle versus drive current characteristics and frequency characteristics. For example, the diameter of the mirror in the S12237-03P is 2.6 mm. This is sufficiently large to be used in combination with semiconductor lasers and other coherent light sources in a wide range of applications. However, the mirror size may not be enough depending on the application, so it is necessary to check that the MEMS mirror can provide the required performance beforehand. When a MEMS mirror scans light, the distance from the light source to the mirror and the distance to the screen that the reflected light from the mirror is to be projected on must be verified.

Even with a collimator lens, it is not possible to make the laser light an ideal collimated light. An ideal Gaussian beam has a divergence angle due to diffraction. The divergence half-angle θ is expressed by equation (4-2).

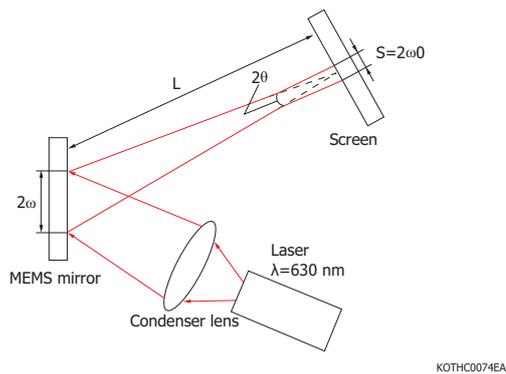
$$\theta = \tan^{-1} \left(\frac{\lambda}{\pi \omega_0} \right) \dots\dots\dots (4-2)$$

λ : laser light wavelength [μm]
 ω_0 : beam waist [μm]

Beam waist is the radius of the beam at the point of focus when the laser light is concentrated with an optical system. Design the optical system to maximize the beam waist to make the beam as close to a collimated light as possible.

Figure 4-3 shows an optical system in which a 630 nm wavelength laser beam is concentrated, reflected at the mirror, and focused on a screen at distance L from the mirror. The beam size on the screen is S ($=2\omega_0$). In this condition, check whether the beam size on the mirror surface is smaller than the mirror size.

[Figure 4-3] Optical system



If distance L to the screen is 100 mm, and the beam is focused on the screen at $S=\phi 100\ \mu\text{m}$, the beam waist ω_0 is 50 μm . When $\lambda=0.63\ \mu\text{m}$ is substituted in equation (4-2), the beam divergence half-angle θ is 4×10^{-3} [rad]. The radius of the beam at the mirror position is $\omega=100\ \text{mm} \times \tan(\theta)=400\ \mu\text{m}$, and the beam size is $\phi 800\ \mu\text{m}$. The beam size is typically defined in area at $(1/e)^2$ the peak power, so even when the spreading of the beam is considered, the S12237-03P mirror size $\phi 2.6\ \text{mm}$ is sufficiently large.

If the distance L to the screen is 1 m and you want to focus the beam at $\phi 100\ \mu\text{m}$ on the screen, calculating the required mirror size in the same manner yields $\phi 8\ \text{mm}$ or greater, and the S12237-03P mirror size is not enough to cover this diameter. However, if the beam can be focused at $\phi 1\ \text{mm}$ on the screen, because the beam divergence angle θ is 4×10^{-2} [rad], the diameter at the mirror position is 1.8 mm, and the S12237-03P mirror size can cover this diameter.

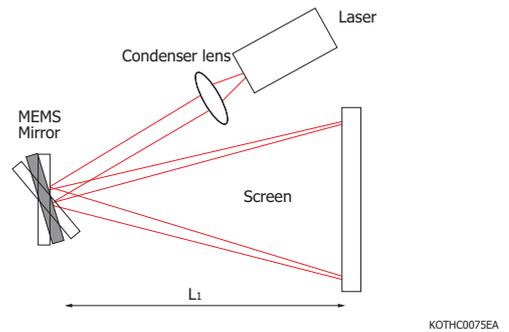
In this way, consider the required beam size and the distance between the mirror and the screen, and check whether the mirror size of the MEMS mirror is sufficient.

4 - 3 Measurement system of optical deflection angle vs. drive current characteristics

As explained in section 3-4, “Electrical and optical characteristics,” the optical deflection angle can be

controlled down to 1° or less by approximating the relationship between the optical deflection angle and drive current with a straight line. Controlling the optical deflection angle at even a higher accuracy requires highly accurate measurement of the relationship between the optical deflection angle and drive current. Figure 4-4 shows an example of such measurement system.

[Figure 4-4] Simple measurement system of optical deflection angle vs. drive current characteristics



The light output from a laser device is concentrated with a condenser lens. The focus position is set on the screen surface where the mirror is directed at. The reflected light from the mirror is projected at a given position on the screen according to the mirror's optical deflection angle. This position is detected to measure the optical deflection angle.

A screen with a scale (e.g., graph paper) is used so that the projected position on the screen can be determined. If you want to detect positions at about 1 mm resolution on the screen, we recommend that the beam size be set to about 500 μm . Making the beam size too small will increase the beam size on the mirror surface due to diffraction. When the wavelength is 632 nm and the beam size 500 μm , the focusing numerical aperture (NA) is about 8×10^{-4} . When a collimated light laser is used, it may be better to insert a beam expander before the condenser lens to widen the beam.

The relationship between the beam position P on the screen and optical deflection angle is expressed by equation (4-3).

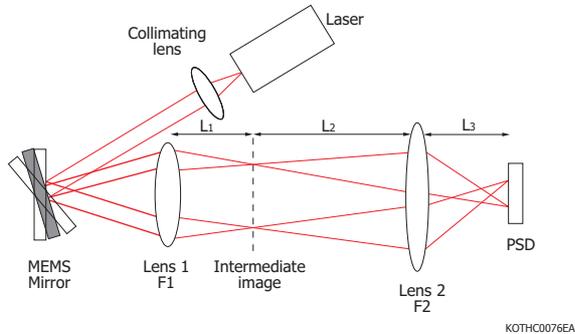
$$P = L_1 \times \tan(\theta) \dots\dots\dots (4-3)$$

With Figure 4-4, if $L_1=30\ \text{cm}$ and the projected positions on the screen are measured at 1 mm resolution, the optical deflection angle resolution is 0.2° . Making L_1 longer can improve the optical deflection angle resolution. If you want to improve the optical deflection angle resolution further or obtain optical deflection angle data automatically, you need to use an optical sensor that detects projected positions [image sensor or position sensitive detector

(PSD)] in place of the screen. As the photosensitive area of optical sensors is not large, an optical system must be used to reduce the projection area.

Figure 4-5 shows a measurement system that uses a PSD for the optical sensor.

[Figure 4-5] Measurement system of optical deflection angle vs. drive current characteristics (using a PSD)



The laser beam is made close to collimated light using a collimating lens. Then, the laser beam is reflected by the MEMS mirror, and the deflection angle information of the beam is converted into position information by lens 1 at the intermediate image position. Set distance L1 from the lens 1 to the intermediate image equal to the focal distance of lens 1. The image size A at this point is expressed by equation (4-4).

$$A = 2 \times F_1 \times \tan(\theta_{\max}) \dots\dots\dots (4-4)$$

F₁ : focal distance of lens 1
 θ_{max}: optical deflection angle's full width at half maximum

For example, if F₁=30 mm and θ_{max}=15°, image size A is 8 mm. If a PSD that can detect this size is placed at the intermediate image position and measurement is taken, the latter stage of the optical system is not necessary. If the photosensitive area of the PSD is small, lens 2 is used to reduce the image. If the distance from the intermediate image to lens 2 is L₂, and the distance from lens 2 to the PSD is L₃, the focal distance of lens 2 must be set to F₂ in equation (4-5).

$$\frac{1}{F_2} = \frac{1}{L_2} + \frac{1}{L_3} \dots\dots\dots (4-5)$$

The intermediate image in this condition is scaled by a factor of L₃/L₂, and the image is formed on the PSD. For the PSD, we recommend our C10443 series PSD module.

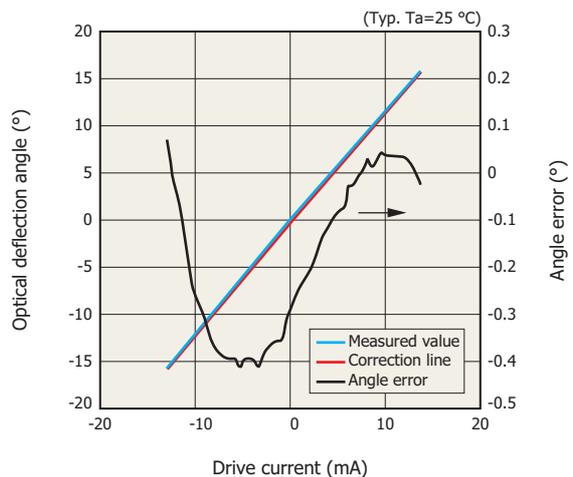
5. High-accuracy control

This chapter explains the parameters that are necessary if you want to control MEMS mirrors with high accuracy. Consideration of these parameters enables the effects of operating temperature on the optical deflection angle to be corrected to some degree. If you need to control a MEMS mirror with even higher accuracy, obtain the necessary parameters in the operating conditions and feed back the values.

5-1 Correction curve for optical deflection angle vs. drive current characteristics

The optical deflection angle versus drive current characteristics of MEMS mirrors are not linear in the strict sense. Driving a MEMS mirror by assuming linearity leads to errors in the optical deflection angles. To avoid this, you need to obtain multiple sets of optical deflection angle and drive current data within the recommended operating conditions of optical deflection angles, calculate the correction curve based on the data, and use it to adjust the drive current. Figure 5-1 shows the angle errors that appear when a correction line is created by connecting the drive currents in the recommended operating conditions of optical deflection angles (±15°).

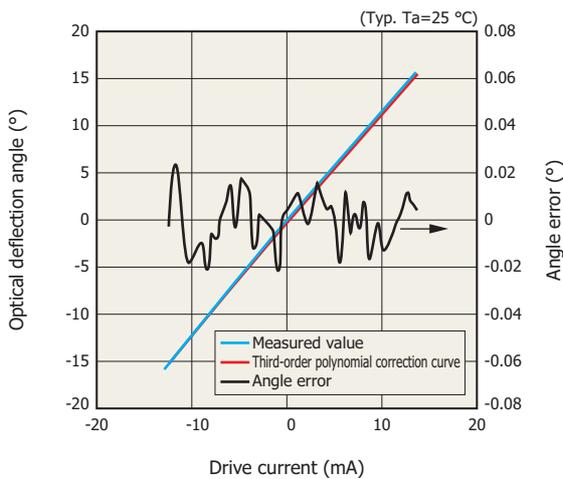
[Figure 5-1] Correction line and angle error



In Figure 5-1, the correction line, especially the drive current in the negative region, is shifted relative to the actual values. The maximum angle error is about 0.4° in the operating optical deflection angle range. Note that when differences between each device and temperature characteristics are considered, it can be assumed that the angle error of about ±1° using this correction method is the limit.

If you want to perform correction with even a higher accuracy, you need to use a correction curve approximated with a third-order polynomial [Figure 5-2]. The angle error in Figure 5-2 is 0.03° or less. The resolution of this measurement system is about ±0.03°, so this means that the angle error is corrected to about the same level. Because reproducibility of optical deflection angle with respect to the drive current is high in MEMS mirrors, using such correction curve to control the drive current yields highly accurate optical deflection angles.

[Figure 5-2] Third-order polynomial correction curve and angle error



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5-2 Low-speed operation and high-speed operation

There are two ways the mirror can operate while the MEMS mirror is driven: low speed and high speed. In low-speed operation, the mirror tilts slowly to a given angle and stops. In high-speed operation, the mirror can either continue to move at high speed within a given angle range or tilt quickly to a given angle and stop (step operation).

In low-speed operation, the optical deflection angle can be controlled with high accuracy by using the correction curve mentioned earlier. Further, if the absolute angle of the mirror is not very important, another way to control the angle is to obtain the drive current and drive frequency that would produce the desired mirror angle in advance and use those values in the actual operation.

» Frequency characteristics during high-speed operation

As MEMS mirrors are mechanical, their frequency characteristics can be expressed with an equation. This equation matches the actual operation to some degree

under given operating conditions. If you want to operate the MEMS mirror (S12237-03P) at a frequency sufficiently lower than the resonant frequency, the frequency characteristics can be expressed with equation (5-1) and equation (5-2) using parameters that can be obtained through simple measurements.

$$|T(\omega)| \cong 1 + \left(\frac{\omega}{\omega_0}\right)^2 \dots\dots\dots \text{equation (5-1)}$$

$$\arg\{T(\omega)\} \cong \tan^{-1} \left\{ \frac{\frac{1}{Q} \cdot \frac{\omega}{\omega_0}}{1 - \left(\frac{\omega}{\omega_0}\right)^2} \right\} \dots\dots\dots \text{equation (5-2)}$$

$$T(\omega) = \frac{\theta_{ac}(\omega)}{\theta_{dc}(\omega)} \dots\dots\dots \text{equation (5-3)}$$

$$Q = \frac{\omega_0}{\omega_2 - \omega_1} \dots\dots\dots \text{equation (5-4)}$$

- T(ω): transfer function
- ω₀: resonant frequency
- θ_{dc}: optical deflection angle at low-speed operation
- θ_{ac}: optical deflection angle at high-speed operation
- Q: Q value
- ω₁: drive frequency at 1/√2 the optical deflection angle when resonating at a lower frequency than resonant frequency
- ω₂: drive frequency at 1/√2 the optical deflection angle when resonating at a higher frequency than resonant frequency

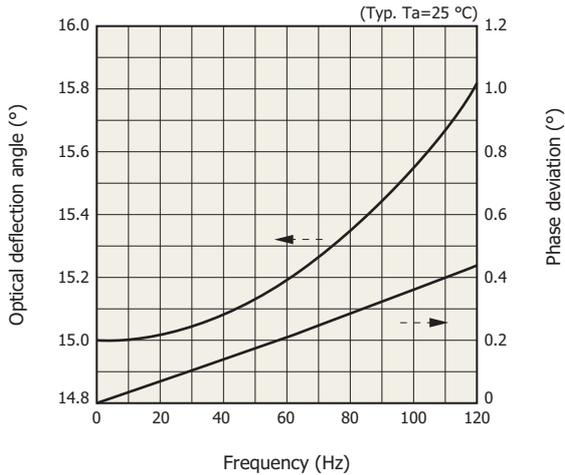
Equation (5-1) expresses the absolute value of the transfer function, and equation (5-2) the phase lag of the optical deflection angle. These are parameters that can all be measured and can be obtained by using a measurement system shown in section 4-3, “Measurement system of optical deflection angle versus drive current characteristics.” Note that equation (5-1) and equation (5-2) are for average Q values (several tens) within the S12237-03P's recommended operating drive frequency conditions of DC to 100 Hz.

5-3 Linear mode

» Frequency range

Figure 5-3 shows the frequency characteristics calculated with equation (5-1) and equation (5-2) [ω₀=approx. 530 Hz, Q=30 (typical S12237-03P value)]. The recommended operating optical deflection angle of 15° is used as the reference. The optical deflection angle at a drive frequency of 50 Hz (about one-tenth the resonant frequency) or less is 15° ± 0.2°. Within the recommended operating conditions of the optical deflection angle, the angle error is 0.2° or less. At 100 Hz (about one-fifth the resonant frequency) or less, the angle error is 0.6° or less. If you need an angle error of 0.5° or less for the accuracy, a drive frequency of 50 Hz or less is recommended. If you need 1° or less for the accuracy, 100 Hz or less is recommended.

[Figure 5-3] Frequency characteristics (S12237-03P)



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At a drive frequency of 100 Hz or less, the phase lag is 0.4° or less, and this can be ignored in many applications. Even in linear mode, angle error occurs according to the drive frequency, so the amplitude must be kept in mind.

Note that operating at a frequency higher than the recommended drive frequency range may cause damage, so use it within the recommended operating conditions.

» How to use linear mode

As explained earlier, in linear mode, using a drive frequency within the recommended operating conditions (1/10 to 1/5 the resonant frequency) yields excellent linearity in the optical deflection angle versus drive frequency characteristics. As such, we recommend that the frequency components of the drive signal be set within the recommended operating conditions of the drive frequency.

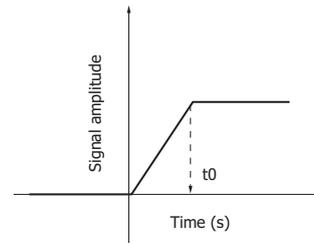
In step operation where the mirror is tilted to a given optical deflection angle and stopped, generating a rising drive signal within the recommended operating conditions of the drive frequency causes the rising of the drive signal to be extremely slow. This may not suffice depending on the application.

The step signal and periodic waveform responses to achieve faster step operation are explained in the following sections.

» Step signal response

This section explains the behavior of the mirror when a step signal with a rising slope is applied [Figure 5-4].

[Figure 5-4] Step signal

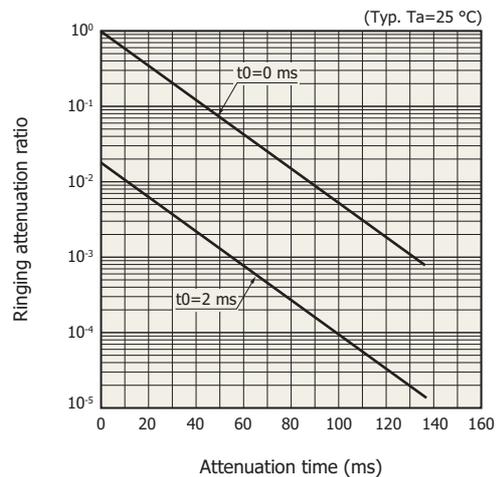


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The step signal contains numerous high frequency components. If the resonant frequency component is included, ringing occurs at that frequency, and settling to a given optical deflection angle takes time. There are two methods to not include the resonant frequency component. One is to set the rise time t_0 to an extremely large value, and the other is to set t_0 to an integer multiple of the reciprocal of the resonant frequency. In the latter, if t_0 deviates from an integer multiple of the reciprocal of the resonant frequency, ringing will occur, so it is important to set t_0 as close to that value as possible. Using these methods will eliminate most of the resonant frequency component from the step signal. However, it cannot be eliminated completely, so some ringing will occur. This ringing is extremely small, so it will converge to a given optical deflection angle in a short wait time.

Figure 5-5 shows the relationship between the ringing attenuation ratio and attenuation time for a resonant frequency of 500 Hz and $Q=30$.

[Figure 5-5] Ringing attenuation ratio vs. attenuation time

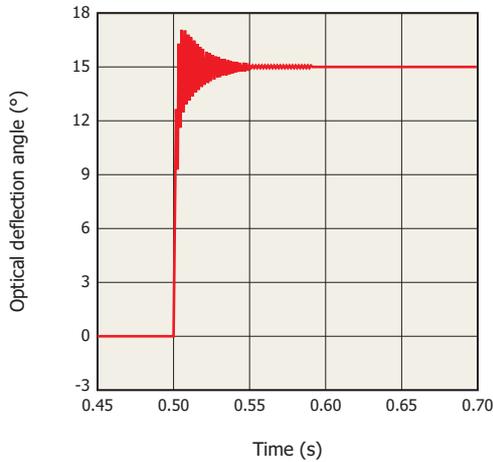


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The attenuation time if you want to make the attenuation ratio of ringing to 1/100 is 87 ms when $t_0=0$ ms and 10 ms when $t_0=2$ ms (the period of the resonant frequency). For example, when varying the optical deflection angle from 0° to 10°, the step signal is raised in $t_0=2$ ms, and 8 ms later, the optical deflection angle stabilizes within $10^\circ \pm 0.1^\circ$. To change the angle

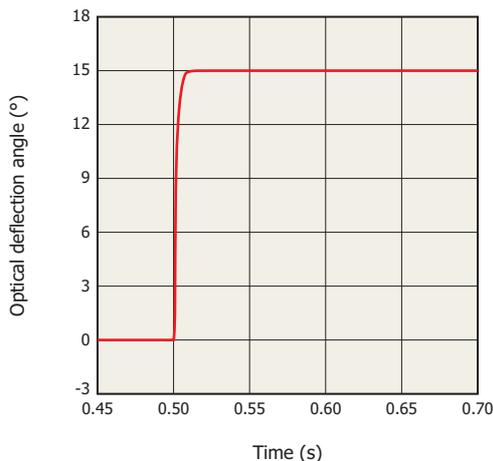
every 1°, the angle can be controlled with an accuracy within about ±0.1° only with a rise time of 2 ms. Figures 5-6 and 5-7 show the monitored response of the step signal using the S12237-03P.

[Figure 5-6] Step signal response (t0=0 ms, typical example)



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[Figure 5-7] Step signal response (t0=2 ms, typical example)



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» Periodic waveform response

Like the step signal, the response when a periodic waveform is applied can also be optimized by not including the resonant frequency component in the drive signal and further reducing the frequency components near it.

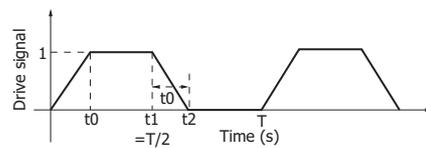
The frequency components of a given periodic waveform can be determined through Fourier series expansion. If the input signal is divided into its frequency components and they contain the resonant frequency component and frequency components near it, the input signal parameters need to be adjusted.

The method of deciding the period of the periodic waveform (T), rise time (t0), rise timing (t1), and fall time (t2-t1) is explained in the following paragraphs.

(1) Square wave

This section explains the case for a square wave (duty ratio: 50%, with the same rise time and fall time) [Figure 5-8]. In this case, $t_2 - t_1 = t_0$ and $t_1 = T/2$, so there are two independent parameters: t_0 and T. Setting the period of this square wave to a value that is not an integer multiple of the period of the resonant frequency will exclude the resonant frequency from the frequency components of the square wave. However, frequency components near the resonant frequency may be included, and the effects of these components must be reduced as much as possible. Therefore, t_0 is set to the period of the resonant frequency (or a frequency near it).

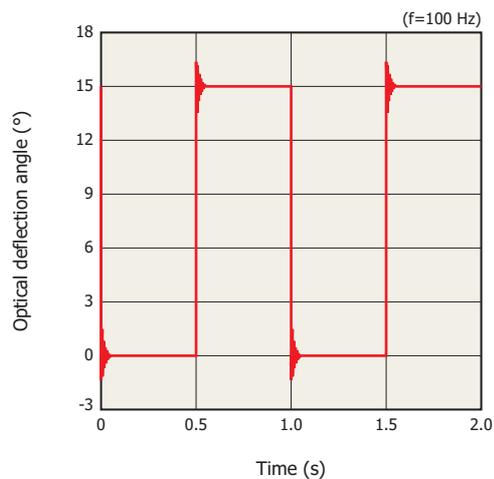
[Figure 5-8] Square wave (duty ratio: 50%)



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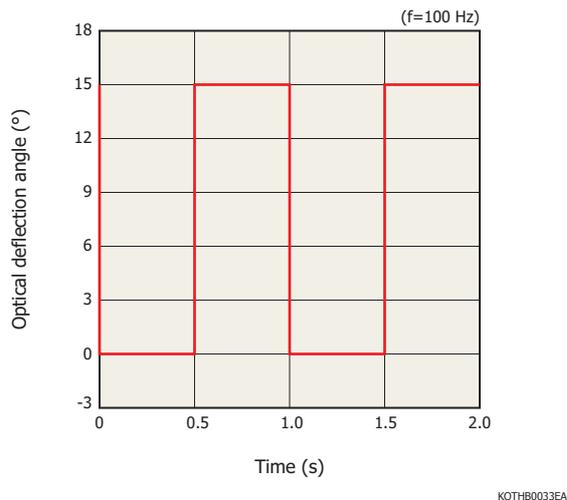
Figures 5-9 (t0=1 ms) and 5-10 (t0=2 ms) show the monitored results of square wave responses using the S12237-03P (resonant frequency: 530 Hz). Ringing can be seen at t0=1 ms, but at 2 ms, which is near the period of the resonant frequency, ringing is suppressed. Note that t0 does not exactly match the period of the resonant frequency. In some cases, it is better that they match exactly, but in other cases, it is better that they are slightly offset. This depends on the relationship between the drive period of the square wave and the resonant frequency.

[Figure 5-9] Square wave response (t0=1 ms, typical example)



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[Figure 5-10] Square wave response
($t_0=2$ ms, typical example)



(2) Sawtooth wave

A sawtooth wave [Figure 5-11] can be obtained by converting t_0 , t_1 , and t_2 of the square wave of Figure 5-8 and can basically be handled in the same manner as the square wave. A sawtooth wave is obtained when $t_1=t_0$ and $t_2=T$ (there are two parameters in this case). For a sawtooth wave, ringing can be minimized in the same manner as the square wave by following the procedure below.

- ① Set the period to a value that is not an integer multiple of the period of the resonant frequency
- ② Set the rise time t_0 to an integer multiple of the period of the resonant frequency

[Figure 5-11] Sawtooth wave

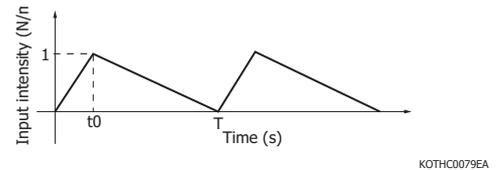
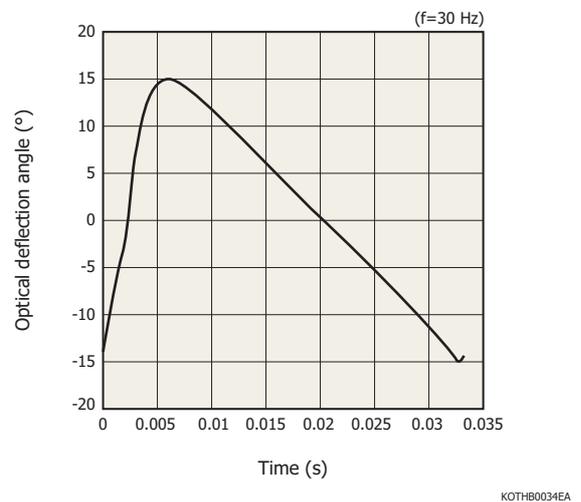


Figure 4-12 shows the changes in the optical deflection angle when a sawtooth wave (period: 30 Hz) is applied to an S12237-03P (resonant frequency: 500 Hz). The rise time of the drive signal is set to about 4 ms, which is double the period of the resonant frequency. In Figure 5-12, a clean response is obtained for the sawtooth wave. Note that the distortion in the response during the rise time cannot be suppressed. Use the response of the falling slope.

[Figure 5-12] Sawtooth wave response
($t_0=4$ ms, typical example)



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