MEMS Optical Scanner "ECO SCAN"
Application Notes

Ver.0

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Preface

This document summarizes precautions and control methods for MEMS optical scanner "Eco Scan" (hereinafter "Eco Scan"). Use this document as reference for Eco Scan.

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1. Operation principles

Eco Scan is an electromagnetic drive MEMS[*1] optical scanner. Figure 1 describes the product configuration. This scanner is configured by aligning permanent magnets around the monocrystal silicon substrate that forms the moving plate (with the mirror and coil on its surface), beams, and supporting section. When the electric current flows through the coil formed on the periphery of the moving plate, running torque (Lorentz force) is generated by the interaction between the electric current and the magnetic field by the permanent magnets. As a result, the moving plate can tilt to the position balanced with the righting moment of the beams. Since the Lorentz force is proportional to the current, by changing the current value, the angle of the moving plate can be changed freely. That is, the optical scanning angle (hereinafter "deflection angle") can be changed freely within the scope of rating. Figure 1 is intended for the one-dimensional type, but the two-dimensional type (two pair of beams) is also available.

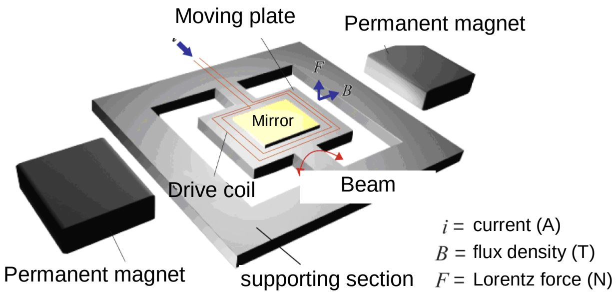


Figure 1. Production configuration of Eco Scan

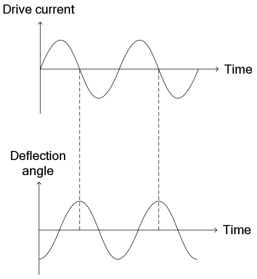
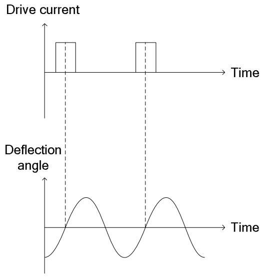
2. Drive System

Two types of drive systems ("resonance" and "dissonance") are available for Eco Scan. With the resonance drive, the current is impressed in accordance with Eco Scan's resonant frequency. It enables a larger deflection angle with low power consumption. The dissonance drive system uses a lower frequency than the resonant frequency. It can change the scanning waveform and velocity freely. The drive system varies depending on the type of Eco Scan. Please check it in advance. The following chapters describe these drive systems.

2.1 Resonance Drive

The resonance drive is divided into the "sine wave drive" and "pulse wave drive" depending on the drive waveform input. Table 1 summarizes their features. Consider their pros and cons to determine the drive system.

Table 1. Resonance drive system and its features

System	Sine wave drive	Pulse wave drive
Merits	Smooth driving without any frequency component other than the drive frequency	Easy to generate waveform
Demerits	Not easy to generate waveform	Oscillation at a frequency component other than the drive frequency may occur.
Deflection angle adjustment method	Adjust it by the drive waveform amplitude.	Adjust it by the drive waveform duty ratio.
Response characteristics of Eco Scan	 The phase difference between the drive waveform and deflection angle is -90 degrees.	 The phase of the drive pulse midpoint matches that of the deflection angle of zero degree.

[*1] Abbreviation for Micro Electro Mechanical Systems. The micro system that integrates electricity and machinery. It is made by the fine processing technology applied from semiconductor manufacturing.

2.2 Dissonance Drive

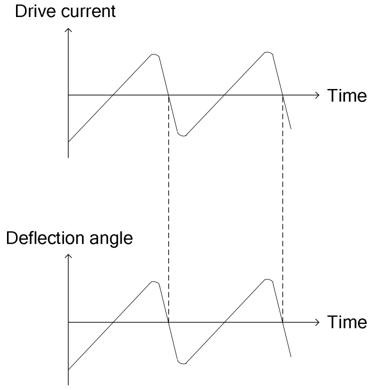
For the dissonance drive, the drive waveform is generally "triangular wave" or "saw-tooth wave". In principle, the triangular wave can be deemed equal to the saw-tooth wave with the 50% duty ratio. This section describes the saw-tooth wave.

Table 2 summarizes the features of the saw-tooth wave drive. The saw-tooth wave consists of multiple frequency components. For example, with the drive frequency of 60 Hz, the spectra are like shown in Figure 2 (a). When inputting this waveform as is into Eco Scan, like shown in Figure 2 (b), the gain around the resonant frequency increases in accordance with Eco Scan's frequency characteristics. Therefore, Eco Scan generates oscillation of resonant frequency components (see Figure 2 (c)).

The notch filter can be inserted to control oscillation. For Eco Scan, the gain of deflection angle is the largest at around the resonant frequency. Therefore, by inserting the notch filter whose center frequency matches Eco Scan's resonant frequency, the gain of deflection angle at around Eco Scan's resonant frequency is offset. However, the vertex of the saw-tooth wave becomes dull, and therefore the linear characteristic range suitable for driving will be narrowed. Figure 3 describes the response characteristics of Eco Scan when the notch filter is inserted.

The dissonance drive is possible also with the sine wave. In this case, the phase difference between the drive waveform and the deflection angle is zero degree, which is the same as the saw-tooth wave drive.

Table 2. Features of saw-tooth wave drive

Merits	• Raster scan is available for the two-dimensional type. • Driving at the resonant frequency or lower is possible.
Demerits	• Oscillation of the resonant frequency component may occur due to the drive frequency.
Deflection angle adjustment method	• Adjust it by the drive waveform amplitude.
Response characteristics of Eco Scan	 The phase difference between the drive waveform and deflection angle is zero degrees.

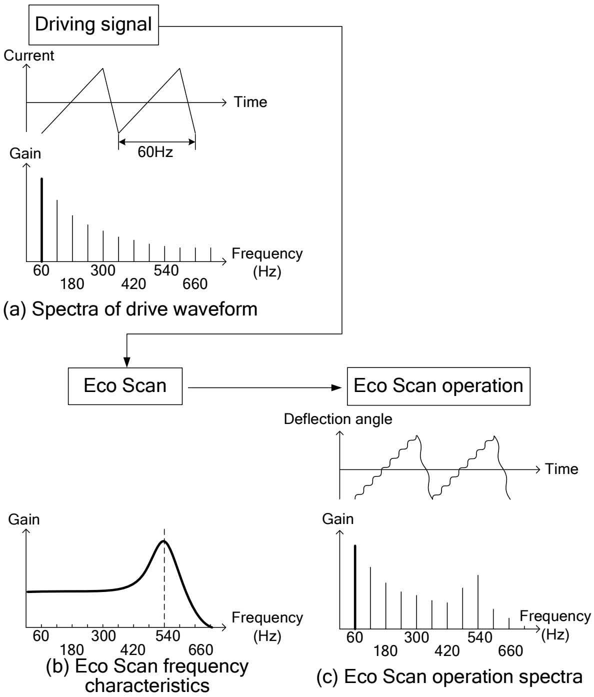


Figure 2. Response characteristics of Eco Scan when saw-tooth wave is driven

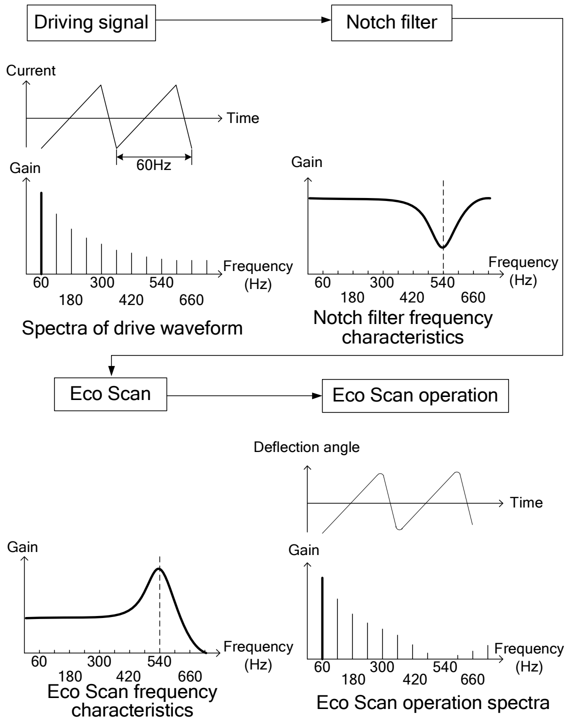


Figure 3. Response characteristics of Eco Scan when the notch filter is inserted

3. Method to Detect Deflection Angle

Eco Scan changes the resonant frequency and driving current depending on the ambient environment (temperature and atmospheric pressure). Therefore, to keep the deflection angle constant, it is necessary to detect the signal corresponding to the deflection angle, and control the drive frequency and driving current. The main methods to detect the deflection angle are (1) the counter electromotive force, (2) piezo signal, and (3) optical sensor.[*2] Table 3 summarizes their features.

3.1 Counter Electromotive Force Method

Eco Scan with counter electromotive force method generates an electromotive force in accordance with the moving plate's movement, and its volume follows the Faraday's law. The formula (1) indicates the calculation formula.

$$E(t) = -N\frac{d\phi(t)}{dt} \quad \cdots (1)$$

$E(t)$: Counter electromotive force
N: Coil winding number
$\phi(t)$: Coil interlinkage flux

The counter electromotive force is a time derivative of the deflection angle, and therefore, like shown in Figure 4, the phase difference between the counter electromotive force and the deflection angle is –90 degrees.

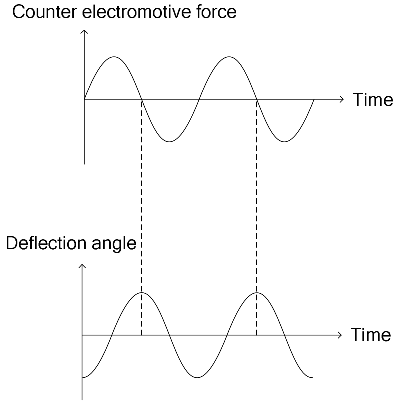


Figure 4. Relation between the counter electromotive force and deflection angle

A counter electromotive force generated on the coil overlaps the drive waveform. Therefore, for the sine wave drive, the counter electromotive force waveform is seen buried in the drive waveform, and is difficult to detect. However, forming a coil on the periphery of the moving plate enables detection of counter electromotive force. On the other hand, for the pulse wave drive, the counter electromotive force can be detected from the driving coil. Figure 5 describes the circuit block example. The different amplifier circuit enables the use of counter electromotive force. Although it depends on the pulse wave duty, detection of about half-cycle movement (counter electromotive force waveform) is possible.

*2) Note that an appropriate method depends on the type of Eco Scan, and required deflection angle precision.

Table 3. Deflection angle detection method and its features

Detection method	Counter electromotive force	Piezo signal	Light sensor
Principles	• Detect a counter electromotive force generated on the coil oscillating in the magnetic field.	• Use the variation of piezoresistive element resistance value to electrically detect the stress generated by oscillation.	• Detect the deflection angle by the elapsed time of reflected light that is detected by the light sensor.
Merits	• No drive circuit for detection is necessary, enabling lower power consumption. • Temperature characteristics are good since the temperature dependability is of magnetic field.	• Less noise of detection signals • Actual movement of Eco Scan can be detected.	• High-precision detection is possible. • Temperature dependability is small.
Demerits	• Actual movement of Eco Scan cannot be detected because a time derivative of the deflection angle is output. • Large noise of detection signals	• The drive circuit of piezoresistive element is necessary. • Temperature characteristics of both the drive circuit and the piezoresistive element must be considered, and therefore temperature control is difficult.[*3]	• External detecting element needs to be installed. • Consecutive detection of deflection angle is not possible, and therefore the actual movement of Eco Scan cannot be detected.

*3) There are ways to lower the temperature dependability by piezoresistive element adjustment or constant current drive.

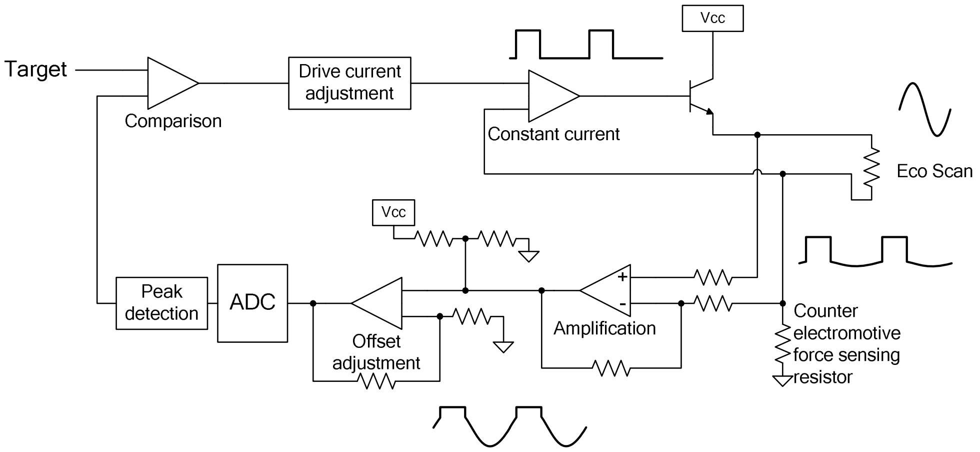


Figure 5. Example of counter electromotive force detecting circuit block

The peak value (negative side) of the detection waveform is the maximum deflection angle of ECO SCAN, and is used for deflection angle control, which is mentioned later.

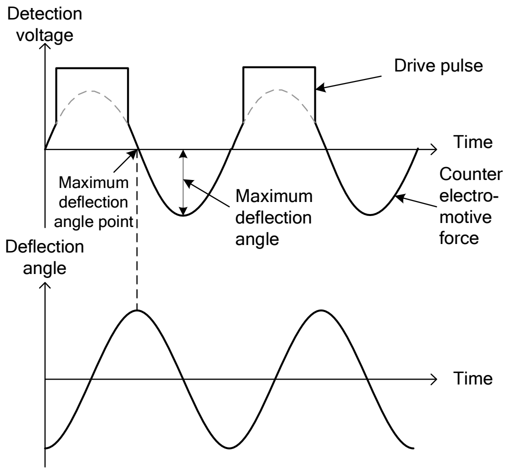


Figure 6. Relation between detection voltage and deflection angle

3.2 Piezo Signaling Method

Piezo signals are output from the piezoresistive elements installed on Eco Scan's beams. When the Eco Scan's beams are twisted, stress is generated in proportion to the deflection angle. Since the piezoresistive elements incorporating bridge circuits are installed in the positions where stress is generated, signals output in accordance with the stress is detected electrically, and that enables detection of deflection angle. The formula (2) indicates the calculation formula. The phase difference between the deflection angle and the piezo signal is zero degree.

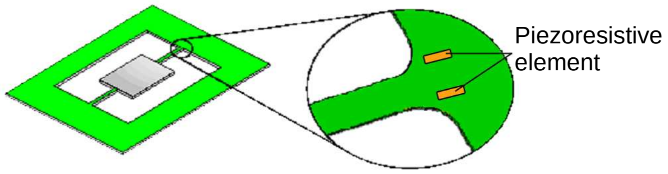


Figure 7. Configuration diagram of piezoresistive elements

$$V_{out} = \frac{1}{2}\pi_{44}R(\sigma_x - \sigma_y)I \quad \cdots(2)$$

V_{out} : Piezo signal output voltage (V)

π_{44} : Piezoresistance coefficient (Pa^{-1})

R : Piezoresistance value (Ω)

σ_x : Stress in X direction (Pa)

σ_y : Stress in Y direction (Pa)

I : Piezoresistance input current (A)

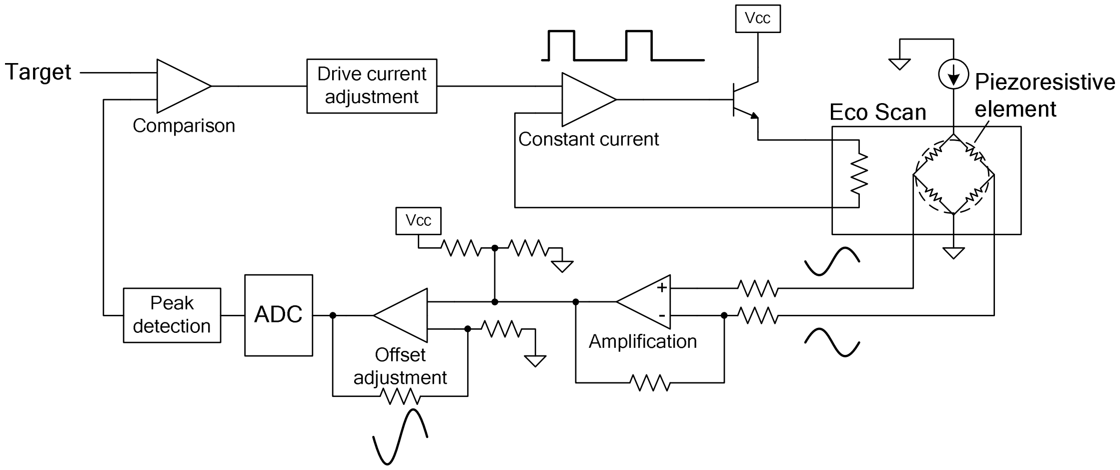


Figure 8. Example of piezo signal detecting circuit block

Figure 8 describes a circuit block example of piezo signal detection. For Figure 8, piezoresistive elements are input in the circuit as differential signals. Therefore, by tuning in to the dynamic range of ADC[*4] with a differential amplifier, they can be used as position detecting signals. Also, detecting signals with less noise is possible because the same phase noise is canceled.

3.3 Light Sensor Method

The light sensor method is to combine laser light with a light sensor such as photodiode to detect the deflection angle. This method basically irradiates laser light to the mirror and detects the laser passing through the light sensor to detect the deflection angle.

For example, in case of the laser projector, by installing a light sensor in the non-drawing area, the image display laser beam can be used to detect the deflection angle.

The light sensor is divided into two types: one outputs passage timing (e.g. photo IC for LBP[*5]), and the other outputs the laser light position (e.g. PSD[*6]). This section describes the detection method using the type that outputs passage timing.

Like shown in Figure 9, placing the light sensor in the detecting position enables detection of deflection angle. However, this method cannot detect the deflection angle consecutively. Also,

*4) ADC: An abbreviation for AD converter, an electronic circuit to convert analog signals to digital signals.

it is necessary to convert the passage time at the light sensor into the deflection angle in order to detect the maximum deflection angle of the mirror (Figure 10).

∗5) LBP: Laser Beam Printer
∗6) PSD: Position Sensitive Detector

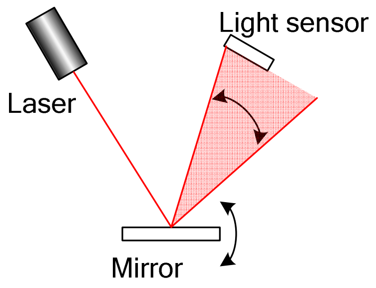


Figure 9. Example of placement of laser and light sensor

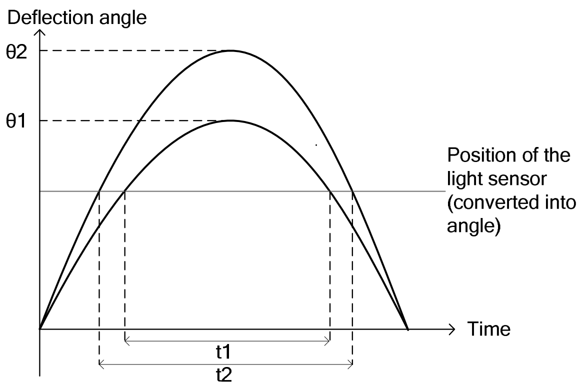


Figure 10. Time dependence of deflection angle

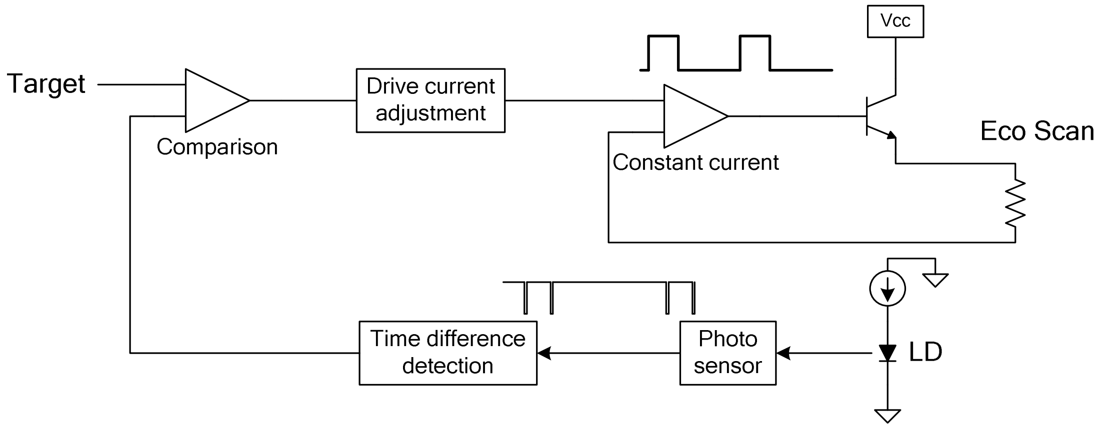


Figure 11. Example of the time difference detecting circuit block

For drive at a constant frequency, the passage time at the sensor is t1 when the maximum deflection angle of the mirror is θ1. It is t2 when the maximum deflection angle of the mirror is θ2. When the relation of deflection angle is θ2 > θ1, the relation of passage time is t2 > t1. Therefore, by detecting the laser passage time, the value equivalent to the maximum deflection angle can be detected. Figure 11 describes an example of circuit block for detecting the passage time at the light sensor.

4. Control Method

To keep the deflection angle constant based on the position detecting signal, two methods “current control” and “current control + resonant frequency tracing” are available. Table 4 summarizes their features.

Table 4. Features of control methods

Method	Current control only (Drive frequency: constant)	Current control + Resonant frequency tracing
Merits	Less control parameters	Efficient driving
Demerits	Inefficient driving	More control parameters

4.1 Current Control

First, set the target value of detection signal corresponding to the deflection angle. Then, compare the deflection angle detected by the method described in Chapter 3 with the target value, and adjust the drive current value to keep the deflection angle constant. Figure 12 shows the flow chart.

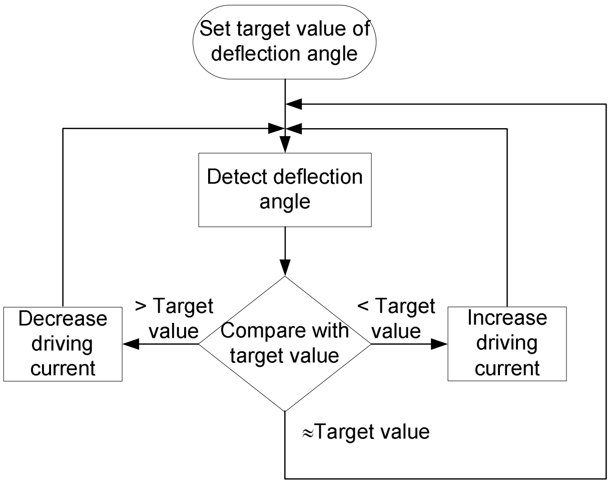


Figure 12. Flow chart of current control

4.2 Resonant Frequency Tracing Control

The resonant frequency tracing control is to have Eco Scan's drive frequency trace the resonant frequency. This control method enables to keep high efficiency drive. However, since the drive frequency is variable, this control cannot be applied to cases where a fixed frequency must be kept.

An applicable parameter for the resonant frequency tracing control is "the phase difference between the driving signal and detection signal". Figure 13 shows frequency characteristics of Eco Scan. For Eco Scan, the phase difference compared to the driving signal is –90 degrees at the resonant frequency. As the drive frequency decreases below the resonant frequency, the phase difference gets close to zero degree, whereas as it increases above the resonant frequency, the phase difference gets close to –180 degrees.

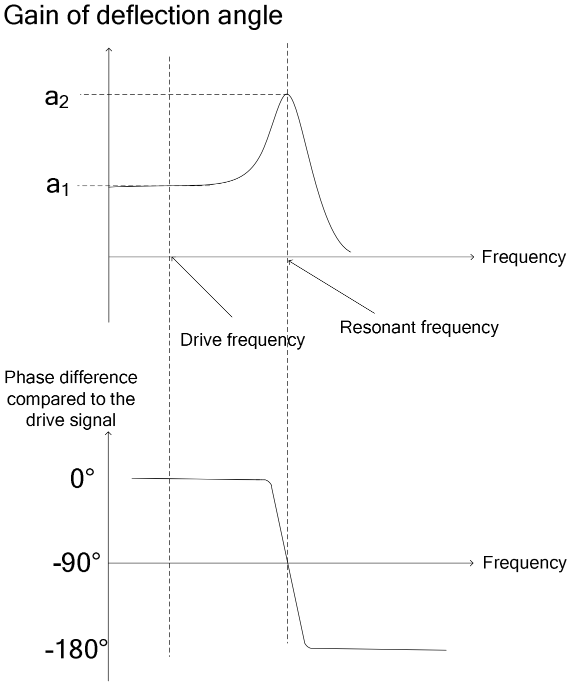
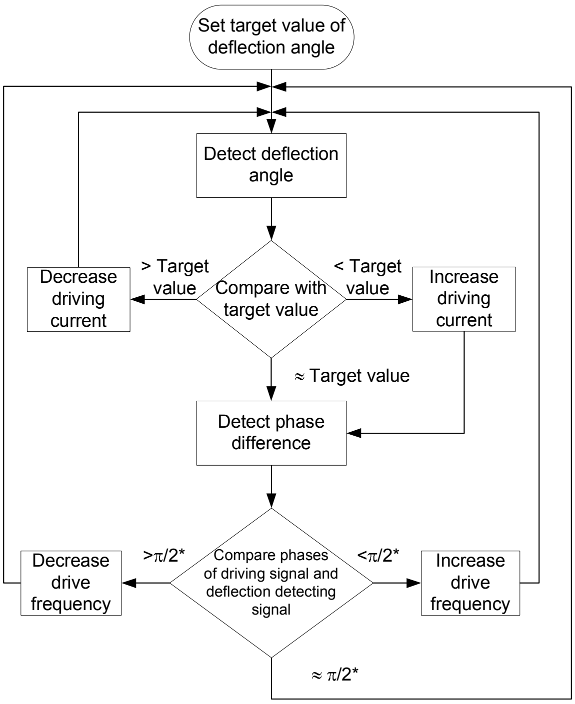


Figure 13. Frequency characteristics of Eco Scan

Detecting the phase difference clarifies the drive frequency divergence from the resonant frequency. Increasing or decreasing the drive frequency to eliminate this divergence ensures that the drive frequency always traces the resonant frequency. Figure 14 shows the flow chart. This chart is an example when the piezo signal is used as detection signal.

It is possible to sweep the frequency so that the frequency at the maximum deflection angle is the resonant frequency, but there may be problems because sweeping takes some time and use in viewing applications such as a projector causes stretching of image.



* π when detecting by the counter electromotive force.

Figure 14. Flow chart of resonant frequency tracing control

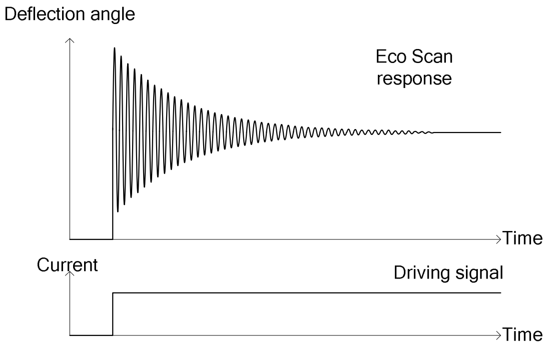


Figure 15. Eco Scan step response characteristic

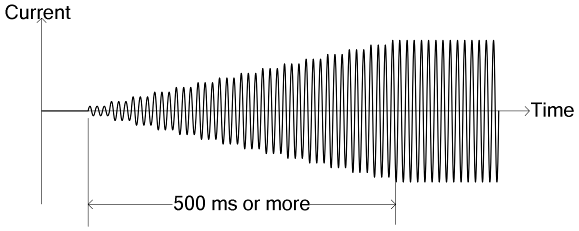


Figure 16. Drive waveform image in slow start

4.3 Control for Further Stability

To use Eco Scan with more stability, the following are recommended.

4.3.1 Slow start

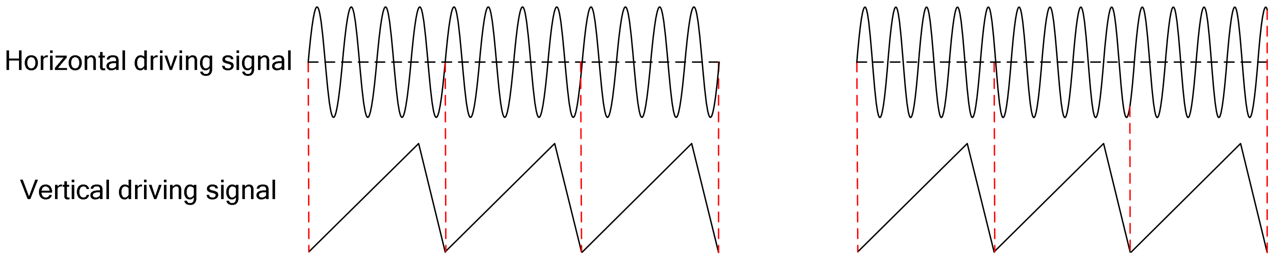
Gradually increasing the deflection angle (slow start) is recommended when starting Eco Scan driving. This is because, like shown in the Figure 15, a large overshoot occurs on the step response due to a high Q factor of Eco Scan. The overshoot places a high load on the beams, and may cause damage to Eco Scan or shorten its lifespan.

Like shown in Figure 16, the overshoot can be prevented by gradually increasing the driving signal current value. Although the time to reach the desired current value varies depending on each Eco Scan, it will take at least 500 msec.

4.3.2 Horizontal/vertical timing control

In case of two-dimensional driving of Eco Scan, it is necessary that the scanning timing in horizontal direction match that in vertical direction. This is because, like shown in Figure 17, starting points of horizontal and vertical scanning do not match for every cycle if the horizontal frequency is not an integral multiple of the vertical frequency.

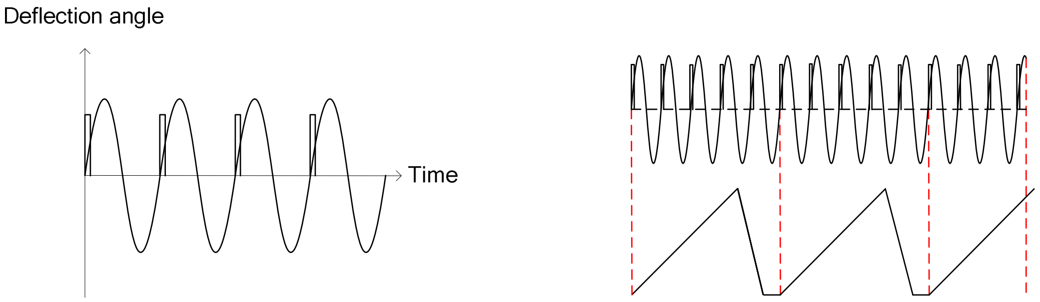
To match these timings, it is necessary to generate a synchronous signal from the detection signal, and adjust the other Eco Scan's driving signal based on that synchronous signal. Figure 18 shows an example for obtaining timing for raster scanning with the sine wave in horizontal direction and the saw-tooth wave in vertical direction. In this method, the saw-tooth wave waits until the synchronous signal at the sine wave is output in order to adjust the timing.



If the horizontal driving signal is an integral multiple of the vertical driving signal, the timing is constant.

If the horizontal driving signal is not an integral multiple of the vertical driving signal, the timing is slipped.

Figure 17. **Timing gap in case of two-dimensional scanning**



Output a synchronous signal at zero cross

Stop the saw-tooth wave until a synchronous signal is output. Restart it when a synchronous signal is output.

Figure 18. **Example of obtaining timing in two-dimensional scanning**