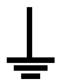
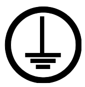
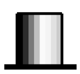
VCFL35(/M)
Voice Coil
Flexure Scanner
User Guide

Table of Contents

Chapter 1 Warning Symbol Definitions

Below is a list of warning symbols you may encounter in this manual or on your device.

Symbol	Description
	Direct Current
	Alternating Current
	Both Direct and Alternating Current
	Earth Ground Terminal
	Protective Conductor Terminal
	Frame or Chassis Terminal
	Equipotentiality
	On (Supply)
	Off (Supply)
	In Position of a Bi-Stable Push Control
	Out Position of a Bi-Stable Push Control
	Caution: Risk of Electric Shock
	Caution: Hot Surface
	Caution: Risk of Danger
	Warning: Laser Radiation
	Caution: Spinning Blades May Cause Harm

Chapter 2 Safety

CAUTION

The device must not be operated in explosion endangered environments!

CAUTION

Equipment is for indoor use only.

ATTENTION

All statements regarding safety of operation and technical data in the manual will only apply when the unit is operated correctly as it was designed for.

CAUTION

The stage screws are well adjusted and fixed. Loosening or removing any screws will change the performance and is strongly discouraged, except where instructed to do so in this manual.

CAUTION

Flexures are fragile. Be careful not to expose the moving stage or frame to excessive force or dropping. This can damage the product.

CAUTION

If the VCFL35(/M) scanner is damaged, resulting in stalling or friction, operation must cease immediately. Damage may cause overheating or a short circuit.

ATTENTION

The safety of any system incorporating the equipment is the responsibility of the assembler of the system.

Chapter 3 Overview

The VCFL35(/M) Voice Coil Flexure Scanner translates Ø1/2" (Ø12.7 mm) optics over a recommended range of 3.5 mm (±1.75 mm from flexure-neutral) at frequencies up to 30 Hz with a 3.5 g optic mounted. Rubber soft stops limit the travel to ±2.3 mm. A motion platform (i.e., moving stage) supports the voice coil actuator between two flexures. Optics may be mounted on the front of the stage via a side optic retention mount using a 0.05" (1.3 mm) hex key. This mirror mount features a patented[1] optic bore design with a monolithic flexure arm to hold the optic. Applying voltage to the female MMCX input connector will result in a current through the voice coil that drives the motion of the stage.

The purpose of the VCFL35(/M) scanner is to provide fast, smooth, and affordable motion of an optical element along one axis. The travel is very predictable to allow for good control. Use cases include various types of interferometry, delay lines, and beam displacement. The path is parabolic, with a vertical runout that reaches about 90 µm at either extreme of travel. While the tilt of the optic is small, it is not zero and varies from unit to unit. In some cases, the scanner is suitable for use in flat mirror interferometers such as the Michelson design and closely related variants. It is more suited to designs that are tilt- and shear-compensated with the use of retroreflectors.[2,3]

Rapid acceleration in the range of 40 m/s^2 is achievable, allowing for shorter travel ranges at higher frequencies. At 300 Hz and 1000 Hz, the expected displacement with a 3.5 g load is greater than ±10 µm and ±1 µm, respectively, for a maximum allowable drive signal. This is suitable for phase modulation of interferometers.

The VCFL35(/M) scanner may be operated open loop using a standard waveform generator with a variety of waveforms. A suitable power amplifier may be used to buffer the output of any signal source to obtain larger accelerations, velocities, and displacements. Closed-loop control of the VCFL35(/M) scanner can be implemented, but requires additional components as explained in 6.2 Closed-Loop Control Application Example. Best performance will be achieved with environmental isolation, including vibration isolation.

The VCFL35(/M) scanner comes with (1) CA3339 MMCX Male to BNC Male, cable, 1 m (39") in length. It can be mounted to a standard breadboard using ¼"-20 (M6) screws preferably 1/2" (12.7 mm) long or via (3) ¼"-20 (M6) threaded holes on the underside, compatible with Thorlabs' **height spacers**, the **BA2**(**/M**) base, and **other Thorlabs' bases** with the same pattern of counterbores.

[1] US Patent 10,101,559 D'Alessio, et al. October 16, 2018, Monolithic optical mounting element, http://pdfpiw.uspto.gov/.piw?Docid=10101559.
[2] P. R. Griffiths and J. A. de Haseth, Fourier Transform Infrared Spectrometry, (New York: John Wiley and Sons, 1986), pp. 143.
[3] W. H. Steel (1983) Interferometry, Cambridge University Press, Cambridge, p. 90.

3.1. Beam Height and Optic Mounting

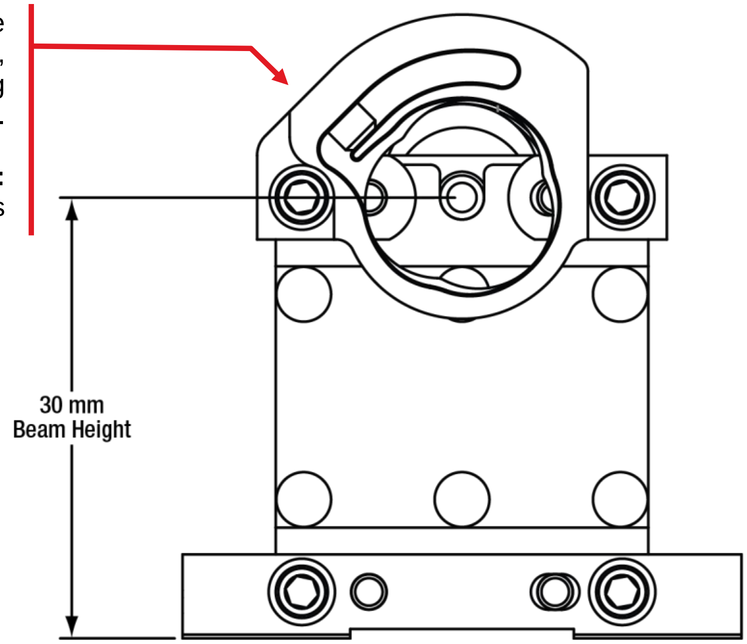
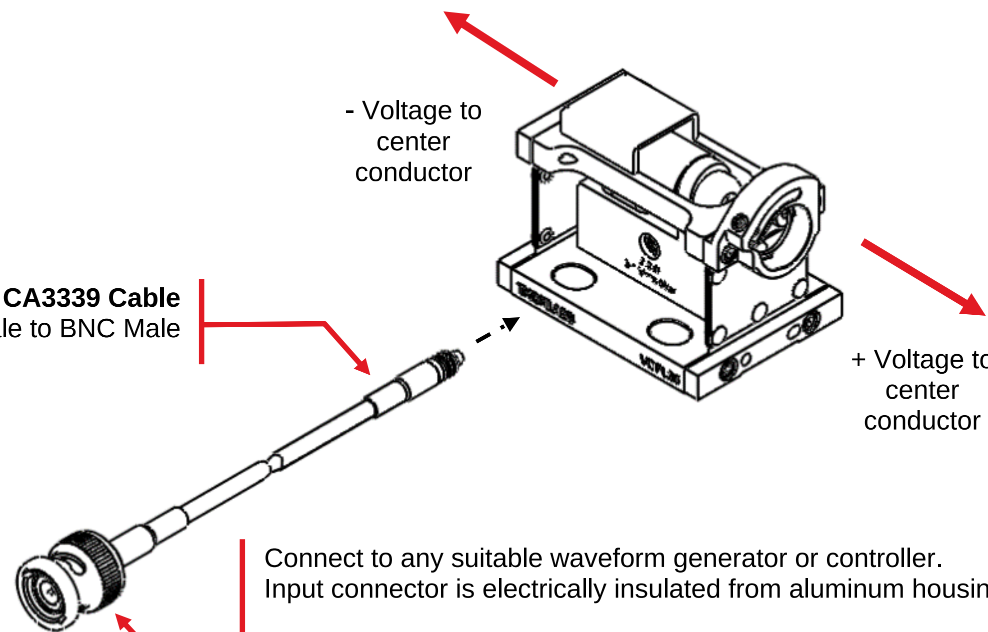


Figure 1 Beam Height and Optic Mounting

3.2. Electrical Connection



Connect to any suitable waveform generator or controller.
Input connector is electrically insulated from aluminum housing.

Scanner Resistance: 2.2 Ω @ 23 °C
Maximum Input Voltage: 3.1 V_{RMS}
Maximum Continuous Current: 1.4 A Applied @ 23 °C

Figure 2 Electrical Connection and Scan Polarity

The VCFL35(/M) scanner may be driven directly from a waveform generator. In most cases, the full voltage swing of the output may be used safely, because typical laboratory waveform generators have a 50 Ω output impedance.

The voltage drop across the output impedance will significantly reduce the current through the VCFL35(/M) scanner to well within safe levels. In this use case, the displacement for a 20 V_{pk-pk} sine wave output will be approximately ±0.5 mm from flexure neutral at frequencies below 10 Hz. It is the responsibility of the user to ensure that the maximum current and power dissipation recommendations are not exceeded. See Section 5.2 Driving Directly from a Waveform Generator for greater detail.

For a complete list of specifications, please see Chapter 7 Specifications. A full mechanical drawing for both the imperial and metric versions of the scanner can be found in Chapter 8 Mechanical Drawings.

Chapter 4 Description

4.1. Flexure Background

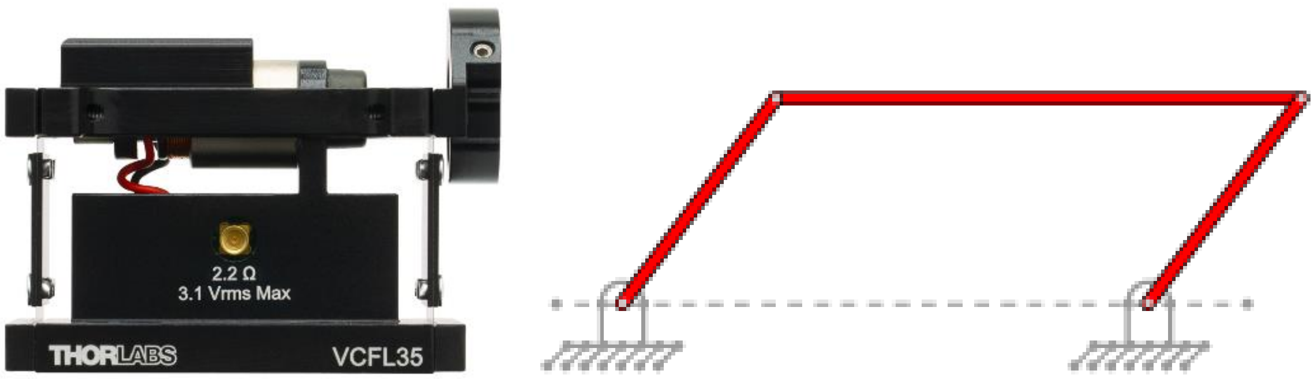


Figure 3 Side View of VCFL35(/M) Scanner Showing Connector (Left) and Equivalent Four-Bar Diagram (Right)

A flexure is a thin connecting member used in mechanical assemblies to allow elastic bending in at least one axis, providing wear-free, essentially frictionless, and backlash-free motion. The moving platform of the VCFL35(/M) scanner is supported by two parallel flexures which stand nominally perpendicular to the table at neutral and allow the mount to translate along a single axis by bending. The right side of Figure 3 shows that the geometry is in the class of four-bar mechanisms, where the shape changes from a rectangle to a parallelogram along the scan axis.

Thus, the VCFL35(/M) scanner is a four-bar system driven by a voice coil actuator. A moving frame is supported by the fixed frame using two parallel flexures. Current passing through the winding of the voice coil actuator produces a proportional force causing the stage to move smoothly as the flexures bend**.** The moving platform or stage provides an optical mount for attaching a Ø1/2" (Ø12.7 mm) mirror or other element.

Flexure bending is nearly frictionless, such that the resulting motion is smoother than many other types of bearings. The resulting purity of motion is attractive for use in optical instruments, particularly interferometers and delay lines. The flexures have been tested beyond 20 million cycles over the full scan range with no failures. The bend radius is designed to be large enough, relative to the thickness of the material, such that the lifetime is essentially infinite. The recommend ±1.75 mm range of travel for which the VCFL35(/M) scanner was designed may be exceeded, but the flexure fatigue lifetime may be reduced.

4.2. Voice Coil Theory

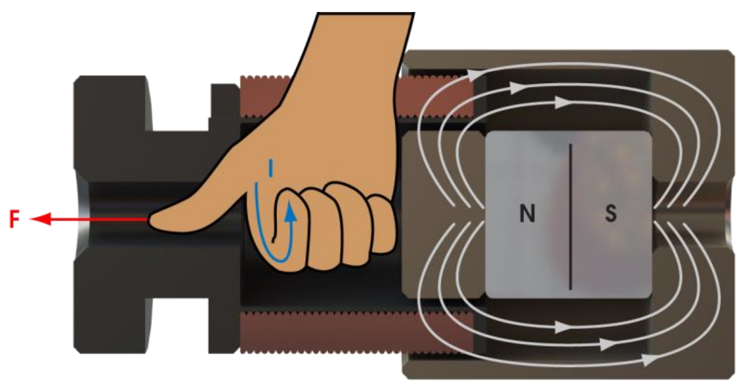


Figure 4 Right Hand Motor Rule

A voice coil can be understood as a length of wire positioned in a nominally uniform magnetic field.[4,5] Current in the wire generates a force that is mutually perpendicular to the magnetic field and the direction of current flow. This force is proportional to the number of turns in the coil and to the strength of the magnetic field, itself a function of the strength of the magnet. The uniform field is created by arranging pole pieces around the magnet to guide the flux.

The right-hand rule is illustrated in Figure 4. For a positive current moving in the direction that the fingers are curled, a force will be generated in the direction indicated by the thumb. For negative currents, the force is generated in the opposite direction.

The copper[6] coil itself has a comparable temperature coefficient of resistance given by:

$$\mathrm{R} = \mathrm{R_{REF}}[(1 + \alpha(\mathrm{T} - \mathrm{T_{REF}})]$$

Here, R is the conductor resistance at temperature T (°C), $\mathrm{R_{REF}}$ is the conductor resistance at a reference temperature, α is the temperature coefficient of resistance for the conductor material (0.00393 for copper), T is the conductor temperature in °C, and $\mathrm{T_{REF}}$ is the reference temperature at which α is specified for the conductor material. Starting from ambient temperature, the resistance can vary by about 25% up to the maximum input power, at a rate of about 0.4% per °C. Over the allowable input power range, typical values of coil resistance are 2.2 Ω increasing to 2.75 Ω, respectively.

A voice coil actuator system has multiple important figures of merit that define the performance. These parameters include magnetic field strength, maximum current, and wire (coil) length which together define the largest force that can be generated.

The thermal conductance (the reciprocal of thermal impedance) of the coil to the ambient environment is another very important figure of merit and limits the continuous power dissipation, which in turn limits the maximum continuous current for safe operation. For most use cases, the majority of the input power is dissipated as heat and most of that heat passes into the air around the coil and magnet assembly. It should be noted that heated air can cause unwanted phase shifts in the beam paths of interferometers.

[4] Electric motor https://en.wikipedia.org/wiki/Electric_motor.
[5] Voice coil https://en.wikipedia.org/wiki/Voice_coil.
[6] Copper – Wikipedia https://en.wikipedia.org/wiki/Copper.

4.3. Flexure Scanner Theory of Operation

4.3.1. Equation of Motion

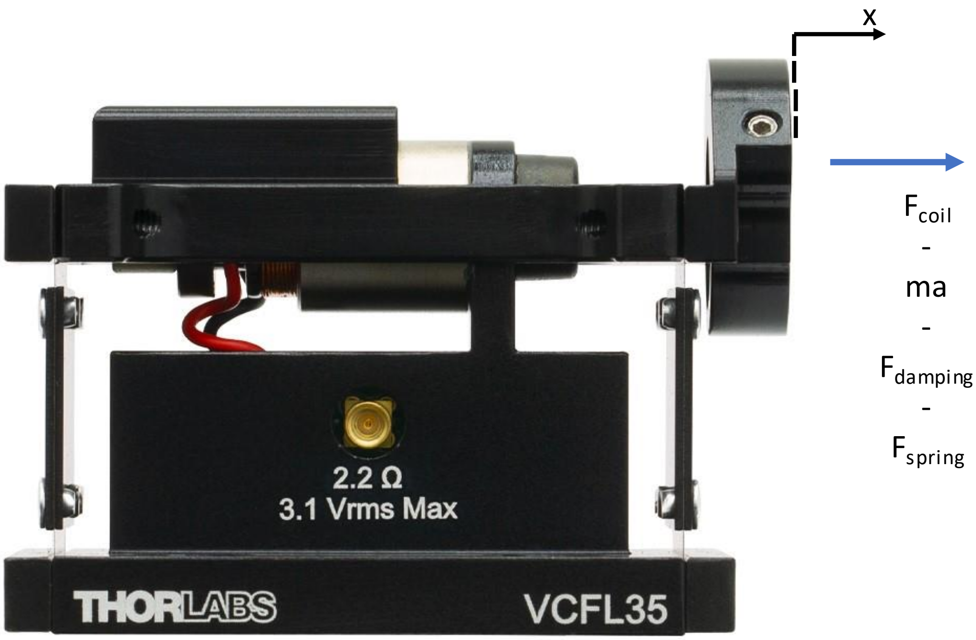


Figure 5 VCFL35(/M) Scanner – Forces that Govern Motion –
Illustrated for Motion in One Direction (Right) but also Applies to Opposite Direction (Left)

The scanning stage of the flexure mechanism is a moving mass that responds to forces generated by the voice coil actuator, by the springs, and by external disturbances. The force generated by the coil and the acceleration of the stage both are proportional to the applied current. Control theory views the stage velocity as an integrator of the input current time series and any external disturbances, resulting in a 90° phase shift and a 1/f frequency response. In the case of displacement, the stage is a double-integrator, resulting in a phase shift of 180° and an amplitude response that is proportional to $1/f^2$. When the VCFL35(/M) scanner is used for closed-loop control of velocity, it is found that good performance is feasible over a wide bandwidth, greater than 1 kHz. Control of position is more difficult and more susceptible to external vibration, because the system starts with a 180° phase shift. The amplitude response at high frequencies is quite small. Position control can work very well, but depending on accuracy requirements, stringent isolation from environmental disturbances is likely to be required. To achieve nanometer positioning, even temperature fluctuations in air must be considered.

A more detailed derivation of the flexure scanner transfer functions follows. The motion of a voice coil scanner, whether operating in open-loop or closed-loop modes, is governed by the simple equations of Newtonian mechanics, with the forces illustrated in the diagram above. The platform or stage is a moving mass. The net force on the stage is the sum of the forces generated by the voice coil, flexures, and damping. A very small contribution from gravity is ignored.

The relationship can be stated as, $F_{coil} = ma + F_{damping} + F_{spring}$

Where m and a are the mass and acceleration of the moving stage and payload.

Taking the double integral of acceleration with respect to time (t) allows us to write the equation of motion as: ma = $m\frac{d^2x}{dt^2}$.

$F_{damping} = cv = c\frac{dx}{dt}$, where c is the damping coefficient and v is velocity, for which the integral gives displacement with respect to time (t). The damping can be caused by eddy currents in the magnet assembly, air friction, and bending of the internal wiring.

$F_{spring} = kx$, where k is the spring constant and x is position along the scan coordinate. The spring force is not perfectly linear with displacement, but linearity provides a very good approximation.

The force generated by the voice coil usually is varying with respect to time. The ordinary differential equation describing the dynamics of the system is given by:

$$F(t) = m\frac{d^2x(t)}{dt^2} + c\frac{dx(t)}{dt} + kx(t)$$

This can be converted to the frequency domain using the Laplace transform, with the VCFL35(/M) transfer function be estimated as:

$$H(s) = \frac{1}{ms^2 + cs + k}$$

such that

F(t) → H(s) → x(t)

The frequency response or transfer function of the system may be represented with the use of a Bode plot as seen in Figure 6. The reason that the transfer function is described as an estimate is that each unit is slightly different, due to variations in manufacturing. The moving mass (m) is 0.020 kg with no optic mounted, the damping coefficient is 0.226 Ns/m, and the spring constant is 193 N/m. The damping coefficient and spring constant can vary by about ±25% and ±20%, respectively. The moving mass (m) will not meaningfully differ from unit to unit.

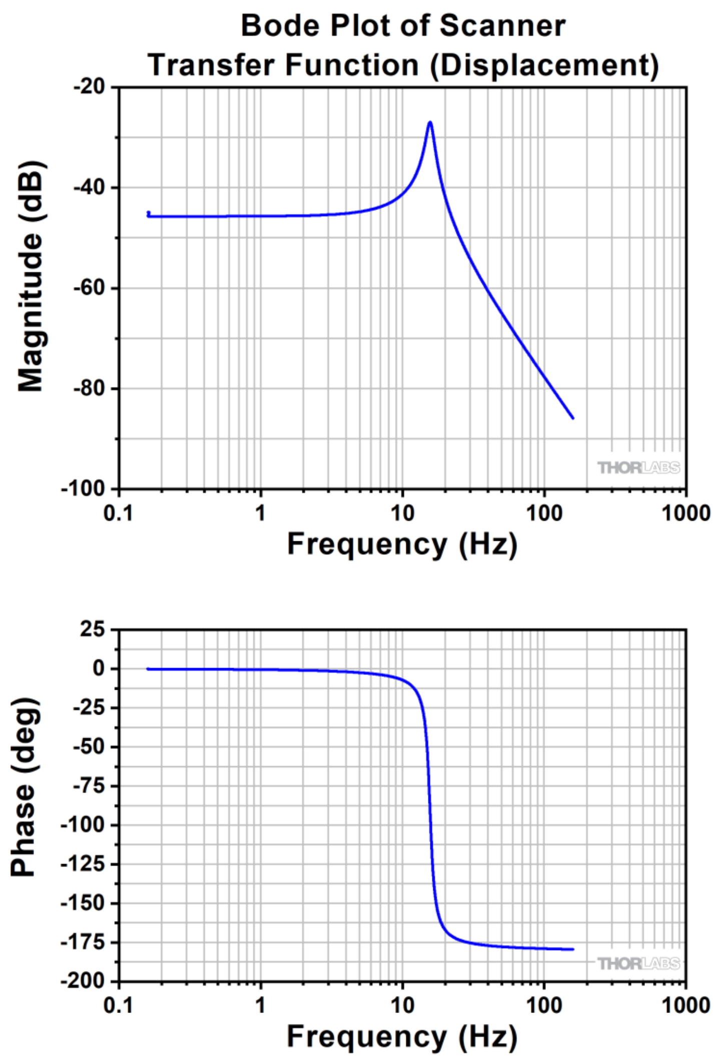


Figure 6 Bode Plot of Transfer Function for Scanner Displacement

Bode plots provide a convenient and intuitive representation of frequency response for linear systems. The top graph of Figure 6 shows the magnitude of the frequency response in displacement, while the bottom graph shows the phase shift. The frequency response is quite flat below the first resonance, because the system response is simply the deflection of the springs produced by the force of the voice coil. At low frequencies, the force essentially is static relative to the system dynamics. The force is the current through the voice coil multiplied by the Newtons/amp parameter, which interacts with the flexure spring constant. The amplitude response to force is proportional to current for any RMS input power below the first resonance. At and near resonance, the amplitude of motion is much larger, because the system efficiently stores and releases kinetic and potential energy in this frequency range. Above resonance, there is a $1/f^2$ roll off in amplitude with increasing frequency. The phase shift is essentially constant at 180°. The $1/f^2$ roll off can be understood in terms of the time for which the force is applied. As the excitation frequency increases beyond the resonance, a smaller and smaller increment of time is available for the mirror to accelerate and move. The $1/f^2$ term arises because both the time for acceleration and the time for motion to occur are reduced simultaneously by 1/f.

It is also useful to define the transfer function for the velocity response. This is done by multiplying the original transfer function by an *s* term such that,

$$F(t) \rightarrow s{*}H(s) \rightarrow v(t)$$

$$s{*}H(s) = \frac{s}{ms^2+cs+k}$$

A Bode plot for s*H(s), the velocity response, is shown in Figure 7.

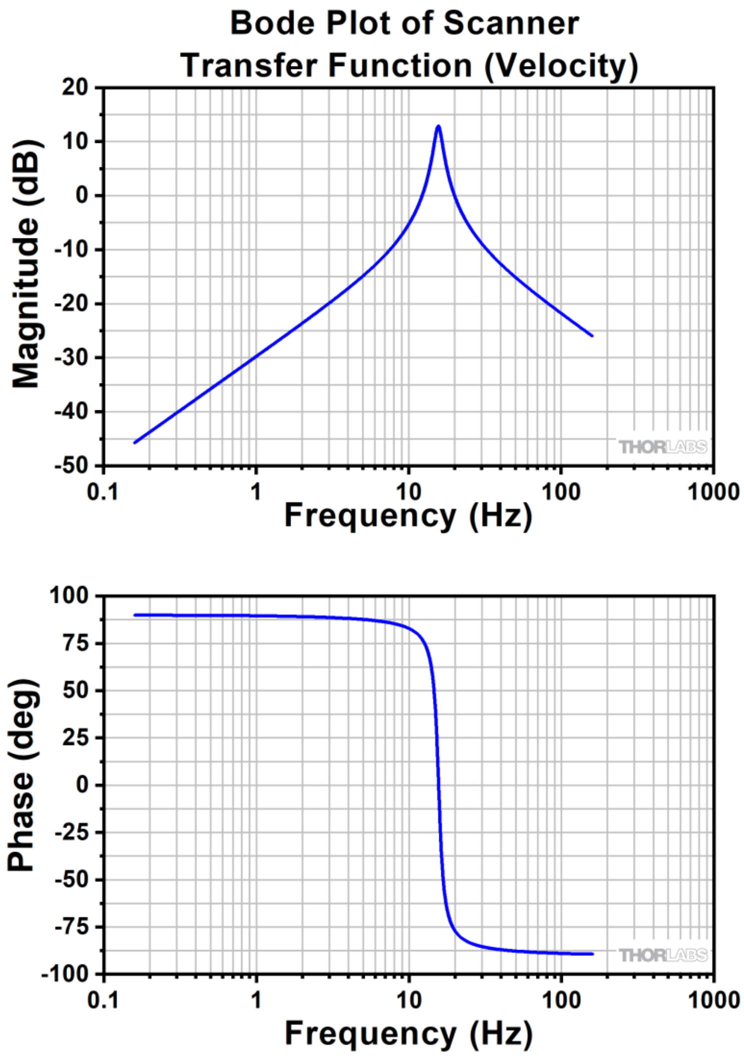


Figure 7 Bode Plot of Transfer Function for Scanner Velocity

As before, the top graph in the Bode plot describes the amplitude of the response while the bottom graph describes the phase. The velocity increases with frequency, up to the first resonance. The efficient recycling of energy at the resonance causes a significant increase in velocity at, and near, the resonance. The phase shift is a constant 90° until the resonance, where there is a 180° phase shift. Position lags velocity by 90°, which is shown clearly in the position and velocity phase response in the Bode plots above. Above the first resonance there is a roll off in magnitude with respect to increasing frequency. Once again, the transfer function and accompanying response curves are estimated from measured parameters and the actual values will differ slightly from unit to unit due to manufacturing tolerances.

4.3.2. Parasitic Resonances

Resonances occur in mechanical systems because of the combination of energy storage in bending of components and the possibility for that mechanical energy to be exchanged with kinetic energy of motion. Because the flexures act as springs, they store and release potential energy during motion, depending on where the flexure is along its scan axis. Likewise, the moving mass of the system stores and releases kinetic energy according to velocity and acceleration along the same axis. A system with two different modes of energy storage may form an oscillator that exchanges energy between the modes over time. In this case, the flexures form a mass-spring oscillator with the stage and any payload mounted on the stage. The natural frequency of the system both with a 3.5-gram payload, and without a payload, is about 14 Hz. This first resonance is expected and well within the controllable bandwidth, which is described briefly in Section 6.2 Closed-Loop Control Application Example. The natural resonance can be used to produce a sinusoidal scan motion, using a very small input of energy that overcomes air friction and eddy current losses in the scanner. Thus, only a small input is required to maintain a large and nearly constant amplitude. In some cases, it may be helpful to control the resonance amplitude and phase using closed-loop feedback. The images in Figure 8 show the VCFL35(/M) scanner's first resonance visualized using finite element modeling. The motion is almost purely along the scan axis. At left, the moving stage is behind the flexure neutral position. In the middle diagram, the moving stage is at flexure neutral. At right, the moving stage is forward of flexure neutral. Only the flexures are deformed.

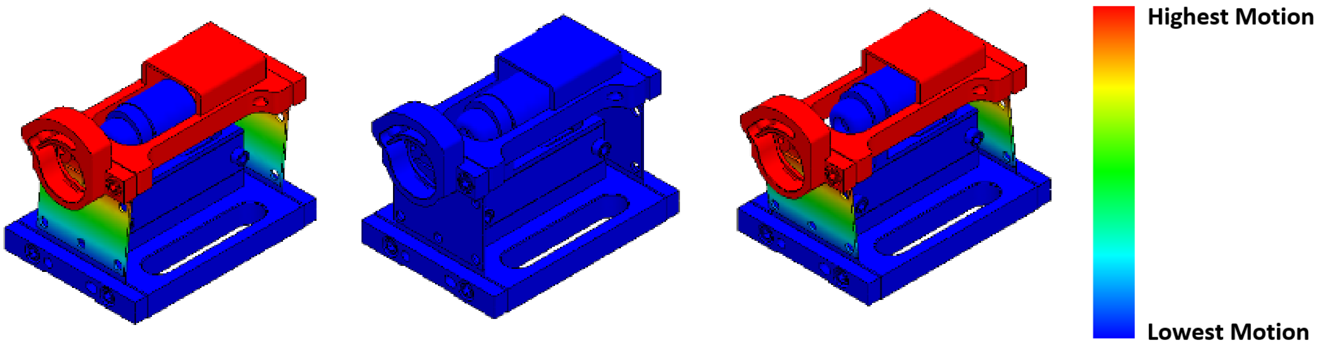


Figure 8 Deflection at Fundamental Resonance, (Left) -90°, (Middle) 0°, (Right) +90°

Also present in many mechanical systems are parasitic resonances, caused by the unintentional and unavoidable presence of other mass-spring oscillators. These resonances arise from non-ideal ("parasitic") parameters of the components. It is impossible to make a mechanical component without parasitic resonances, because every component has a modulus of elasticity associated with deflections, and every real component has mass, which moves during deflection. It would be preferable for the flexures to be weightless. Instead, the flexure mass interacts with higher order bending modes to create resonances starting at about 1500 Hz. These modes are different from the simple flexure bending that is desirable. Likewise, any flexibility in the stage will lead to internal resonances, where the stage itself experiences cyclical internal deformation. The internal stage deformations usually occur at higher frequencies than the undesirable flexure resonances. If the control bandwidth is chosen appropriately, none of these parasitic resonances will interfere with operation. For the VCFL35(/M) scanner, appropriate control bandwidths will be in the range of 100 Hz to more than 1 kHz. Choosing the exact value is case dependent and requires good engineering judgment. Many techniques are described in the control literature to tailor gains, bandwidths, phase delay, as well as track and mitigate the effects of resonances.[7,8] These are fundamental principles in control and adaptive control systems that are beyond the scope of this manual. Section 6.2 Closed-Loop Control Application Example describes two simple examples and provides additional references to the literature on control of dynamic systems.

The internal flexibility of the stage also represents an undesirable parasitic spring element, interacting with the internal mass of the stage to produce resonances. Only some of the stage resonances will interact with the excitation from the drive coil, which generates forces almost perfectly aligned to the scan axis. The mass and center of mass of an optic mounted to the moving stage will have some impact on these resonance modes. This impact generally is insignificant for small optics, such as a 3.5 g retroreflector, but undesirable modes may be shifted lower in frequency when heavier and larger optics are mounted, especially if the center of mass extends further from the moving stage of the VCFL35(/M) scanner (i.e., "cantilevered loads").

These resonances can interfere with closed-loop control and even may be seen in open-loop operation, if resonant high-frequency energy is applied to the coil. The images below illustrate some of the VCFL35(/M) scanner's parasitic resonances, which were estimated with the use of finite element modeling. In general, the actual resonance frequencies are very close to those predicted by the model. Not all of the parasitic resonances couple to the drive

[7] *Bernard Widrow and Samuel D. Stearns, Adaptive Signal Processing (Englewood Cliffs: Prentice-Hall, Inc. 1985).*
[8] *Gernot Grabmair, Simon Mayr, Embedded Adaptive Self-Tuning Control Development by a Free Toolchain, Universal Journal of Control and Automation 3(2): 33-38, 2015.*

coil but can be excited by external vibrations. The twisting motion seen in Figure 9 and Figure 10 has a different symmetry than the drive coil can provide.

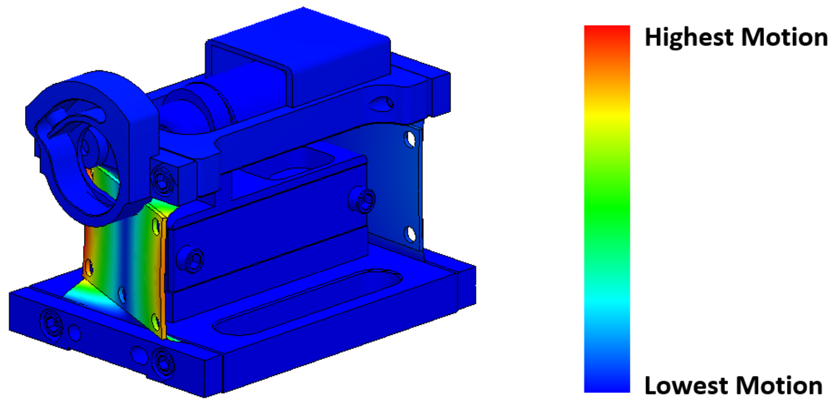


Figure 9 Deflection at a Parasitic Resonance – Flexure Bending in Other Axis

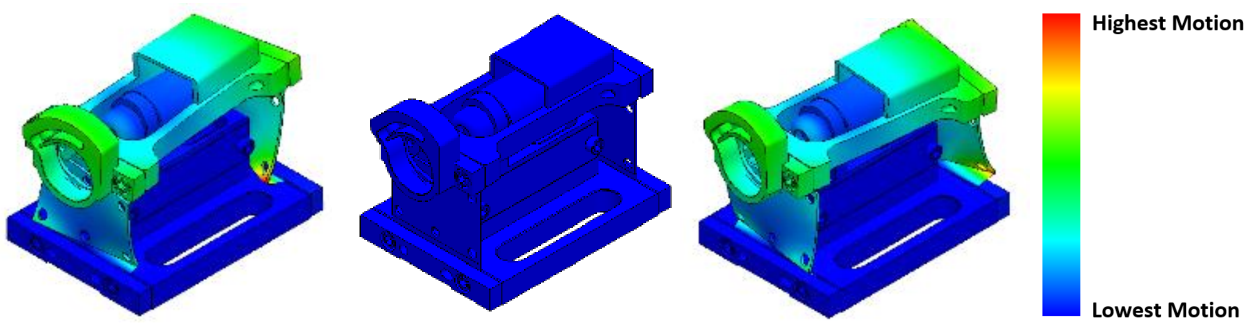


Figure 10 Deflection at a Parasitic Resonance – Moving Stage Twisting Out of Scan Axis (Left) -90°, (Middle) 0°, (Right) +90°

4.3.3. Open- and Closed-Loop Control Background

The VCFL35(/M) scanner does not directly provide position, velocity, or acceleration information, because it does not have a built-in encoder.[9] One typical use case is interferometry,[10,11,12] where a laser interference signal can provide very accurate position information. A built-in encoder would provide similar motion and position information, by outputting digital or analog signals indicating where the stage is along the scan axis and how fast it is moving. One key difference between a conventional linear encoder and the interferometer output is that an encoder can provide absolute position information, while an interference signal generally provides only relative information. Velocity signals easily can be extracted from laser interference signals.

[9] *Linear encoder https://en.wikipedia.org/wiki/Linear_encoder.*
[10] *Transformations in Optics, Lawrence N. Mertz, New York: John Wiley and Sons, Inc. (1965).*
[11] *Sumner P. Davis, Mark C. Abrams, James W. Brault - Fourier Transform Spectrometry, Academic Press (2001).*
[12] *Brian C. Smith, Fundamentals of Fourier Transform Infrared Spectroscopy CRC (1995).*

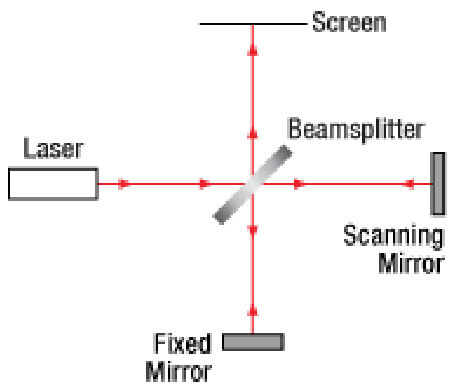


Figure 11 Michelson Interferometer Arrangement that Produces Very Accurate Mirror Motion Information

Michelson interferometers and similar two-beam instruments divide a light source on a beamsplitter into two beams that follow different paths as shown in Figure 11. The beamsplitter behaves as a half-silvered mirror where approximately 50% of the incident light is reflected and 50% is transmitted. These beams are returned from the two terminal mirrors (labeled Fixed Mirror and Scanning Mirror) to the beamsplitter, where they are split again. Half of the returning energy is lost in the direction of the source. The other halves of the returning beams combine to form a new beam that goes to the detector. For a monochromatic laser source, the intensity at the detector is a sinusoidal function of scanning mirror position. When either of the paths is varied, a change in phase is seen at the detector. When a reference laser beam passes through the system, the result is a regular sinusoidal variation. If the mirror is scanned at a constant velocity, then the laser signal is modulated with a constant frequency. Each cycle of interference is called a fringe, which can be measured to great precision using a Thorlabs' PDA100A2 Si detector or equivalent photodetector. The output of the photodetector can be digitized, and the fringes counted to determine position, velocity, and acceleration. In some cases, a second laser channel called "quadrature" provides direction information. These signals are equivalent to the ones provided by conventional encoders, but capable of much higher resolution.

In many interferometric applications, the optical signals are converted to electronic signals that pass through filters. If the velocity of a moving mirror is constant, then the frequencies passing through the filter experience a constant attenuation factor, constant phase delay and consequently, are more stable than if the mirror velocity varies.[13,14] In open-loop operation, useful velocity and position control can be achieved by applying tailored waveforms to the VCFL35(/M) scanner. The results will be much better if the flexure scanner is isolated from ambient vibration and other disturbances such as airflow and sound.

4.3.3.1 Advantages of Closed-Loop Operation

Voice coil actuators are routinely used in high-precision applications for both position and velocity control, down to the nanometer level. In general, some type of feedback is required to achieve these performance levels. Of equal importance is rigorous isolation of the system from ambient disturbances, especially vibration and convection. Vibration isolation for optical tables is routine in many laboratories. However, velocity control in the range of 0.1% to 2% stability can be routinely achieved with minimal environmental isolation. The VCFL35(/M) scanner is generally intended for interferometer applications where the necessary feedback signals are derived from laser

[13] *James W. Brault, Appl. Opt. **35**, 2891 (1996).*
[14] *R. C. M. Learner, A. P. Thorne and J. W. Brault, Appl. Opt. **35**, (1996).*

measurements, typically involving a mirror payload. There is extensive scientific literature on interferometry and control theory.[15,16,17,18]

[15] Gene F. Franklin, J. David Powell, Abbas Emami-Naeini, Feedback Control of Dynamic Systems 6th Edition, Pearson College Division; 6th edition (2009).
[16] Katsuhiko Ogata MATLAB® for Control Engineers, Pearson (2007).
[17] Gordon S. Brown and Donald P. Campbell, Principles of ServoMechanisms: Dynamics and Synthesis of Closed-Loop Control Systems (1948).
[18] Control System Design: An Introduction to State-Space Methods, Bernard Friedland, Dover Books on Electrical Engineering.

Chapter 5 Operation in Detail

5.1. Max Operating Parameters and Exceptions

As explained in Section 4.2 Voice Coil Theory, for a given current through the copper windings of the voice coil actuator, the voice coil produces a proportional force. The nominal resistance of the coil is 2.2 Ω at 23 °C which is almost entirely in the copper windings. As explained in Section 4.2, the electrical resistance of copper increases with temperature. If a constant voltage is applied to the coil, the current will decrease as the device warms. A variety of electronic feedback systems can improve this behavior by compensating for resistance changes.

The maximum continuous DC-equivalent voltage that may be applied safely is 3.1 V_{RMS}. Beyond this level, irreversible damage to the magnet may occur, permanently reducing the field strength, and therefore, permanently reducing the force the actuator is capable of producing. Use caution when driving the device near its maximum power level. Under transient conditions, higher peak voltages may be used so long as the heating is managed either by duty cycle or active cooling.

This maximum voltage is specified for the case when there is no movement (moving stage stalled), which is a worst-case situation with regard to heat dissipation. As the device scans faster, thermal coupling from the voice coil to ambient air increases, and thus, for the same input voltage, the temperature rise will be reduced somewhat. Caution is advised when operating near the limits of power dissipation.

5.2. Driving Directly from a Waveform Generator

In general, when the VCFL35(/M) scanner is powered directly from a laboratory waveform generator, the full voltage swing of the output may be used safely. Typical laboratory waveform generators have a 50 Ω output impedance, which is in series with the 2.2 Ω coil resistance of the VCFL35(/M) scanner, and a maximum output of 20 $V_{pk\text{-}pk}$. This output impedance significantly reduces the maximum current through the VCFL35(/M) scanner, in most cases to less than 0.2 A. This is for typical waveform generators and is well below the damage threshold.

There are exceptions and it is the user's responsibility to verify the input current is below the power dissipation limit.

$$3.1\ V_{RMS} MAX = I_{RMS} * 2.2\ \Omega$$

$$I_{RMS}\ MAX = \mathbf{1.41\ A}$$

When the full output swing of a standard waveform generator is used, typically 20 $V_{pk\text{-}pk}$, the VCFL35(/M) scanner's scan displacement is about ±0.5 mm from the flexure neutral position (1 mm from one scan extreme to the other) at frequencies below the first resonance. At and around the first resonance near 14 Hz, the VCFL35(/M) scanner functions as a mass-spring oscillator. Under these conditions, the energy of motion is very efficiently recycled from scan to scan. The energy is alternately stored in the springs during turnarounds and as kinetic energy of motion between turnarounds. The resulting motion is sinusoidal. The system response at the first resonance is quite large and full stroke scanning can be done with a small input from a signal generator. Please see the maximum displacement vs. frequency in Figure 12.

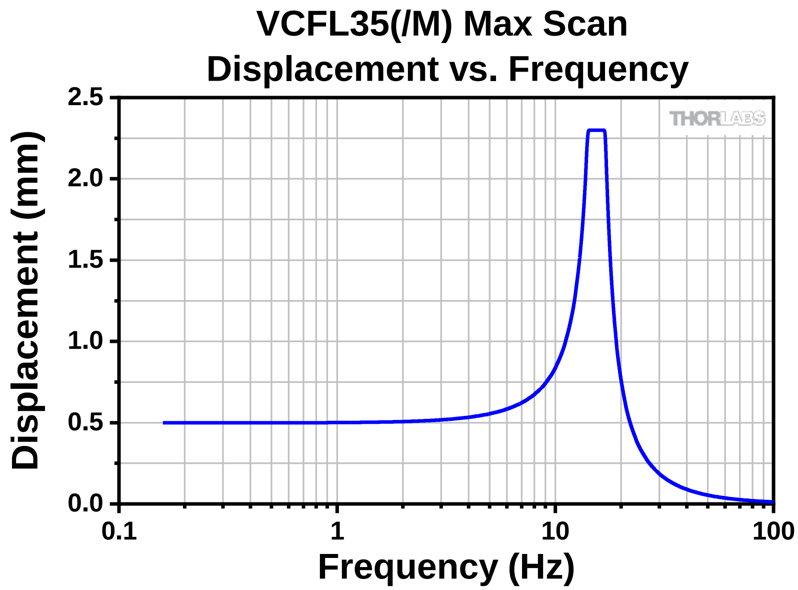


Figure 12 Maximum Scan Displacement from Flexure Neutral Driving with a Sine Wave Directly from a Waveform Generator

For the graph above, a sine wave was used. Note that the spike in theoretical displacement at the resonance would be much greater than the 2.3 mm shown here, however, the VCFL35(/M) scanner has rubber soft stops that limit the travel to nominally ±2.3 mm. It is not advised to intentionally allow the moving platform to hit the soft stops as this range of motion may fatigue the flexures, reducing scanner lifetime.

5.2.1. Waveform Generator Amplification

In cases where a waveform generator does not provide sufficient power to drive the VCFL35(/M) scanner through a desired (larger) range of motion, or at a sufficiently high velocity, an amplifier may be used to increase the acceleration, velocity, and amplitude. In general, a DC-coupled amplifier is preferred, as this allows displacement of the center of the scan range. For the typical case of an amplifier with a voltage input, voltage output, and fixed gain, the input can be scaled by adjusting the signal generator output. In some cases, it is helpful to use an offset capability of a signal generator to adjust the neutral position in the scan range to coincide with some particular optical path. That feature can be especially useful for scanning the stage repeatedly through a particular position, such as the zero-path difference of an interferometer. There are a variety of amplifier options available on the market, including DIY options using an amplifier IC or by purchasing an amplifier evaluation board.

5.3. Force Constant as a Function of Position

Because the magnetic field intensity is not perfectly uniform, and the overlap of the coil to the field also varies with position, the voice coil actuator within the VCFL35(/M) scanner will produce a slightly different force per ampere depending on its position in the magnetic field. In Figure 13 below, the red line denotes the voice coil's position when the flexures are at rest (neutral). At either scan extreme from neutral, recommended not to exceed 1.75 mm, the force constant will decrease by about 10%.

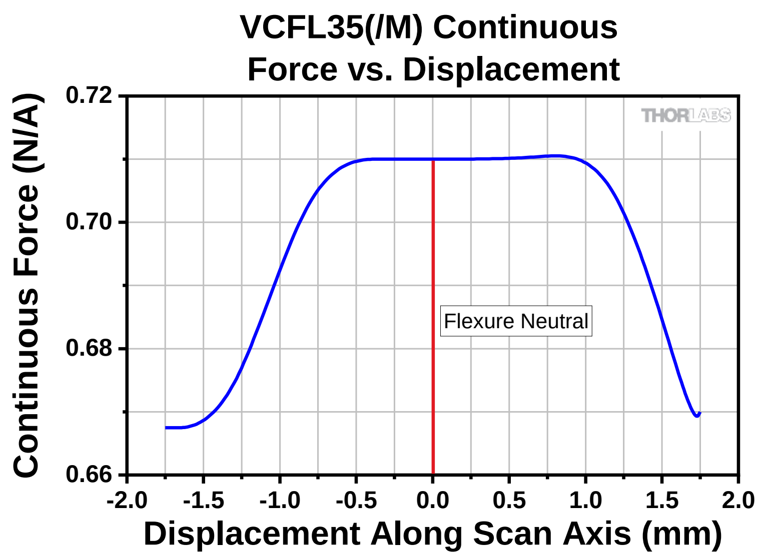
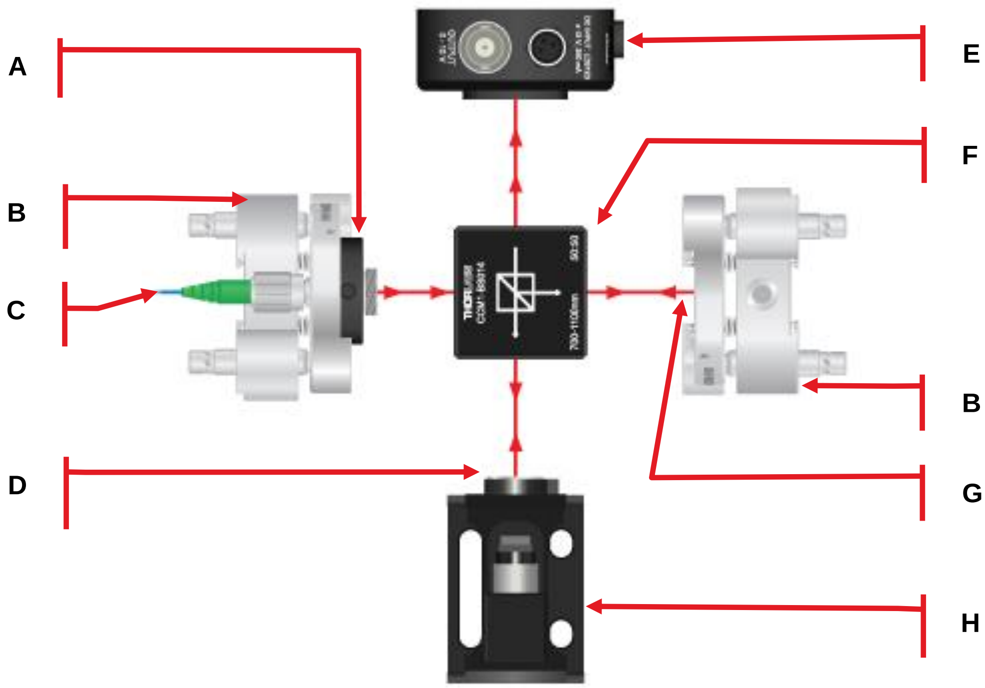


Figure 13 Force as a Function of Scanner Position - Total Variation Less Than 10%

Chapter 6 Open- and Closed-Loop Operation

6.1. Open-Loop Application Example

The VCFL35(/M) scanner may be configured to scan the moving arm of a standard Michelson interferometer. A diagram of a suitable optical setup, which was assembled on a vibration-isolated optical table, is shown in Figure 14. All components below are offered in the Thorlabs catalog. In addition, either a signal generator or PID controller is required to drive the VCFL35(/M) scanner, in open-loop or closed-loop operation, respectively.



Callout	Part Description
A	F220APC-780 FC/APC Fiber Collimator Package with AD11NT Adapter
B	POLARIS-K1S4 Polaris® Ø1" Mirror Mount
C	FPV785P 785 nm, 50 mW, Wavelength-Stabilized Single Frequency Laser Diode
D	PF05-03-P01, Ø1/2" Protected Silver Mirror, Mounted at Front
E	PDA100A2 Si Photodetector
F	CCM1-BS014 Cage Cube-Mounted Non-Polarizing Beamsplitter
G	PF10-03-P01 Ø1" Protected Silver Mirror
H	VCFL35(/M) Voice Coil Flexure Scanner

Figure 14 Interferometer Arrangement for Tracking Mirror Position, Velocity and Acceleration

The light source is a FPV785P VHG Wavelength-Stabilized SF Laser Diode collimated using an F220APC-780 Fiber Collimator. A CCM1-BS014 beamsplitter is used to divide the laser beam into two perpendicular beams, each containing nominally 50% of the original intensity. One beam reflects from a fixed PF05-03-P01 flat mirror and the other reflects from a PF05-03-P01 flat mirror mounted to the moving stage of the VCFL35(/M) scanner. The beams are reflected back to the beamsplitter, where they both are split again. One of the resulting recombined beams passes to the PDA100A2 detector, which measures the intensity. The other recombined beam returns in the direction of the laser source and is lost. The PDA100A2 detector shows that the intensity of the recombined beam changes with the optical path difference of each arm. While not used for the results presented in this example, Thorlabs' **optical enclosures** should be placed over interferometers when stringent isolation from environmental disturbances is required, particularly for position control. **Vibration-isolation** tables are highly recommended if the motion requirements are stringent.

By processing the analog output of the PDA100A2 detector through a suitable ADC (analog-to-digital converter), the position, velocity, and acceleration of the VCFL35(/M) scanner can be monitored by splitting the data into small increments and calculating the fringe phase, for each increment. For the purposes of this application example, the velocity stability is defined as the standard deviation divided by the mean for the dataset of velocity values.

For open-loop operation, the VCFL35(/M) scanner may be driven using any waveform within the operating power limits. Depending on the application, the input signals most likely to be useful will be tailored to optimize the motion along a repeating trajectory. For sinusoidal waveforms, the amplitude need only be scaled correctly for the response of the scanner at the desired frequency. For some use cases, such as FT-IR spectrometers, a more desirable motion profile will closely resemble a triangular waveform which exhibits constant velocity in both directions with quick turnarounds.

It is helpful to consider the transfer function of the flexure scanner described previously in Section 4.3.1 Equation of Motion as the trajectory is the complex product of the input waveform and the transfer function. Because of the large increase in amplitude response at the fundamental resonance, it is important to tailor the waveforms to not excite the fundamental resonance. The use of purely triangular waveforms, which are comprised of a series of harmonics, usally including ones that coincide with the fundamental resonance of the VCFL35(/M) scanner, will result in poor velocity stability and multiple unintentional turnarounds at the low velocities near the desired turnarounds.

Figure 15 shows a purely triangular waveform used to drive the VCFL35(/M) scanner and the resulting velocity vs. time for a single scan, from one extreme to the other (3.5 mm travel), is shown in Figure 16. The shaded region of Figure 15 is the section of the waveform for which the velocity vs time is shown.

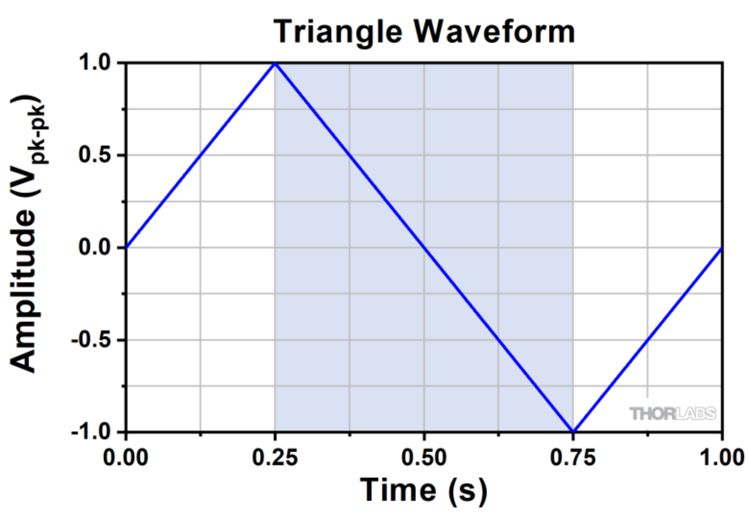


Figure 15 Triangle Waveform Drive Signal

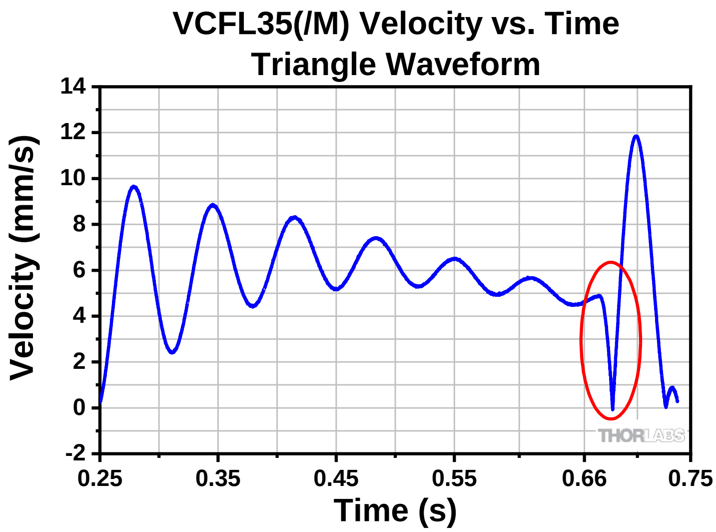


Figure 16 Velocity vs Time of Unfiltered Triangle Drive Signal – Unwanted Turnaround Circled in Red

The velocity stability for the center 65% of the scan shown in Figure 16 is 18.6%, and this is repeatable for multiple units tested. As before, the velocity stability is defined as the standard deviation divided by the mean. An unwanted turnaround (circled in red) occurred before the end of the scan.

If energy that would excite the fundamental resonance of the VCFL35(/M) scanner is removed from the waveform by filtering, the resulting motion will better follow the desired trajectory and velocity stability will improve significantly. The resulting filtered triangular waveform will, when plotted, have rounded peaks at each turnaround. In this case, a simple moving average filter was used.[19,20] The greater the filter window length, the smoother the turnarounds become.

Fundamentally, the smoothing of the turnarounds results in more time spent during turnarounds and less time scanning. However, the velocity stability during the scanning periods is greatly improved. A variety of window lengths were tested and a balance between stability and duty cycle efficiency was chosen at a window length of 7.5% of the sampling frequency. This waveform, used to drive the VCFL35(/M) scanner, is shown in Figure 17 and the velocity vs time for a single scan, from one extreme to the other (3.5 mm travel), is shown in Figure 18. The highlighted region is the portion of the waveform for which the velocity vs time is shown.

---

[19] Lawrence R. Rabiner and Bernard Gold, Theory and Application of Digital Signal Processing, (Englewood Cliffs: Prentice-Hall, Inc., 1975).
[20] Alan V. Oppenheim and Ronald W. Schafer, Discrete-Time Signal Processing (Englewood Cliffs: Prentice-Hall, Inc., 1989).

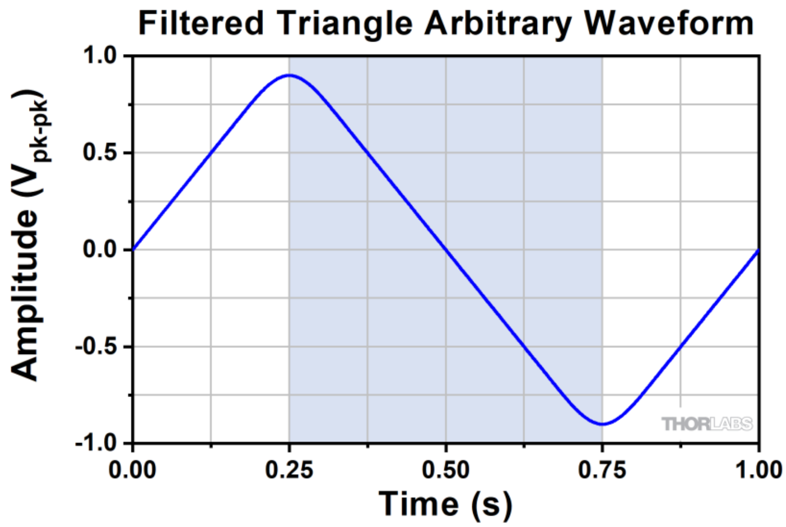


Figure 17 Triangle Waveform with Harmonics Filtered Out

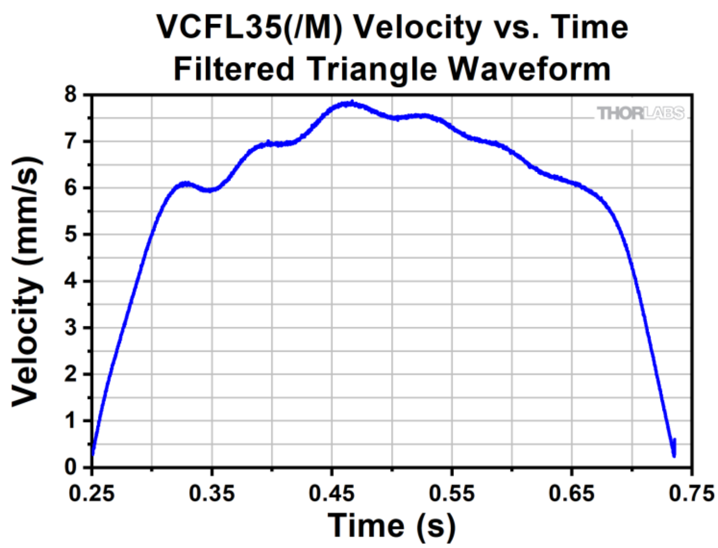


Figure 18 Velocity Profile with Filtered Triangle Waveform

The velocity stability is greatly improved by filtering compared to the original triangular waveform. The velocity stability for the center 65% portion of the scan is 8.0% and this is repeatable for multiple units tested.

The code written in Octave[21] used to generate the waveform can be found in Chapter 9 Appendix and the raw Excel file of the waveform may be downloaded from the **product webpage**. Most modern signal generators accept .csv file imports, either via a serial cable or memory.

To better visualize why filtering improves the velocity stability, the triangle waveform and filtered triangle waveform can be analyzed by Fourier transformation to show the harmonic content, as shown in Figure 19.

[21] GNU Octave, https://www.gnu.org/software/octave/, Scientific Programming Language.

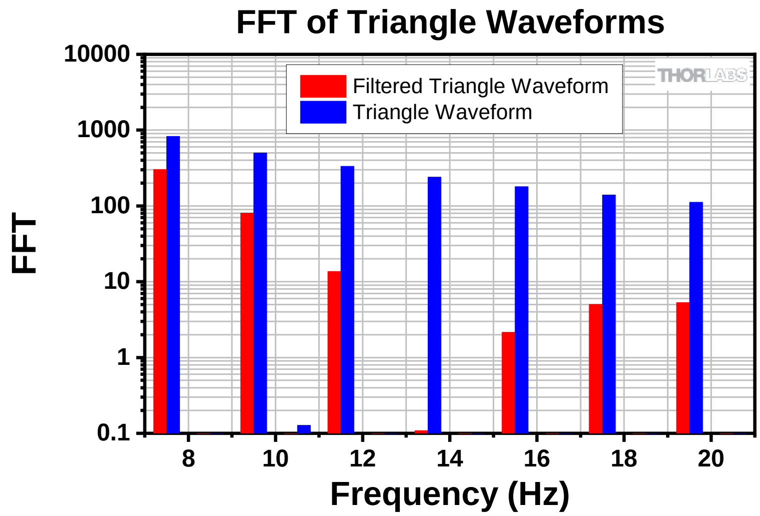


Figure 19 Fourier Analysis Showing Reduced Harmonic Content After Filtering

The frequency components that would excite the fundamental resonance of the VCFL35(/M) scanner are much larger in the triangle waveform than in the filtered waveform.

6.2. Closed-Loop Control Application Example

One traditional method for closed-loop control of position and velocity is to use an encoder attached to the moving platform to generate position and velocity signals to provide input to a motion controller. A variety of encoders are available, but those would add undesirable cost and complexity to the scanner mechanism. A variety of industry-standard motion controllers are available, but are relatively expensive. The majority of industry-standard controllers use high-frequency pulse-width modulation (PWM) that introduces undesirable electromagnetic interference (EMI). The intended use case for the VCLF35(/M) scanner is modulation of optical signals, which intrinsically provide much better velocity and position information than traditional encoders.

There are two simple and straightforward methods to generate optical position signals from mirrors mounted on the flexure scanner. The first is elegant for its simplicity, requiring only two components. This arrangement is illustrated in Figure 20. A laser beam is reflected from the flat mirror at an angle such that the reflected beam translates back and forth across the face of a position sensitive detector in response to mirror motion. The output of the detector can be compared to a setpoint to control the position, or the derivative of the position can be compared to a setpoint to control the velocity. In the example, the laser source is a PL202 module, and the photodetector is a PDP90A position-sensitive sensor. A very simple analog circuit with a few op amps can be used to provide closed-loop control. One of the most powerful and popular of these techniques is the proportional-integral-differential (PID) controller.[22,23]

[22] *PID controller https://en.wikipedia.org/wiki/PID_controller.*
[23] *Paul Horowitz, The Art of Electronics 3rd Edition, Cambridge University Press; 3rd edition (2015), p. 1074.*

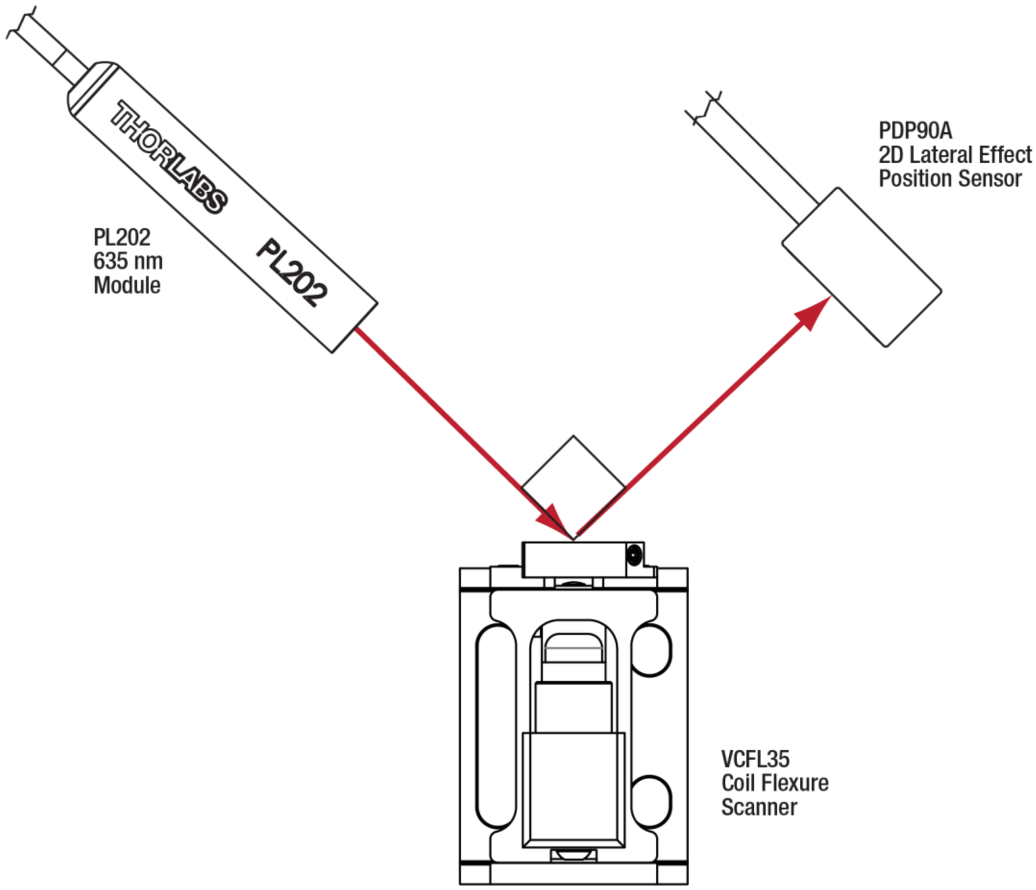


Figure 20 Simple Optical Tracking of Mirror Position

The minimum set of components to provide interferometric encoding of the scanner position includes a laser or other high-coherence source, a beamsplitter, a fixed mirror, and a mirror mounted to the VCFL35(/M) scanner. A photodiode circuit equivalent to the Thorlabs' PDA100A2 detector is required to convert the optical signal from to an electrical signal. The resulting voltage then can be digitized and processed. Two traditional approaches to process the resulting laser signal or signals to position and velocity are described briefly here.

The first laser signal processing approach is conceptually simpler and appropriate for laser modulation frequencies greater than about 1 kHz. The time between zero crossings can be measured to estimate the mirror velocity. This avoids the need for an analog-to-digital converter, but requires a comparator and time. Laser fringes can be counted to maintain knowledge of how far the mirror has moved in the previous microseconds to seconds of scan time. In cases where isolation from the ambient environment is very good, particularly using vibration-isolation tables, lower modulation frequencies than 1 kHz can be used. In higher vibration environments, such as industrial settings where heavy machinery is operating, higher laser frequencies are required to obtain accurate position and velocity information from measuring the time between zero crossings. A simple digital circuit can measure the timing information. A comparator may be used to compare the laser signal to a filtered average to create a square wave version of the signal. Each zero crossing appears as an edge in the square wave. This is equivalent to a one-bit digitizer, and the timer then measures the width of each half cycle to provide rapid, but not truly continuous updates of the velocity.

A more powerful approach to process the laser signal or signals is to digitize to high resolution, at least 14 bits, then process the resulting data to nearly continuous updates of phase. This approach can allow for very accurate monitoring and control of the mirror position and velocity at much lower velocities, including zero. If the digitizer operates at a sufficiently high speed, for example, 1 to 10 MHz, then fringe counting will be very robust even in the presence of vibration. The derivative of phase is proportional to mirror velocity, and the phase itself provides extremely accurate position information. The position and velocity can be used as inputs to a proportional-integral-derivative (PID) controller that manages the mirror velocity and turnarounds.

If a reference laser channel is used to track interferometer mirror position and velocity during scanning, it is straightforward to implement fringe counting. If only a single laser channel is used for fringe counting, errors may be introduced at turnarounds because of the ambiguity in direction. This can be interpreted as a susceptibility to vibration, especially for low velocities. Vibration often will cause multiple turnarounds. These reversals of direction occur due to vibration as the mirror slows down, stops, and accelerates in the opposite direction. At times when the mirror is moving slowest, it is most susceptible to even small vibrational disturbances reversing the direction. A single laser channel cannot distinguish direction of motion during and after a turnaround. Thus, for accurate fringe counting, it is important to avoid ambiguity. Reference points such as the centerburst location in the signal channel, centerburst location in an auxiliary channel, or end of travel sensors may be used to update (“reset”) the fringe count. Because the optical path difference of the reference points essentially is fixed in relationship to the fringe counting, other than the effect of CTE (coefficient of thermal expansion) mismatch that causes small and mostly reversible shifts in relative position. A particularly useful alternative to a single laser channel is to provide a second laser channel that is phase-shifted approximately 90° from the first. The second laser often is a called a quadrature channel. The details of how to set up quadrature can be found the literature.[24,25] The second laser channel and many permutations of the concept can be used to resolve the ambiguity in direction. If a turnaround occurs at an extremum of the laser, either a maximum or minimum, the signal appears to be the same in both directions. An extremum of the laser signal, either a maximum or a minimum is a point of even symmetry. A second laser signal with a 90-degree phase shift has odd symmetry that resolves the direction ambiguity, allowing for very robust fringe counting.

In many interferometric instruments, a mirror scanning mechanism needs to undergo a very rapid deceleration and reacceleration in the opposite direction. This necessitates a significant current spike in the drive coil to generate the appropriate force, which should be as large as possible without exciting mechanical resonances. While closed-loop control can be maintained through the entire turnaround, it often is more convenient to just turn off the control and apply a suitable turnaround waveform from a lookup table. After the turnaround is complete, the velocity control can be turned on. While the first resonance will be excited by the sharp transient, the low frequency is so far within the control bandwidth that it disappears almost instantly when velocity control is reasserted after completing the turnaround. This is not the case in open-loop operation. In principle, the energy stored in the resonance could be predicted and nulled using techniques of adaptive signal processing. In practice, it is easier to implement closed-loop control. Even then, techniques from adaptive signal processing are useful.

The VCFL35(/M) scanner was installed into the Michelson interferometer, shown in Figure 14, to provide interferometric encoding of position, velocity, and acceleration, as is explained in the paragraphs above. The velocity stability of the VCFL35(/M) scanner in this closed-loop system is shown in Figure 21.

[24]US Patent 4,480,914 Thompson, et al. November 6, 1984, Vibration compensating interferometer mirror drive system, http://pdfpiw.uspto.gov/.piw?Docid=04480914.
[25] Linear encoder https://en.wikipedia.org/wiki/Linear_encoder.

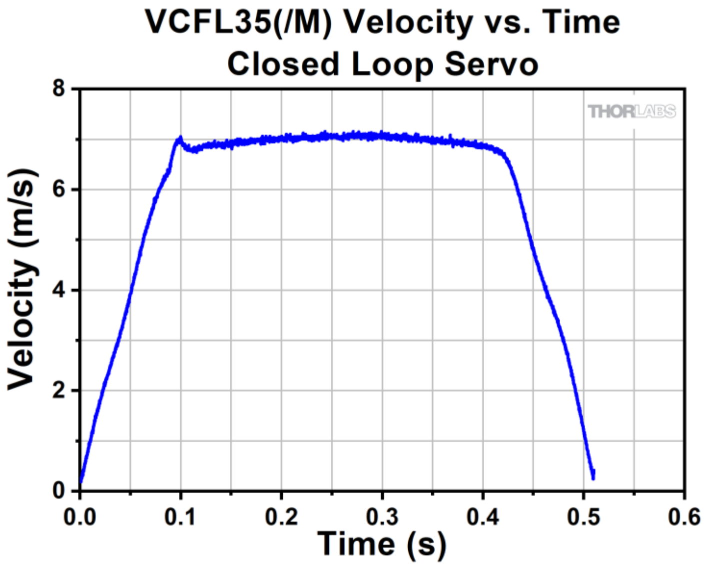


Figure 21 Velocity Profile During Closed Loop Control

The velocity stability of the closed-loop system for the center 65% of the scan is 1.4% and this is repeatable for multiple units tested. Closed-loop performance provides significantly improved velocity stability when compared to open-loop operation. Equivalent improvements are possible for position control. However, closed-loop control is more difficult to engineer and requires at least a few additional components.

Chapter 7 Specifications

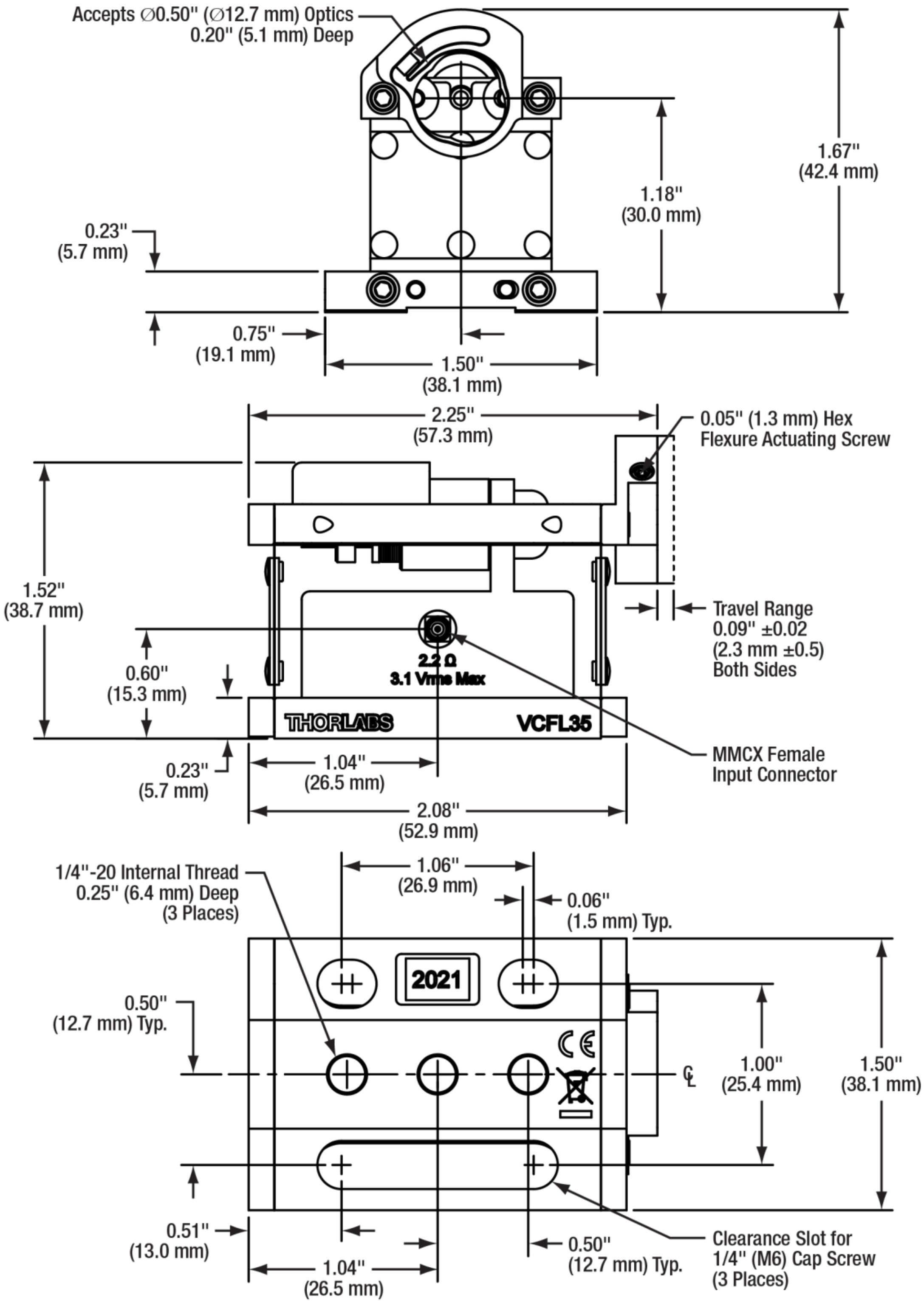
General Specifications	
Recommended Travel Range[26]	1.75 mm
Maximum Travel Range[26]	2.30 mm ± 0.50 mm
Maximum Input Voltage	3.1 V_{RMS}
Scanner Resistance	2.2 Ω @ 23 °C
Maximum Continuous Current[27]	1.4 A Applied @ 23 °C
Voice Coil Inductance	167 µH
Force Constant[28]	0.71 Newtons/Amp
Static Travel Constant[26]	0.27 A/mm
Flexure Spring Constant[29]	193 N/m ± 20%
Maximum Recommended Load[30]	3.5 g
Absolute Maximum Load	12.5 g
Recommended Optic Mounting Torque[31]	8 oz-in
Minimum Optic Thickness	3.2 mm
Vertical Runout[32]	90 µm
Dimensions[33]	57.3 mm x 38.1 mm x 42.4 mm
Weight	68 g
Weight (Moving Stage Only)	20 g
Structural Material	Aluminum, Steel
Input Connector	Female MMCX
Input Connector Mating Cycles	500
Included MMCX Male to BNC Male Cable Length	1 m

Resonance Specifications[34]			
	No Load	**2 g Optic Mounted**	**3.5 g Optic Mounted**
First Resonance	14.9 Hz	14.1 Hz	13.2 Hz
Max Scan Frequency[35]	33 Hz	32 Hz	30 Hz
First Parasitic Resonance[36]	Greater than 1.5 kHz		

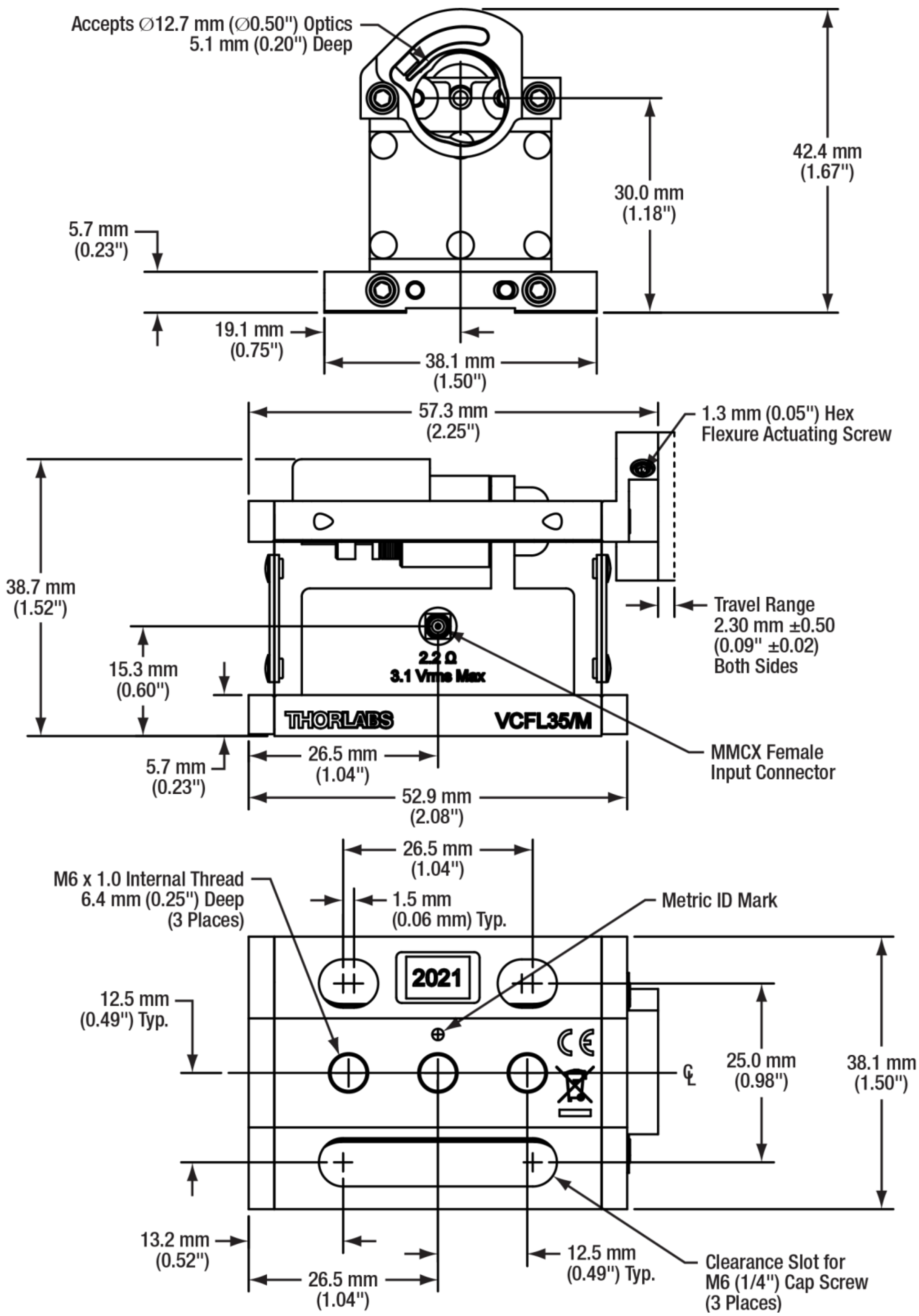
[26] Specified for Each Direction from Flexure-Neutral
[27] For constant voltage, current will decrease as device warms.
[28] Specified at Flexure Neutral – Force Constant Decreases by ~10% at ±1.75 mm
[29] Specified for Both Flexures Combined
[30] Maximum Load Used for All Application Examples and Explanations in this Manual
[31] Specified for Optics with a Diameter Tolerance of up to +0/-0.1 mm.
[32] Specified at 1.75 mm in Each Direction from Flexure-Neutral
[33] At Flexure-Neutral
[34] All resonant frequencies decrease as load increases.
[35] Specified to Achieve Full ±1.75 mm Stroke Using a Triangle Waveform at Maximum Input Power
[36] Theoretical, see Section 4.3.2 Parasitic Resonances for more information.

Chapter 8 Mechanical Drawings

8.1. VCFL35 Voice Coil Flexure Scanner



8.2. VCFL35/M Voice Coil Flexure Scanner



Chapter 9 Appendix

Filtered Triangle Waveform Generator

This code was written in Octave 6.2.0 as a *.m* script file but is expected to run in Matlab® with the *Signal Processing Toolbox* installed.

The program takes as input a sampling rate, amplitude, frequency, and filter window length coefficient to generate a triangle waveform, then passes it through a moving average filter to "smooth" the sharp peaks and valleys of the triangle waveform. The resulting filtered triangle waveform is output as.csv format for upload to arbitrary waveform generators.

Everything else remaining constant, the filter window length coefficient (variable N in the code below), controls the smoothing of the sharp turnarounds of a triangle waveform. Longer window lengths result in smoother turnarounds.

Please note, arbitrary waveform generators that accept .csv uploads may have a maximum number of significant figures supported for each datapoint and/or a maximum number of datapoints supported. Reduce the significant figures per data point in Microsoft Excel and reduce the number of datapoints by changing the sampling frequency (fs).

```
%Sampling frequency in Hz - Dictates number of datapoints in .csv output waveform
fs = 100000;
%Define time (t) as linearly spaced elements equal to the sampling freq from 0 to
2pi.
t=linspace(0,(2*pi),fs);
%Amplitude (A) Arbitrary Units
A = 1;
%Frequency in rad/s
w = 2*pi;
%Frequency in Hz
f = 1/w;

%Define triangle waveform
Triangle = ((2*A)/pi)*asin(sin((2*pi*f)*t));

%Window Length Coefficient - window length is N*sampling frequency (fs)
N = 0.075;
%For the same sampling frequency, greater window length = smoother waveform after
filtering

%Create a matrix of zeros to fill with filtered waveform
Filt_Tri = zeros(size(Triangle));

%Define filter kernel
fk = 1/(N*fs)*ones((N*fs),1);

%Forward and reverse filter the triangle waveform
Filt_Tri = filtfilt(fk,1,Triangle);

%Transpose waveform datapoints form row to column
Filt_Tri = Filt_Tri';

%Write filtered waveform to csv
csvwrite ('Filt_Arb.csv', Filt_Tri);

%Program arbitrary waveform generator using this csv file
```

Chapter 10 Regulatory

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return “end of life” units without incurring disposal charges.

- This offer is valid for Thorlabs electrical and electronic equipment:
- Sold after August 13, 2005
- Marked correspondingly with the crossed out “wheelie bin” logo (see right)
- Sold to a company or institute within the EC
- Currently owned by a company or institute within the EC
- Still complete, not disassembled and not contaminated

Wheelie Bin Logo

As the WEEE directive applies to self-contained operational electrical and electronic products, this end of life take back service does not refer to other Thorlabs products, such as:

- Pure OEM products, that means assemblies to be built into a unit by the user (e. g. OEM laser driver cards)
- Components
- Mechanics and optics
- Left over parts of units disassembled by the user (PCB’s, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

Waste Treatment is Your Own Responsibility

If you do not return an “end of life” unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of life products will thereby avoid negative impacts on the environment.

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs Inc.

Of: 56 Sparta Avenue, Newton, New Jersey, 07860, USA

in accordance with the following Directive(s):

2006/42/EC	Machinery Directive (MD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***VCFL35 and VCFL35/M***

Equipment: ***Voice Coil Flexure Scanner***

is/are in conformity with the applicable requirements of the following documents:

EN ISO 12100	Safety of Machinery. General Principles for Design. Risk Assessment and Risk Reducti(	2010

Authorised to compile the technical file: Thorlabs GmBH
Münchner Weg1, 85232 Bergkirchen, Deutschland

EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requireme	2013

and which, issued under the sole responsibility of Thorlabs, is/are in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

contains no substances in excess of the maximum concentration values tolerated by weight in homogenous mat

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: *On:* 03 March 2022

Name: Danielle Strong

Position: Director of Quality and Compliance *EDC - VCFL35 and VCFL35/M -2022-...*

CE

Chapter 11 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at **www.thorlabs.com/contact** for our most up-to-date contact information.

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