How a Tubular Linear Motor Works

Introduction

A tubular linear motor is a direct-drive electric actuator that produces linear motion without any mechanical transmission. Unlike a conventional servo motor, which requires a gearbox, lead screw, or belt to convert rotation into translation, a tubular linear motor generates force directly along the axis of movement. The result is a system with zero backlash, high dynamic response, and virtually no mechanical wear.

NiLAB tubular linear motors are used in a wide range of industrial applications: pick-and-place systems, press and forming machines, dispensing, medical equipment, semiconductor handling, and as direct replacements for pneumatic cylinders

Core Components

A tubular linear motor consists of two main parts:

The Stator (Coil Assembly)

The stator is the fixed, outer housing that contains a set of copper windings arranged in three phases (U, V, W). These windings are distributed along the axis in a specific spatial pattern, typically with a pole pitch that matches the magnet arrangement of the moving rod. The stator is analogous to the winding assembly of a rotary motor that has been “unrolled” and wrapped around a cylinder.

The stator housing is usually made of aluminium alloy for effective heat dissipation. Thermal protection is provided by a PTC (Positive Temperature Coefficient) sensor embedded in the windings, which is monitored by the servo drive to prevent overheating.

The Forcer / Mover (Magnet Rod)

The moving part is a cylindrical rod containing a series of permanent magnets arranged in alternating polarity along its length. High-energy NdFeB (Neodymium-Iron-Boron) magnets are typically used to achieve a high force density in a compact diameter.

The magnet rod slides axially inside the stator bore with a very small air gap. It is the only moving mechanical element — no ball screws, no belts, no gears. End caps and rod seals protect the interior from contamination in industrial environments.

The Integrated Encoder

Position feedback is provided by an encoder integrated directly into the motor body. In NiLAB motors this is a high-resolution **SIN/COS incremental encoder** (1 Vpp signal), delivering sub-micron resolution when combined with a servo drive interpolator.

The encoder PCB is fixed inside the stator detecting the magnetic field from the rod. This arrangement provides position information within one motor stroke without external linear scales. Some models (BISS-C option) support absolute multi-turn serial encoders, allowing instant position readout after power-on without a homing cycle.

The Anti-Rotation Mechanism

Because the stator produces a pure axial force, the magnet rod is free to rotate unless constrained. For applications where the rod must not spin (e.g., when carrying a guided payload), NiLAB motors provide an **anti-rotation accessory** — typically a keyway sleeve or an external linear guide that prevents rotational movement while allowing free axial travel.

Operating Principle

Lorentz Force — From Current to Linear Motion

The fundamental operating principle is based on the **Lorentz force law**: a current-carrying conductor placed in a magnetic field experiences a force perpendicular to both the current direction and the magnetic field vector.

In a tubular motor the current flows circumferentially through each winding coil, and the permanent magnets on the rod create a radial magnetic field. The interaction produces an axial (thrust) force. By controlling the magnitude and direction of the current in each phase, the servo drive controls both the amplitude and direction of the linear force.

The theoretical peak force F [N] for a single coil is:

$$F = B \cdot I \cdot L \cdot N$$

Where B is the magnetic flux density [T], I is the phase current [A], L is the effective conductor length [m], and N is the number of turns per coil. In a real motor the total force is the sum of contributions from all active coils simultaneously carrying current.

Three-Phase Commutation

Like a brushless rotary servomotor, a tubular linear motor uses **three-phase AC commutation** (sinusoidal field-oriented control, or FOC). The servo drive generates three sinusoidal current waveforms, phase-shifted by 120°, applied to the three winding phases U, V, W.

As the magnet rod moves, the encoder continuously reports the position to the drive. The drive uses this position to compute the instantaneous **electrical angle** (commutation angle), which determines how much current flows in each of the three phases at every instant. This ensures the current vector in the stator is always maintained at 90° to the rotor flux — the condition that maximises force per amp.

The **motor pole pitch** (τ) defines the spatial period of the commutation cycle. For a motor with pole pitch τ = 60 mm, one complete electrical period occurs every 60 mm of linear travel.

Force–Speed Characteristic

The tubular linear motor force–speed curve has two regions:

* **Continuous force (F_{cont})**: The force level that can be sustained indefinitely, limited by the thermal rating of the windings.
* **Peak force (F_{peak})**: Typically 2–4× F_{cont}, available for short duty cycles (acceleration bursts). Limited by drive current capability.

At higher speeds, back-EMF (voltage generated by the moving magnets) reduces the available current for force generation, creating a characteristic force roll-off region. The speed at which this roll-off begins depends on the supply voltage and the motor's back-EMF constant (Ke).

The relationship between peak velocity, supply voltage, and motor parameters is:

$$V_{max} \approx (V_{dc} - I \cdot R) / Ke$$

This is why selecting the correct bus voltage is important when high-speed operation is required.

Position Feedback and Closed-Loop Control

The servo drive implements a cascaded control loop:

- **Current loop** (innermost): regulates the three-phase currents to follow the force command. Bandwidth: typically 5–10 kHz.
- **Velocity loop**: regulates the rod velocity based on encoder-derived speed. Bandwidth: typically 100–500 Hz.
- **Position loop** (outermost): regulates the absolute position of the rod to the target setpoint. Bandwidth: typically 20–100 Hz.

The SIN/COS encoder signals are interpolated by the drive to achieve resolutions in the range of **0.1 µm to 1 µm** depending on the interpolation factor. This makes tubular linear motors suitable for precision positioning tasks that would be impossible with pneumatic or open-loop electric actuators.

Thermal Management

The primary source of heat in a tubular linear motor is **Joule heating** ($I^2 \cdot R$ losses) in the copper windings. At continuous operation the stator housing must dissipate this heat to the environment or to a cooling circuit.

NiLAB motors are rated for continuous operation up to a winding temperature of 130°C (Class F insulation). The aluminium housing conducts heat outward, and convective cooling is usually sufficient for moderate duty cycles.

For high duty-cycle or high-force applications, **forced air cooling** (via an axial fan blowing over the stator fins) or **liquid cooling** (water jacket around the stator) are available options. Liquid cooling can increase the continuous force rating by a factor of 2–3× compared to natural convection.

The PTC sensor in the windings provides a direct winding temperature signal to the servo drive, which can trigger a warning or fault before the thermal limit is reached.

Advantages Over Traditional Actuators

Parameter	**Tubular linear motor**	**Pneumatic Cylinder**	**Ball screw Actuator**
Force ripple	Very low (< 1%)	Moderate	Low
Positioning accuracy	+/-0.1 mm	No position control	+/-10 microns or less
Speed	Up to 5 m/sec	Up to 2-3m/sec	Up to 1 m/sec
Mechanical backlash	Zero	Not applicable	0.02 - 0.1 mm
Maintenance	None (no wear parts)	Seals, filter, lubrication	Lubrication, nut wear
Energy efficiency	High	Low (15-20%)	High
Programmable force profile	Yes (full)	No	Indirect (via current limit)
Noise level	Very low	High (exhaust)	Moderate

Summary

A tubular linear motor is essentially a **three-phase brushless servomotor unrolled into a straight line**. Permanent magnets on a rod travel axially inside a wound stator, driven by Lorentz forces generated by field-oriented current control. An integrated encoder closes the loop to the servo drive, enabling precise position, velocity, and force control with no mechanical transmission losses. The result is a highly dynamic, maintenance-free, and energy-efficient alternative to pneumatic cylinders and electromechanical screws.