Advanced Motion Control for Durability, Part Characterization and Dynamic Mechanical Analysis (DMA)

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This white paper reviews technologies used to produce motion and exert forces on a test specimen using Dynamic Mechanical Analysis (DMA) and related testing applications. Refer to Figure 1 for typical types of DMA testing.

Generally, there is an interest when studying materials to understand their dynamic modulus (elasticity, tensile strength, etc.) that describes the relationship between stress and strain in the material. When studying widgets (shock absorbers, rubber mounts, etc.), interest is usually in the durability of the widget in a variety of operating conditions. Both of these tests consider specific operating points and ranges of frequencies, temperatures, and/or displacements.

Fundamentally, these tests are conducted by placing the specimen in a machine that will:

- Apply a force to the specimen and measure the displacement. The force applied may be static or vary in frequency.
- Cause a displacement and measure the force. Often the displacement is swept over a frequency and/or distance range.
- In some cases, velocity and acceleration of the test specimen motion is also measured or controlled. For instance, a frequency sweep of varying displacement that applies a constant acceleration to the Unit Under Test (UUT) may be desired.

Traditionally these applications use servo-hydraulic solutions – actuators and controls. Lately interest has been noted in using electric actuators and servo controllers to provide characterizations not possible with servo-hydraulic solutions, in addition to the “green” factor that electric solutions provide. This is not to imply that electric solutions are superior to servo-hydraulics in all applications. As with most engineering decisions, the best solution depends on the specific requirements.

Dynamic Mechanical Analysis (DMA)	DMA applies a small linear motion to a sample (e.g., rubber) in a cyclic manner. The intensity of the stress is known and the strain of the sample is measured.
Dynamic Mechanical Thermal Analysis (DMTA)	DMTA is the same as DMA but it also simulates environmental conditions during the test (e.g., UV curing, saltwater, gastric acid, high or low temperature, etc.).
Thermo-Mechanical Analysis (TMA)	TMA consists of stretching a sample at a constant static force, then heating or cooling it to examine deformation.
Fatigue Testing	Fatigue testing simulates the use and wear of a part to provide an estimated life-span. It applies a linear motion in a cyclic manner. Many consumer products have been fatigue tested (e.g., dampers, keyboards, smartphones, shoes, etc.).
Tensile Testing	Tensile testing consists of slowly increasing the force (tension) applied to a sample until the sample fails.

Table 1. *Common types of DMA testing.*

Design Factors to Be Considered

To properly determine material or part characteristics it is important to create motion or apply forces in a perfect sinusoidal pattern. The "quality" of the sinusoidal movement/force depends on the actuators, measurement devices, machine frame mechanical structure, and the controller used.

Depending on the specific application, electric, servo-hydraulic, or piezo actuation may be best. Factors to consider when designing the system include:

- Magnitude of applied force
- Amount of displacement required
- Frequency of movement
- Resolution of displacement measurement required
- Control architecture

The current trend in many manufacturing and test facilities is to be "greener." This leads to end-users seeking alternatives to the traditional servo-hydraulic solution. Higher performance is always a key to competitiveness, so that more complicated motion profiles are required, and lower force resolution and better force control are needed.

Two motion types are normally used with samples or the UUT:

- Sinusoidal motion
- Replica of the motion the UUT will experience in operation

Sinusoidal Motion

Sinusoidal motion is required to understand the frequency response of the UUT. Higher performance systems demand higher frequency testing and better sinusoids to stimulate the UUT. Typically phase is not important but amplitude and sine-wave fidelity are critical. In this case, Total Harmonic Distortion (THD) can be used to measure sine-wave fidelity. Achieving this motion is not the usual control problem of minimizing following error but rather ensuring that a perfect sine wave is applied to the UUT over the frequency range of interest. The algorithms used and tuning techniques will differ. When tuning for low servo error higher bandwidth is usually better; however, to achieve low THD, loop shaping can be more effective. The controller used is as important as the actuation technology. For instance, if the actuator is perfect (no cogging distortion, no friction, and no force limitations) but the motion commanded is imperfect, the results will be equally imperfect and the measurements will be incorrect.

Replicating Operation

When replicating the motion the UUT will experience in actual operation, it is necessary to collect data during UUT operation and then replay that on the machine. Here trajectory generation and controller sample time is critical to represent the motion properly. In playback testing the phase is more important than in sine-wave testing and often machine setup optimizes the traditional servo tracking error. In playback mode it is usually important to replicate the motion experienced by the UUT in operation (sometimes in multiple directions –i.e. multiple axes of motion) to fully characterize the durability and operation of the UUT. In sine-wave testing usually the material properties are being measured and the fidelity of the sine wave (but not the phase) is important for this calculation. A machine that can test both requires a flexible controller that can quickly change parameter sets for different operating modes.

The accurate and coincident measurement of the displacement and forces applied are important for the accurate measure of modulus, as well as to understand how the UUT responds in actual use. Therefore, it is necessary not only to have the correct actuator but also the appropriate instrumentation (feedback devices for displacement and force) that can be sampled simultaneously, continuously, and with sufficient resolution. To accommodate both types of testing the controller should be flexible enough to switch machine setups quickly to test a variety of samples for a variety of characteristics. Testing diverse samples usually implies larger displacement requirements to accommodate a range of UUT. The implication is that the dynamic response of the machine must be equivalent at any point in the travel and that machine setup is quick.

Figure 1 delineates the typical range for each of the applicable technologies. Servo-hydraulic designs are combined (for instance, single stage and dual-stage servo actuators). However, several electrical actuators are shown.

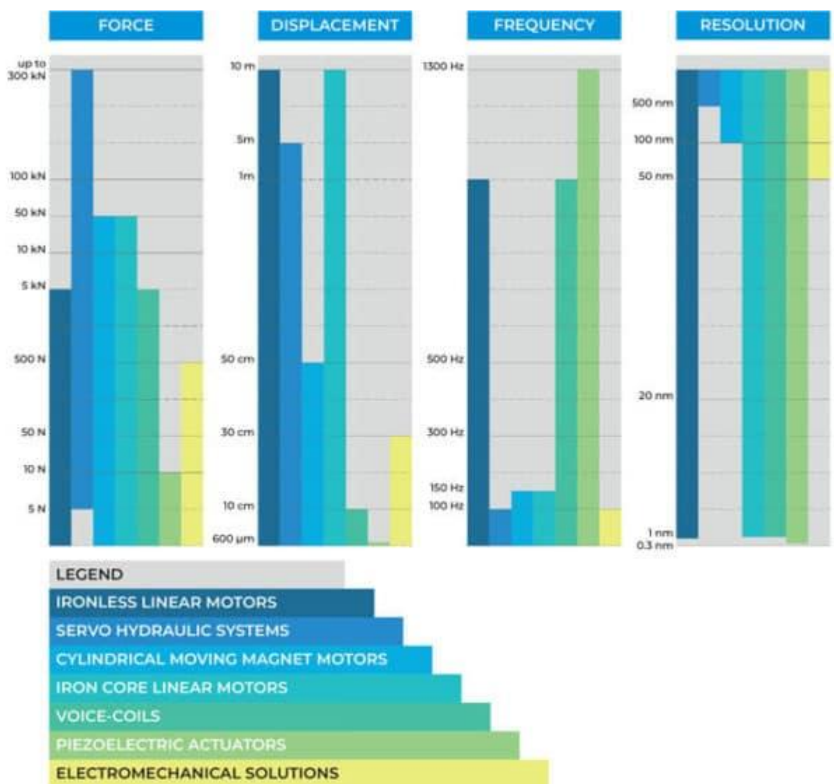

Figure 1. *Characteristics of common linear motion technologies used for DMA[1].*

The easiest parameter to compare is displacement. Displacement of more than 600 microns eliminates piezo actuators and more than 10 cm rules-out voice coils. Ball-screw-driven actuators are limited to about 30 cm. Linear motors and servo-hydraulics are both capable of 5.0 meter displacements, which is enough for 99% of DMA applications. Applications requiring forces higher than 50 kN require servo-hydraulic solutions. Iron-core-type motors are applicable below 50 kN and ironless motors are applicable below 10 kN.

The highest frequencies (1300 Hz) can be obtained with piezo actuators followed by ironless motors and voice coils at 1000 Hz. Servo-hydraulic systems are usually limited to 100 Hz.

The smallest displacement resolution, 0.3 nm, is achievable with piezo actuators, followed by 1 nm achieved by any servomotor technology.

Broadly, very high force applications require servo-hydraulic solutions, while very high frequency, small displacement applications require piezo actuators. Below 10 kN electric motor technology is optimal. Which electric motor technology selected– ironless, iron core, or voice coil — depends on the displacement and quality of motion required. Ironless motors will produce better quality motion than iron-core motors and any travel beyond 10 cm eliminates voice coils.

Technology Review

Electromechanical Solutions

Figure 2. *An Aerotech ball-screw linear stage.*

A rotary electric motor is used for system input and linear motion is accomplished with the mechanical conversion of rotary motion to linear motion in electromechanical actuation. The most common technologies used to convert rotation into linear motion are:

- Crankshaft and rod
- Lead screw or ball-screw systems
- Belt and pulley
- Rack and pinion
- Gears

The main advantage of these systems is their price. None of the rotary motors used for these applications would be as expensive as a comparable direct-drive linear motor. These electromechanical actuators are suitable for lower performance, less versatile analyzers.

Limitations of electromechanical actuators include:

- Less flexibility for variable testing
- Mechanical errors such as backlash
- Limited lifetime due to wear
- Disturbances in applied linear motion
- Poor accuracy
- Complex feedback systems with dual encoders
- Larger structures to isolate induced vibration
- Displacement limited to 30 cm

Direct-Drive Linear Actuation

Direct-drive systems don't require mechanical conversion of rotary to linear motion and so don't suffer from issues inherent in electromechanical solutions. There is no need to convert rotary to linear motion and therefore there is no need for rack and pinions or gears or belts and pulleys. Linear motion is generated by the interaction of magnetic fields and permanent magnets. There are several types of direct-drive linear actuation available: cylindrical moving magnet, flat iron-core and ironless, and U-channel ironless linear motors.

Cylindrical Moving Magnet Linear Motors

Cylindrical moving magnet linear motors were the first electromagnetic linear motors to find significant commercial application because they are the same shape as hydraulic cylinders making them an easy replacement. They work the same way as magnetic actuators (voice coils) but with a replicated number of coils to extend the stroke.

Common limitations of cylindrical moving magnet linear motors are cogging torque and flux leakage. Cogging torque, also known as "no current" torque, comes from the magnetic flux and the iron core of the forcer. It causes disturbances in motion and in certain cases creates large friction preventing small moves. Cogging torque can even be observed when moving the motor manually, as might occur while attempting to prevent small forces from being applied to soft test materials. Cogging torque may preclude this motor's use depending on the frequency range and displacement requirements of the mechanical analyzer.

Flux leakage refers to the lack of containment of the magnetic field. This should be considered with care, especially if other components or the sample under test are sensitive to magnetic fields.

The main advantage of cylindrical moving-magnet linear motors is that they are compact. The bearing is usually integral with the motor and it can also achieve higher forces than an ironless linear motor.

U-Channel Ironless Linear Motors

Figure 3. Aerotech U-channel ironless linear motors.

Two parallel magnet tracks with an ironless forcer running between them form a U-channel linear motor. The device design must have a bearing system to handle the loads required and to maintain the forcer between the magnet tracks. Magnet tracks can be added together for longer travels. Displacement is only limited by:

- Cable management
- Encoder length
- Ability to machine long, flat, stiff structures
- Machine size

- Bearing length

In contrast to cylindrical moving-magnet linear motors, U-channel linear motors are designed to reduce magnetic flux leakage. The forcer is made of coils and epoxy for a reduced mass allowing very high acceleration, which is useful for fatigue testing. The key advantage of this technology is that, due to the ironless design, there are no cogging forces. This delivers the following advantages:

- The forcer can be moved manually when not powered
- No motion disturbances are experienced at any velocities
- No minimum force limits – very small forces can be applied
- No minimum displacement
- Freedom to design the bearing system for specified use
- Higher accuracy and repeatability
- No attractive force – requires lower cost bearings than iron core motors
- Less wear of the bearings due to no attractive force equals lower cost of ownership

The disadvantages of this motor are:

- Higher cost to force ratio
- May require a mechanical brake for vertical operation

Iron-Core Linear Motors

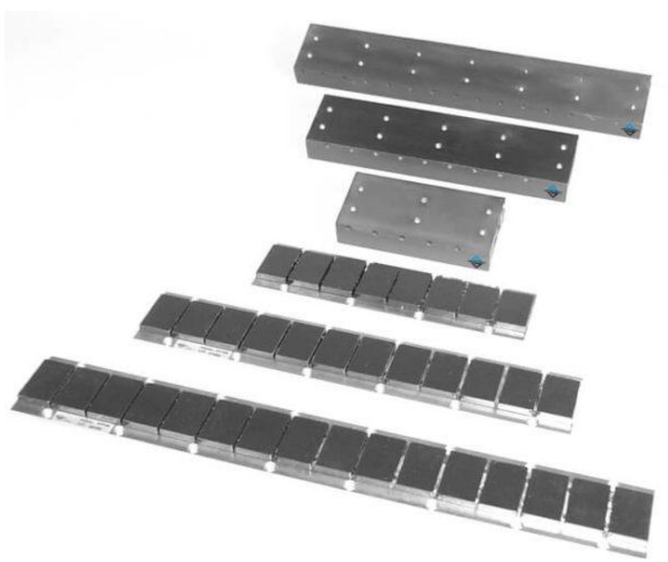

Figure 4. *Aerotech iron-core linear motors.*

This family of motors has a track with a single row of magnets, and with coils mounted on an iron-laminated plate to focus the flux towards the magnets. The presence of iron in the motor amplifies the force generation but also causes attraction force between the forcer and the magnet track. This introduces cogging forces that cause errors in the motion. Another variant of this motor is the slotted design where the coil windings are inserted into a steel structure to create the coil assembly. This also significantly increases the force output as well as the cogging effect.

The disadvantages of using iron-core linear motors are:

- Cogging torque, also known as "no current" torque, comes from the magnetic flux and the iron core of the forcer. It causes disturbances in motion and in certain cases creates large friction preventing small moves. Cogging torque can even be observed when moving the motor manually, as might occur while attempting to prevent small forces from being applied to soft test materials. Cogging torque may preclude this motor's use depending on the frequency range and displacement requirements of the mechanical analyzer.
- Flux leakage refers to the lack of containment of the magnetic field. This should be considered with care, especially if other components or the sample under test are sensitive to magnetic fields.

Depending on the final application, these motors could be used when high force is needed. Nevertheless, cogging will cause issues with the motion imparted to the UUT as it will add to or subtract from the force applied resulting in incorrect motion. However, if the displacement is very small relative to the pole pitch of the motor, the cogging will not have a significant effect on the motion over the distance traveled – essentially the cogging force will be a constant value. But in this case the controller must be able to eliminate a constant force disturbance. Moreover, if a different size UUT is put in the machine for testing, the amount of constant cogging force applied will be different since the dynamic test will occur in a different location relative to the electrical cycle. To help reduce this phenomenon, magnets could be skewed, but this will not prevent cogging completely.

Voice Coils

A voice coil works on the same principle as a linear motor but is composed of only one coil and two magnets (i.e., one electrical cycle). Voice coils are easy to control but offer limited stroke and suffer from a decrease in power as the displacement increases. Voice coils are suitable for applications that do not require large amplitude but a high frequency, especially for DMA. Electrodynamic shakers often are voice-coil-based systems.

Piezoelectric Actuators

Figure 5. *Aerotech piezo technology.*

Piezoelectric actuators use the physical behavior of piezo crystals. In this case, an applied voltage to the crystal causes the crystal to expand, creating linear motion. These actuators are highly reliable and suitable for sub-micron precision applications at extremely high frequencies. Piezos are expensive compared with motor technologies.

Servo-Hydraulic Systems

This technology has been the workhorse of the industry for many years. Servo hydraulic is required for very high force testing such as hard materials or large industrial parts (e.g., complete aircraft landing gear) for frequencies less than 100 Hz. The drawbacks are:

- Force disturbances at low force level measurements especially noticeable during reversal of motion
- Low accuracy and repeatability due to backlash, hysteresis, and oil sensitivity to aging
- Extreme space budget both inside (hoses, distributors, accumulators, etc.) and around your device (e.g., fluid barrels in stock, hydraulic power unit, etc.)
- High cost of ownership (e.g., oil replacement and infrastructure required)
- Dirtiness – every hydraulic system leaks

Capabilities of Ironless Linear Motors

This being the newest technology used in DMA, some data is presented to highlight the capability of these motors. Figures 7 through 10 show the Pareto Curves for frequency, velocity, acceleration, and force output. Using a BLMX-502-B motor (see datasheet in

Appendix A), displacements over 1.0 meter at low frequencies and displacements of 0.2 mm at 300 Hz can be achieved. The resulting minimum and maximum velocities and accelerations range from 0 m/s to 50 m/s and 3.6g at low frequencies to 39g at high frequencies with small displacements. The continuous force output for a single motor is 1600 N. One advantage of linear motors is that they can be grouped together to create more force. For instance, grouping four motors in one machine yields a continuous force of 6400 N and a peak force of 25,600 N.

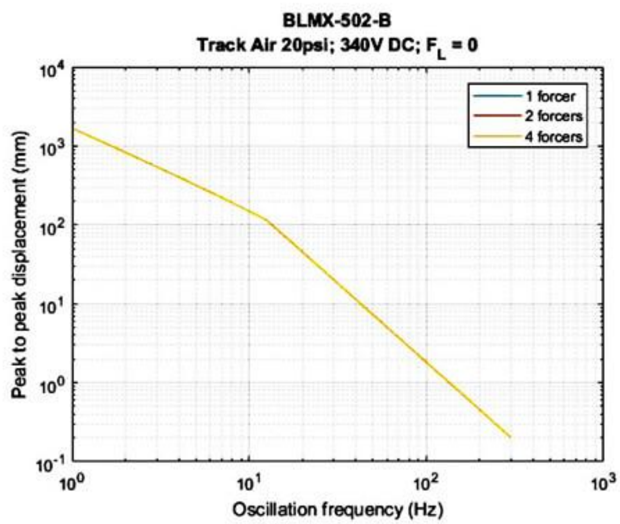

Figure 6. *No load displacement vs oscillation frequency for 1, 2 and 4 forcers.*

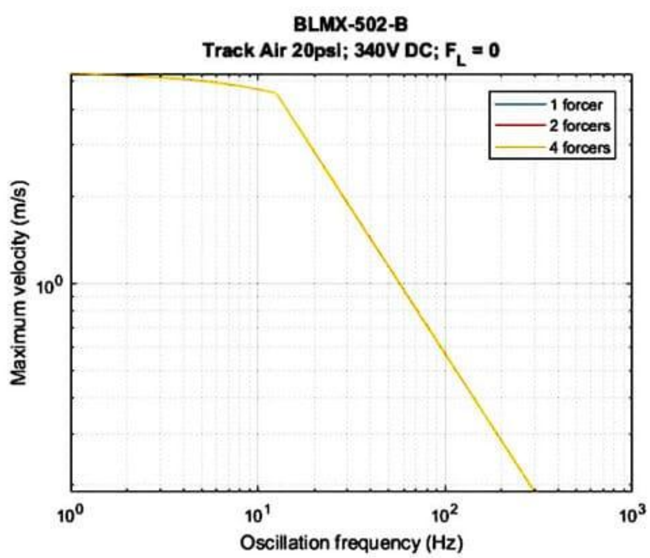

Figure 7. *No load velocity vs oscillation frequency for 1, 2 and 4 forcers.*

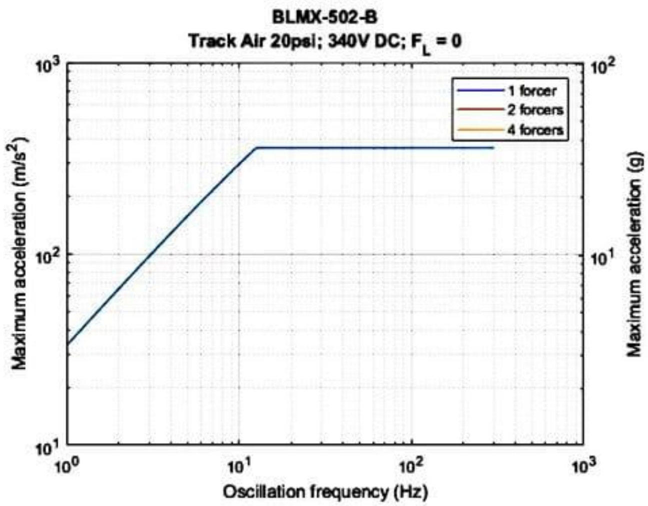

Figure 8. *No load acceleration vs oscillation frequency for 1, 2 and 4 forcers.*

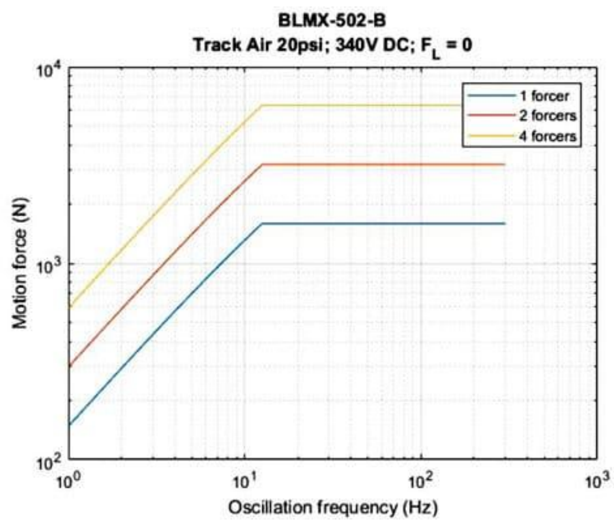

Figure 9. *No load force generation vs oscillation frequency for 1, 2 and 4 forcers.*

Figure 10 compares displacement vs frequency for servo-hydraulic and linear motor solutions. In the middle range of frequencies (40 Hz to 90 Hz) and displacement (0.8 mm to 3 mm), both technologies produce about the same motion. However, at the higher frequencies the linear motor technology is superior in the frequencies that can be reached (below 1 mm displacement).

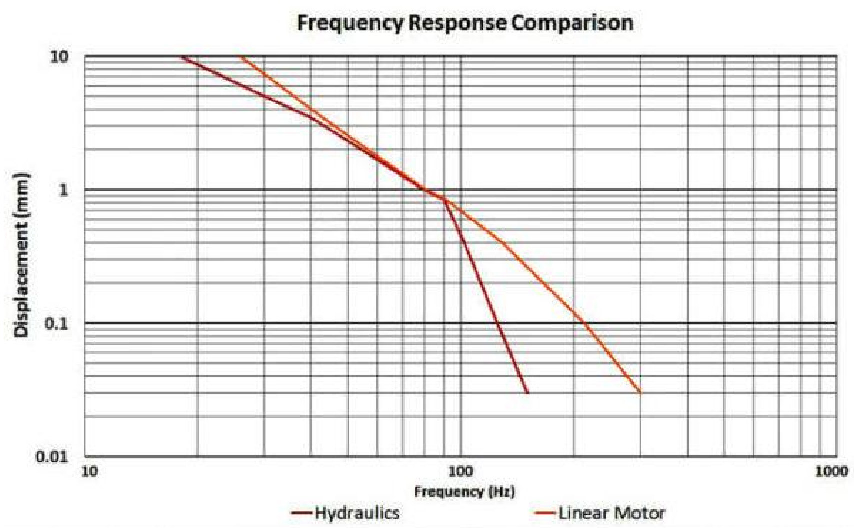

Figure 10. *Comparison of servo-hydraulic and linear-motor-based DMA machines.*

Capabilities of Servo Controllers

Linear motors require a servo controller. The quality and performance of the DMA machine is equally affected by the controller and amplifier selection. When selecting a controller some consideration should be given to the control law– does the structure minimize tracking errors by including feedforward control and disturbance rejection? The sample time must be sufficiently fast not just for the servo loop computations but also for the amplifier switching frequency and the commutation of the linear motor. To generate a high fidelity 300 Hz oscillation, the trajectory must have sufficient points and the actuating command must be calculated fast enough.

Beyond the basics, what algorithms does the controller have for optimizing the output sinusoid? For instance, advanced time-varying filters can be used to eliminate unwanted harmonics in the motion. Use of a Harmonic Cancellation filter can provide a drastic improvement in sine-wave fidelity as shown in Figures 11 and 12. Figure 12 shows the position error is drastically less when using the Harmonic Cancellation filter. This results in a much higher fidelity sine wave at the desired frequency.

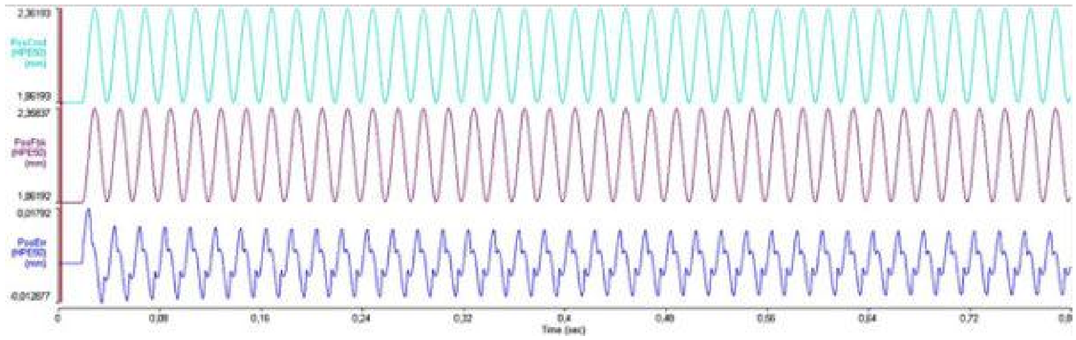

Figure 11. *Oscillation without Harmonic Cancellation.*

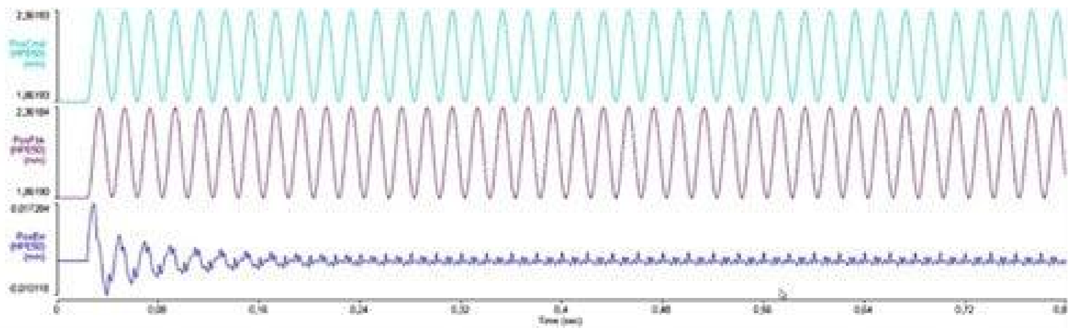

Figure 12. *Oscillation with Harmonic Cancellation.*

When considering the frequency range of interest, the tuning capability of the controller is also important. For instance, measuring the frequency response (bode plot) of the machine and being able to loop-shape the bode plot to meet specific gain and phase criterion in a frequency range can reduce the Total Harmonic Distortion (THD) resulting in higher fidelity sine waves in the frequency of interest.

Another controller consideration is the resolution of the feedback device that can be used. Two common encoders are TTL and Amplified Sine (AS) encoders. TTL have less resolution than AS encoders after multiplication. Controllers that have the ability to multiply the AS signal to very fine resolutions (such as 2 nm) will improve the control of the system and allow higher frequencies to be reached.

Figure 13 uses a linear motor with a TTL encoder and Figure 14 uses the same system (linear motor, bearings, and controller) with an AS encoder. The system using the TTL encoder can produce motion up to 152 Hz whereas the system using the AS encoder can produce high-fidelity motion up to 318 Hz, more than double the TTL frequency range.

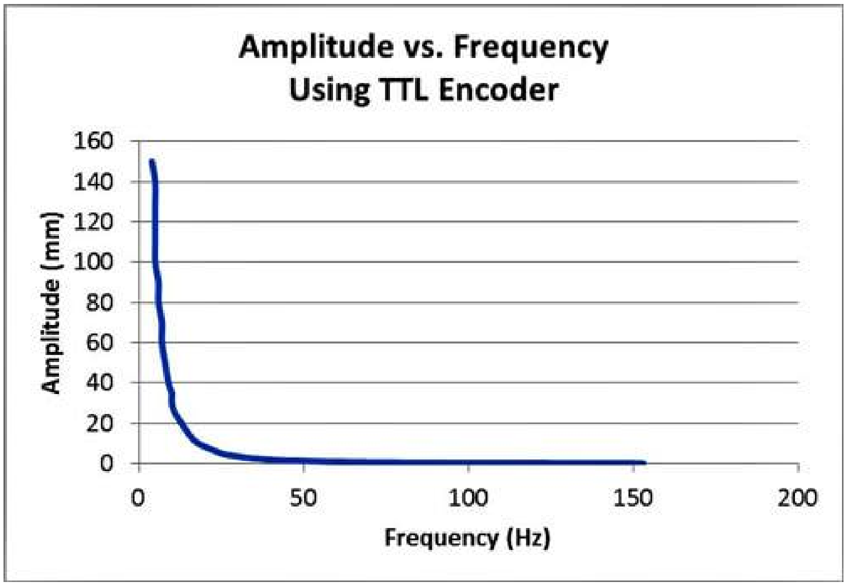

Figure 13. *System using TTL encoder. Maximum Frequency = 152 Hz.*

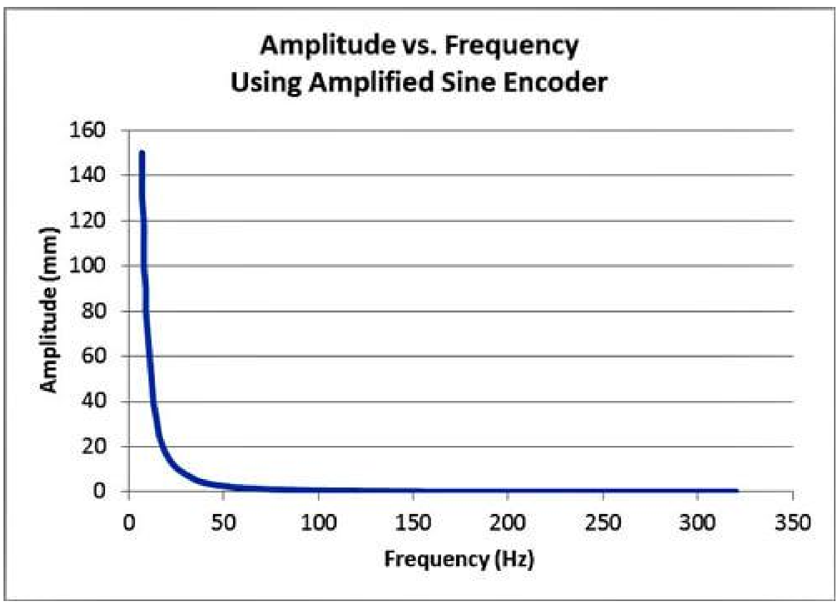

Figure 14. *System using an AS encoder. Maximum Frequency = 318 Hz*

One final consideration for the controller is its ability to collect data from multiple sensors in real-time. Precise measurements captured at the same sample time of both force and displacement (and sometimes velocity, acceleration, and temperature) are critical inputs to these calculations to characterize the UUT. Other factors to consider are resolution of the measurement, sample period, and how many samples can be collected.

Conclusions

New DMA and test machines are rapidly adopting linear motor technology for new designs that require 10 kN and below of applied force while not introducing any force ripple into the motion at frequencies ranging from DC to 1000 Hz. These afford "greener" designs than servo-hydraulic systems while improving machine performance and capability at a competitive price point. In low-force applications (≤10 kN), it is possible to reach higher frequencies with better THD than with traditional servo hydraulic machines. When high fidelity force trajectories and/or low resolution force applications are the goal, ironless linear servomotors are the best choice. However, this performance is not a result of just using linear servomotors. This technology must be combined with the correct feedback, control (loop structure, algorithms, and trajectory generation) and instrumentation to achieve superior results. To understand more about these technologies and their application to DMA and testing visit or contact us at +1-412-963-7470.

References

1. Data in Figure 1 based on Aerotech's market research for closed-loop solutions.