Application Note #5426

Tuning Ultrasonic Ceramic Motors

This application note gives some tips for tuning ultrasonic ceramic motors using Galil's ceramic motor special firmware. It also includes a brief description of how to connect a Galil Controller to the Nanomotion Brand LS2 Ceramic Motor. Galil's ceramic motor firmware is available for a one-time $400 fee and is highly recommend for optimum ceramic motor performance.

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1 Command Summary

The commands associated with the ceramic firmware are as follows:

ZP and ZN: Antifriction Bias parameters that add an open loop voltage to the controller's command signal when there is position error. The ZP provides a positive voltage when the error is positive, and ZN provides negative voltage when the error is negative

DS and DB: Dead band with hysteresis parameters. The DS specifies the range in encoder counts in which the PID and antifriction Bias are turned off, and the DB specifies the range in which they are turned back on. This is done when there is no profiled motion.

CP and CT: Dead band with IL increment and motor shut off. The CP specifies the error dead band at the end of a move in which the amplifiers will be disabled. The CT increments the integrator limit to insure that the motor reaches this final range. Note: The CT command is not available on Accelera-series motion controllers.

K1, K2 and K3: Second set of PID gains that are active during motion.

FC and FN: Distance selectable velocity feedforward gain. The FC specifies the positive or negative feedforward gain, and FN specifies the distance from the end of the move that FC is engaged.

2 Tuning

For the sake of tuning ultrasonic ceramic motors, it is strongly recommended that the user purchase Galil's WSDK software. The storage scopes in WSDK make it easy to view position error, command position and torque levels during commanded moves. The alternative to WSDK is using interrogation commands like TE (Tell Error) to monitor the response of the motor.

2.1 Servo Loop Update Rate (TM)

After downloading the firmware special onto the controller, the first step is to reduce the TM value to 250 or lower if possible. The TM command controls the servo update rate; the smaller the value the faster the update rate. See the controller manual appendix for the lowest TM value available. Be aware that all speed and acceleration parameters will be altered (i.e. for TM 500 the motor velocities will be twice as much as they were for TM 1000). Lowering the value of TM allows the PID and other tuning parameters to sample more often, thus having better control over the motor.

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2.2 Antifriction Bias Parameters (ZP and ZN)

Once the TM has been set, the next step is to adjust the antifriction bias parameters, ZP and ZN. The procedure for finding an acceptable ZP value is detailed below.

1. Turn the motor off with the MO command
2. Set KP, KD, KI, K1, K2, and K3 to zero
3. Set the motor in the middle of travel and define the position as zero: DP 0
4. Turn the motor back on with the SH command
5. Implement a positive position error by setting IP 50
6. Increment the value of ZP by 0.1 Volt until the motor makes a significant jump in the forward direct (more than 2 or 3 counts). The current motor position can be queried with the TP command, and the error comes from the TE command.
7. Once the motor jumps, reduce the value of ZP by 40%.
8. Repeat this procedure for the ZN command, but make sure to use IP –50 for a negative position error.
9. Due to inconsistencies in the Ceramic strip, the necessary anti-friction bias may vary over the full travel of the motor. It may be helpful to find the minimum values of ZP and ZN in order to have better overall performance.

2.3 Dead band Parameters (DS and DB)

With the antifriction biases set, the next step is adjusting the dead band parameters DS and DB. These values can be adjusted according to the users liking, but DB must be greater than or equal to DS. Also, if the user sets a very small dead band, it is more likely that the motor will oscillate. This is because high static friction makes it difficult for the motor to settle in a very small position window.

2.4 Motor Off Dead Band (CP and CT)

If the user needs to completely eliminate oscillation at the end of a profiled move, then the DS and DB may not be sufficient. The alternative is to use the CP command to disable the amplifier when the motor is within a target distance of the final position. Once the amplifier is disabled, the idea is that motor’s static friction will hold the load in place. However, if the static friction is not strong enough, the motor will be free to drift without Galil Control. Therefore, if the user wants control to be restored when the motor ventures outside of the dead band, he will need to use the DS and DB commands instead.

The CT command is used along with the CP command to set the rate at which the integrator limit (IL) will be incremented in order to achieve the target distance. Because the amplifiers are disabled when using the CP command, the user will have to issue the SH command before beginning another move. To disable the CP command, enter a negative value as the operand (i.e. CP –5).

Note: The target range specified by the CP command only takes effect when the controller has finished the profiled move. This means that if the motor is following the profile very closely (within the target window) then the amplifier will be disabled before the IL begins to increment. Note: The CT command is not available on Accelera-series motion controllers.

2.5 PID gains (K1, K2, K3 and KP, KI, KD)

In order to adjust the two sets of PID, the user will need to write and download a program similar to the one below.

```
#A
 DP0
#B
 IP500
 AMX
 WT250
 IP-500
 AMX
 WT250
JP#B
EN
```

When executed, this program will increment the ultrasonic motor back and forth 500 counts. The WT250 will leave 250 servo samples of dwell between the IP commands and will allow for the motor to settle after each increment. Using the Storage Scopes in WSDK, the user can graph Actual and Commanded Position on the same display. This will show how well the motor is following the profiled position for the given PID gains. The K1, K2, and K3 values take effect when the controller is producing a motion profile. The K1 is the proportional gain, K2 is the integrator gain, and K3 is the differential gain. When the motion profile is complete, the KP, KI, and KD are the effective gains. Due to static friction and the mechanics of the piezo-strips, ultrasonic motors have very nonlinear motion characteristics. Having two sets of PID allows the user to better compensate for these non-linear effects and make the motor more responsive.

The values of the PID gains will vary greatly depending on the TM value of the controller, the resolution of the encoder, and the type of amplifier used. Typically it's best to increase the differential gains to the brink of instability and then adjust the proportional and integrator gains for better motor performance and accuracy. The differential gains will always be greater than the proportional gains, and the proportional gains are usually greater than the integrator gains. For point-to-point moves, it is advised to set a negative integrator limit (i.e. IL –9.99) so that the integrator is frozen during the profiled move. This prevents profile overshoot and motor oscillation.

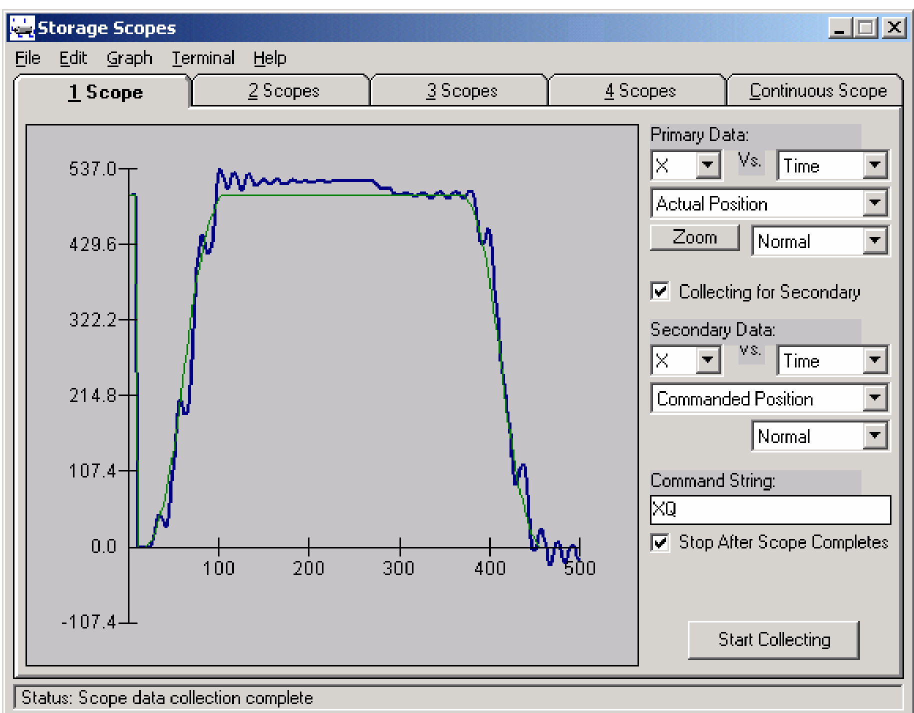
2.6 Feedforward Gains (FC, FN, FV, FA)

In addition to the PID parameters, the program above can also be used to set the FV, FC and FN commands. As with any standard firmware, the FV (Feedforward Velocity) command applies a bias voltage to the amplifier during a profiled move. The FC works the same way as the FV except that it may have negative values and can be selectively enabled at “n” counts before the end of the move. Typically, this function is enabled during the deceleration phase of the motion with negative values of FC. This will decelerate the motor faster, thereby reducing the chance for a target overshoot. The FA (Feedforward Acceleration) command can also be used to provide bias voltage during the acceleration and deceleration ramps of the velocity profile.

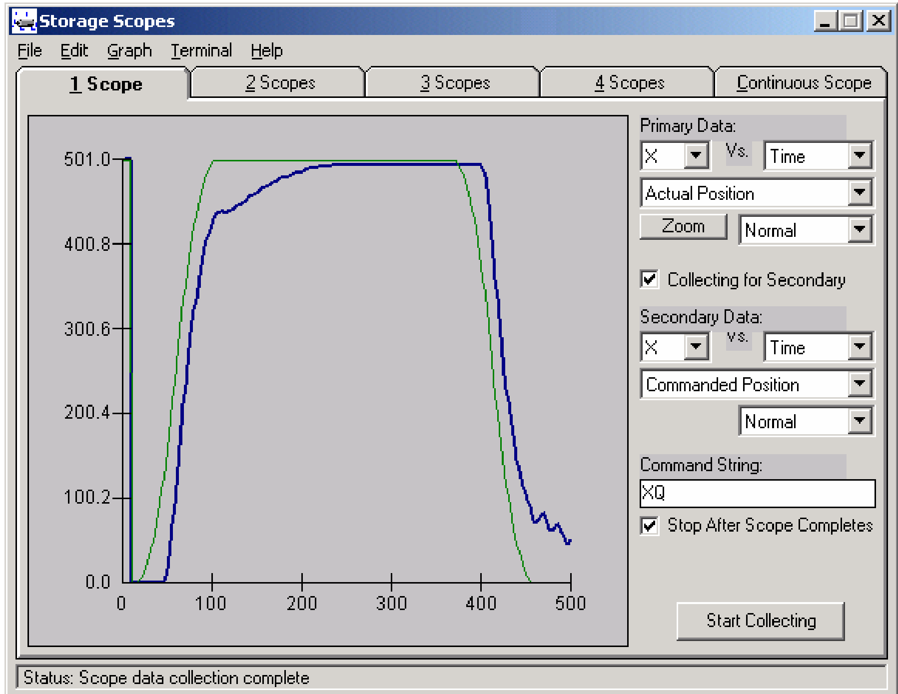
3 Response Graphs

3.1 Antifriction Bias Parameters (ZP and ZN)

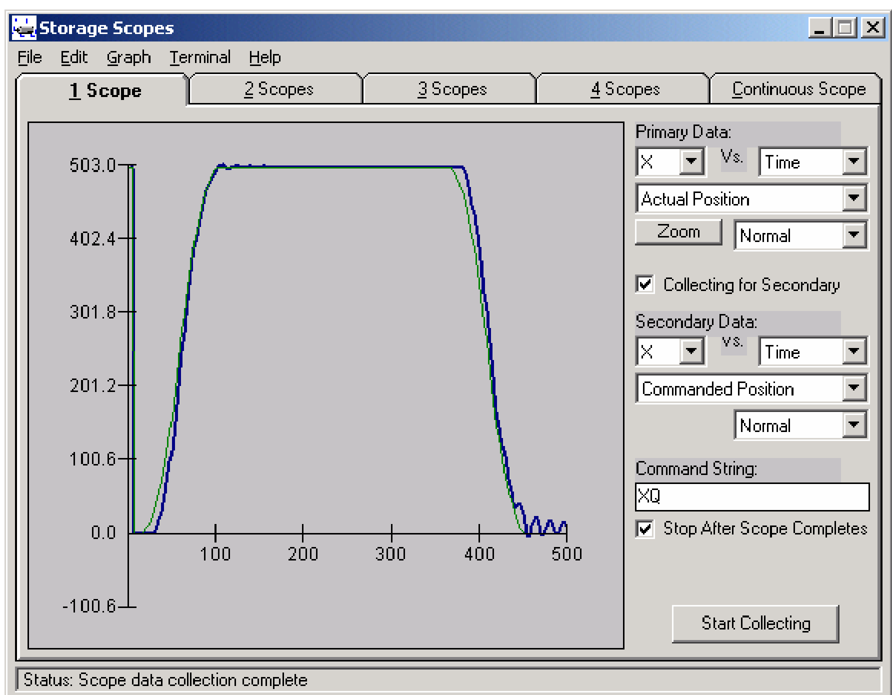
Of all the tuning parameters mentioned above, the ceramic motors are most sensitive to the values of ZP and ZN. Excessive values of ZP and ZN can cause motor vibration, whereas limited values will cause position error. The three pictures below show the performance of a Nanomotion LS2 ceramic motor with varying ZP values. The blue lines represent the actual motor position and the green lines are the commanded position. The program used to produce these screen shots was identical to the one written above.



Oscillations due to a ZP value that’s too large



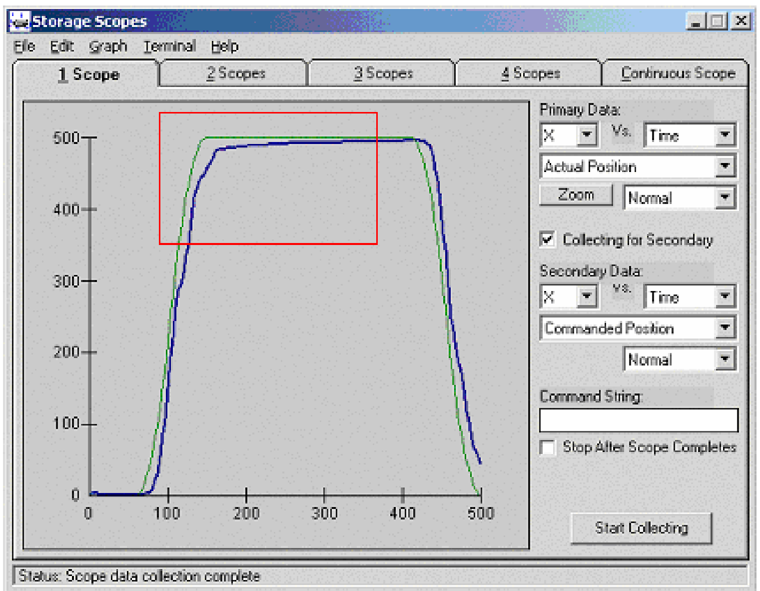
Position error due to a ZP value that's too small



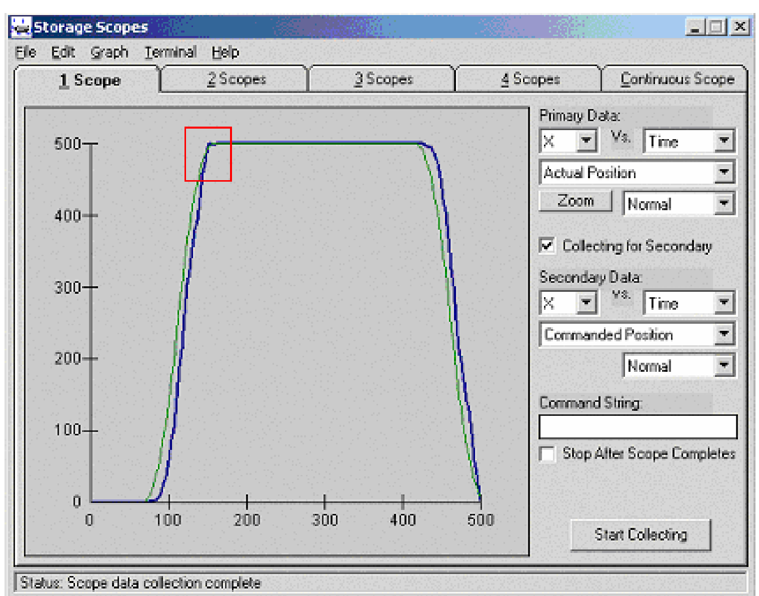
Motor response with the proper ZP value

3.2 Distance-Selectable Velocity Feedforward Gain (FC, FN)

Although not as sensitive, the values of FC and FN are also very important in optimizing ceramic motor performance. Below are two screen shots that demonstrate motor response with and without the use of FC and FN. Again, the program used to produce these screen shots is the same as the previous tests. The value of FN was set to 100 so that FC would be applied 100 counts prior to the end of the profiled move. The FC has been set to 20 because the motor lags behind the profile. It will be necessary in most other systems to apply a negative FC to prevent the motor from leading the profile.



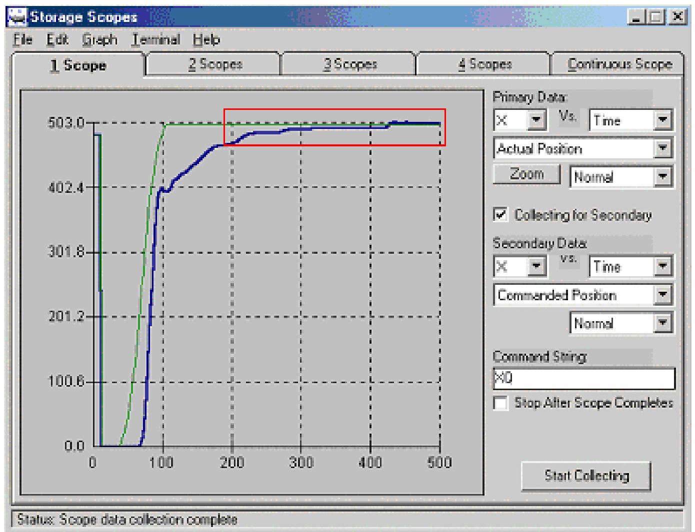
Motor response without the use of FC and FN



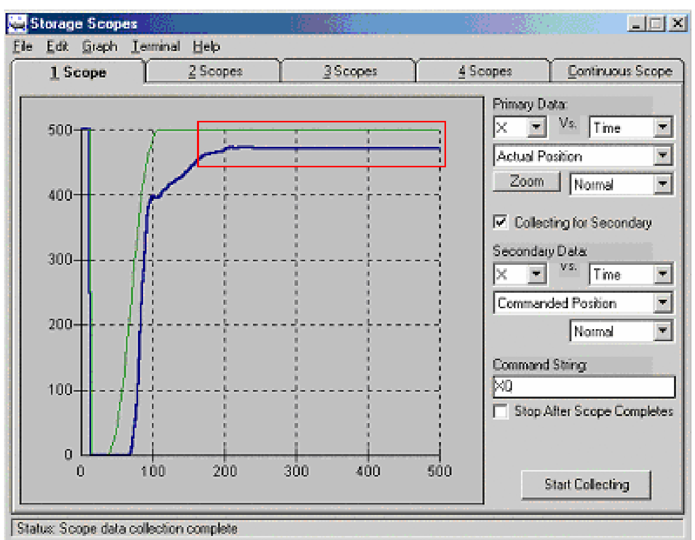
Motor response with FC and FN

3.3 Motor Off Dead Band (CP and CT)

The final two screen shots demonstrate the use of CP and CT. The example shows a 500 count move with a motor that doesn't follow the profile very accurately. The CP distance has been set to 20, and the CT is also 20. Notice, in the second picture, that the motor slowly approaches the target range and stops without reaching 500 counts. From then on there is no motion because the amplifier is disabled. The second picture isn't meant to show better motor response but rather to demonstrate the use of CP and CT. Obviously, the 20 count dead band is an over-exaggeration.



Profiled move without CP and CT



Profiled move using CP and CT

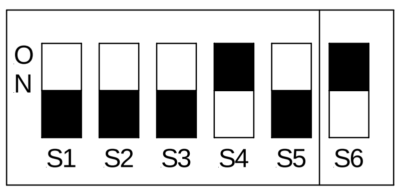
Note: The CT command is not available on Accelera-series motion controllers.

4 AB1 Driver and LS2 Ceramic Motor Setup

The next page shows a setup diagram between a Galil ICM-1900 and a Nanomotion LS2 ceramic motor system. The AB1 Driver Box is a Nanomotion product and can be configured to accept a +/-10V control signal from a Galil Controller. Since the Galil command signal is single ended, it must be connected to the +Vin input on the Driver Box, and the –Vin should be grounded. If a product other than Nanomotion is used, contact the motor manufacturer for connection information.

Note: The AB1 driver box requires a 5V, low amp enable signal. This means that the drive is enabled at 0V and disabled at 5V. When ordering a Galil interconnect module, be sure to specify the LAEN option. If a high amp enable interconnect module is used, contact Galil for modification information.

Inside the AB1 Driver box, there is a dipswitch bank that needs to be configured for +/-10V analog mode. These switches are on the AC1 Card, and the necessary settings are shown in the following diagram. See the AB1 Driver Box User Manual for more details.



Dip Switch Settings for the AB1 Driver Box

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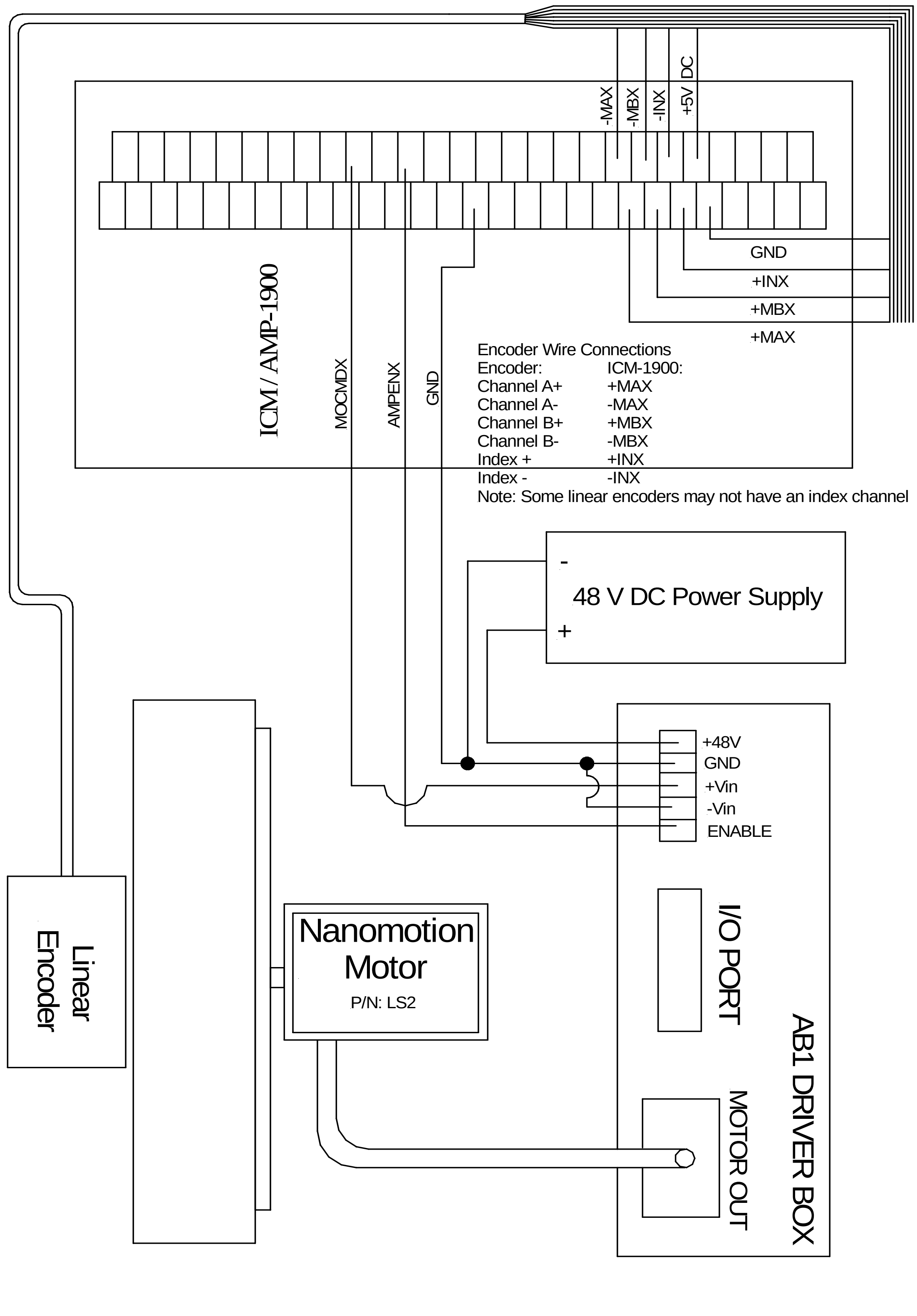
-MAX
-MBX
-INX
+5V DC
GND
+INX
+MBX
+MAX
ICM / AMP-1900
MOCMDX
AMPENX
GND
Encoder Wire Connections
Encoder: ICM-1900:
Channel A+ +MAX
Channel A- -MAX
Channel B+ +MBX
Channel B- -MBX
Index + +INX
Index - -INX
Note: Some linear encoders may not have an index channel
-
48 V DC Power Supply
+
+48V
GND
+Vin
-Vin
ENABLE
I/O PORT
AB1 DRIVER BOX
MOTOR OUT
Nanomotion Motor
P/N: LS2
Linear Encoder

5 Command Reference

CP

FUNCTION: Dead band within which the motor is shut off (MO)

DESCRIPTION:

After a move is complete (_BGn = 0) and the absolute value of the position error TE becomes less than the dead band CP, the motor is turned off. SH must be issued before further motion can be commanded. CT can be used to increment the integrator limit to ensure that the motor reaches the dead band.

ARGUMENTS: CP n,n,n,n,n,n,n,n or CPA=n where

n is an integer in the range 0 to 65535 in counts. If n >= 32768, the feature is disabled

n = ? Returns the value of the dead band for the specified axis

USAGE: **DEFAULTS:**

While Moving	Yes	Default Value	65535
In a Program	Yes	Default Format	-
Command Line	Yes		
Controller Usage	**ALL CONTROLLERS**		

OPERAND USAGE:

_CPn contains the value of the dead band for the specified axis

RELATED COMMANDS:

CT* Specifies the rate at which the integrator limit IL is incremented

EXAMPLES:

```
:^R^V
DMC1842 Rev 1.0n-CM-F
:^R^S
:ED
0 #L
1  MG _RPX, _TEX, _ILX, _MOX
2  WT100
3 JP#L
4

:IL0
:CP100
:CT2
:KI0.01
:PR1000
:BG;XQ
:: 0.0000 19.0000 0.0000 0.0000
 934.0000 669.0000 0.0000 0.0000
 1000.0000 684.0000 2.0406 0.0000
 1000.0000 656.0000 4.6783 0.0000
 1000.0000 429.0000 7.2166 0.0000
 1000.0000 340.0000 9.8544 0.0000
 1000.0000 83.0000 9.9982 1.0000
 1000.0000 82.0000 9.9982 1.0000
```


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CT*

FUNCTION: Specifies the rate at which the integrator limit IL is incremented

DESCRIPTION:

When the dead band is turned on (CP between 0 and 32767), CT specifies how fast IL is incremented when the move is complete (_BGn = 0) but the error TE is still greater than the dead band CP. IL will stop incrementing if it reaches 9.998 or if the absolute value of the error TE becomes less than the dead band CP. Note: The CT command is not available on Accelera-series motion controllers.

ARGUMENTS: CT n,n,n,n,n,n,n,n or CTA=n where

n is an even integer in the range 0 to 126 (0, 2, 4… 124, 126).

0 turns the IL increment off. 2 increments IL fast and 126 is slow.

n = ? Returns the value of the integrator limit rate for the specified axis

USAGE: **DEFAULTS:**

While Moving	Yes	Default Value	0
In a Program	Yes	Default Format	-
Command Line	Yes		
Controller Usage	**ALL CONTROLLERS**		

OPERAND USAGE:

_CTn contains the value of the integrator limit rate for the specified axis

RELATED COMMANDS:

CP Dead band within which the motor is shut off (MO)

EXAMPLES:

```
:^R^V
DMC1842 Rev 1.0n-CM-F
:^R^S
:ED
0 #L
1   MG _RPX, _TEX, _ILX, _MOX
2   WT100
3 JP#L

:IL0
:CP100
:CT2
:KI0.01
:PR1000
:BG;XQ
:: 0.0000 19.0000 0.0000 0.0000
 934.0000 669.0000 0.0000 0.0000
 1000.0000 684.0000 2.0406 0.0000
 1000.0000 656.0000 4.6783 0.0000
 1000.0000 429.0000 7.2166 0.0000
 1000.0000 340.0000 9.8544 0.0000
 1000.0000 83.0000 9.9982 1.0000
 1000.0000 82.0000 9.9982 1.0000
```

* The CT command is not available on Accelera-series motion controllers.

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DB

FUNCTION: Range in which PID and antifriction bias are turned on (on band)

DESCRIPTION:

When the absolute value of the error TE is greater than DB, the torque output TT will be set back to normal (reflecting KP, KD, KI, ZP, and ZN). This is used to avoid oscillation when holding position. DB should be set greater than or equal to DS.

ARGUMENTS: DB n,n,n,n,n,n,n,n or DBA=n where

n is an integer in the range 0 to 32767

n = ? Returns the value of the on band for the specified axis

USAGE:

While Moving	Yes
In a Program	Yes
Command Line	Yes
Controller Usage	**ALL CONTROLLERS**

DEFAULTS:

Default Value	0
Default Format	-

OPERAND USAGE:

_DBn contains the value of the on band for the specified axis

RELATED COMMANDS:

DS Range in which PID and antifriction bias are turned off

EXAMPLES:

```
DSX=100        ;'set off band on X axis to +/-100 counts
DBX=200        ;'set on band on X axis to +/-200 counts
```


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DS

FUNCTION: Range in which PID and antifriction bias are turned off (off band)

DESCRIPTION:

When the absolute value of the error TE is less than DS, the torque output TT will be set to the offset OF (the contributions of KP, KD, KI, ZP, and ZN are set to zero). This is used to avoid oscillation when holding position. DB should be set greater than or equal to DS.

ARGUMENTS: DS n,n,n,n,n,n,n,n or DSA=n where

n is an integer in the range 0 to 32767

n = ? Returns the value of the off band for the specified axis

USAGE:		DEFAULTS:	
While Moving	Yes	Default Value	0
In a Program	Yes	Default Format	-
Command Line	Yes		
Controller Usage	**ALL CONTROLLERS**		

OPERAND USAGE:

_DSn contains the value of the off band for the specified axis

RELATED COMMANDS:

DB Range in which PID and antifriction bias are turned on

EXAMPLES:

```
DSX=100     ;'set off band on X axis to +/-100 counts
DBX=200     ;'set on band on X axis to +/-200 counts
```


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FC

FUNCTION: Distance-selectable velocity feedforward gain

DESCRIPTION:

Adds a bias to the torque output TT proportional to the commanded velocity if the distance from the end of the move is less than FN. FC is the same as FV but activated FN counts from the end of the move and both positive and negative values are allowed.

Bias in volts = $1.22 \cdot 10^{-6} \cdot FC \cdot$ (commanded Velocity in counts/s)

ARGUMENTS: FC n,n,n,n,n,n,n,n or FCA=n where

n is an integer in the range -8191 to 8191

n = ? Returns the value of the distance-selectable velocity feedforward gain for the specified axis

USAGE: **DEFAULTS:**

While Moving	Yes	Default Value	0
In a Program	Yes	Default Format	-
Command Line	Yes		
Controller Usage	**ALL CONTROLLERS**		

OPERAND USAGE:

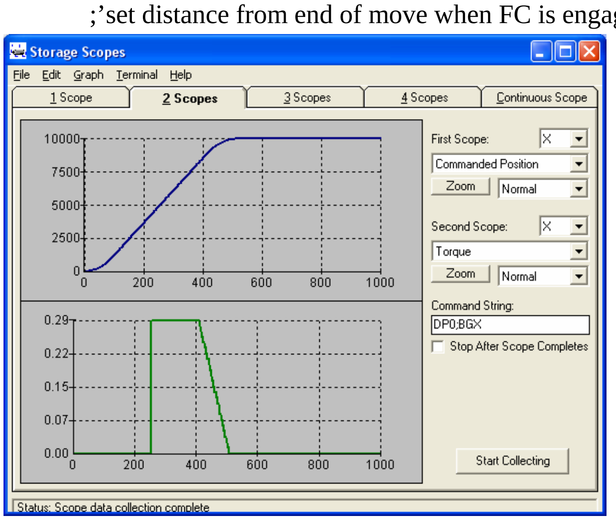
_FCn contains the value of the distance-selectable velocity feedforward gain for the specified axis

RELATED COMMANDS:

FN	Distance from end of move when FC is engaged
FV	Standard velocity feedforward gain

EXAMPLES:

```
FCX=10          ;'set distance-selectable velocity feedforward gain to 10
FNX=1000        ;'set distance from end of move when FC is engaged to 1000 counts
```



Commanded position and torque vs. time. KP0; KI0; KD0; K10; K20; K30; FC10; FN5000; PR10000

FN

FUNCTION: Distance from end of move when FC is engaged

DESCRIPTION:

Adds a bias to the torque output TT proportional to the commanded velocity if the distance from the end of the move is less than FN. FC is the same as FV but activated FN counts from the end of the move and both positive and negative values are allowed.

Bias in volts = $1.22 \cdot 10^{-6} \cdot FC \cdot$ (commanded Velocity in counts/s)

ARGUMENTS: FN n,n,n,n,n,n,n,n or FNA=n where

n is an integer in the range 0 to 2147483647 in counts

n = ? Returns the distance from the end of the move when FC is engaged for the specified axis

USAGE:

While Moving	Yes
In a Program	Yes
Command Line	Yes
Controller Usage	**ALL CONTROLLERS**

DEFAULTS:

Default Value	0
Default Format	-

OPERAND USAGE:

_FNn contains the distance from the end of the move when FC is engaged for the specified axis

RELATED COMMANDS:

FC Distance from end of move when FC is engaged

FV Standard velocity feedforward gain

EXAMPLES:

```
FCX=10          ;'set distance-selectable velocity feedforward gain to 10
FNX=1000        ;'set distance from end of move when FC is engaged to 1000 counts
```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K1

FUNCTION: P gain during motion

DESCRIPTION:

K1 is the proportional gain in effect when the profiler is commanding motion (RP is changing). When no motion is commanded (RP constant), KP is in effect. Some systems will oscillate when holding position unless the gains are lowered.

ARGUMENTS: K1 n,n,n,n,n,n,n,n or K1A=n where

n is a number in the range 0 to 1023.875 with a resolution of 1/8

n = ? Returns the value of the P gain during motion for the specified axis

USAGE: **DEFAULTS:**

While Moving	Yes	Default Value	6
In a Program	Yes	Default Format	-
Command Line	Yes		
Controller Usage	**ALL CONTROLLERS**		

OPERAND USAGE:

_K1n contains the value of the P gain during motion for the specified axis

RELATED COMMANDS:

KP	Proportional gain when holding position
K2	Integral gain during motion
K3	Derivative gain during motion

EXAMPLES:

```
K1X=10        ;'set X axis P gain in effect during motion
K2X=1         ;'set X axis I gain in effect during motion
K3X=100       ;'set X axis D gain in effect during motion

KPX=6         ;'set X axis P gain in effect when holding position
KIX=0         ;'set X axis I gain in effect when holding position
KDX=64        ;'set X axis D gain in effect when holding position
```

K2

FUNCTION: I gain during motion

DESCRIPTION:

K2 is the integral gain in effect when the profiler is commanding motion (RP is changing). When no motion is commanded (RP constant), KI is in effect. Some systems will oscillate when holding position unless the gains are lowered.

ARGUMENTS: K2 n,n,n,n,n,n,n,n or K2A=n where

n is a number in the range 0 to 2047.875 with a resolution of 1/128

n = ? Returns the value of the I gain during motion for the specified axis

USAGE: **DEFAULTS:**

While Moving	Yes	Default Value	0
In a Program	Yes	Default Format	-
Command Line	Yes		
Controller Usage	**ALL CONTROLLERS**		

OPERAND USAGE:

_K2n contains the value of the I gain during motion for the specified axis

RELATED COMMANDS:

K1	Proportional gain during motion
KI	Integral gain when holding position
K3	Derivative gain during motion

EXAMPLES:

```
K1X=10        ;'set X axis P gain in effect during motion
K2X=1         ;'set X axis I gain in effect during motion
K3X=100       ;'set X axis D gain in effect during motion

KPX=6         ;'set X axis P gain in effect when holding position
KIX=0         ;'set X axis I gain in effect when holding position
KDX=64        ;'set X axis D gain in effect when holding position
```

K3

FUNCTION: D gain during motion

DESCRIPTION:

K3 is the derivative gain in effect when the profiler is commanding motion (RP is changing). When no motion is commanded (RP constant), KD is in effect. Some systems will oscillate when holding position unless the gains are lowered.

ARGUMENTS: K3 n,n,n,n,n,n,n,n or K3A=n where

n is a number in the range 0 to 4095.875 with a resolution of 1/8

n = ? Returns the value of the D gain during motion for the specified axis

USAGE:

While Moving	Yes
In a Program	Yes
Command Line	Yes
Controller Usage	**ALL CONTROLLERS**

DEFAULTS:

Default Value	64
Default Format	-

OPERAND USAGE:

_K3n contains the value of the D gain during motion for the specified axis

RELATED COMMANDS:

K1	Proportional gain during motion
K2	Integral gain during motion
KD	Derivative gain when holding position

EXAMPLES:

```
K1X=10          ;'set X axis P gain in effect during motion
K2X=1           ;'set X axis I gain in effect during motion
K3X=100         ;'set X axis D gain in effect during motion

KPX=6           ;'set X axis P gain in effect when holding position
KIX=0           ;'set X axis I gain in effect when holding position
KDX=64          ;'set X axis D gain in effect when holding position
```

ZN

FUNCTION: Negative antifriction bias

DESCRIPTION:

ZN adds a negative open loop voltage to the controller's command signal when the position error is negative.

ARGUMENTS: ZN n,n,n,n,n,n,n,n or ZNA=n where

n is a number in the range -9.999 to 0 volts with a resolution of 0.0003

n = ? Returns the value of the negative antifriction bias for the specified axis

USAGE:

While Moving	Yes
In a Program	Yes
Command Line	Yes
Controller Usage	**ALL CONTROLLERS**

DEFAULTS:

Default Value	0
Default Format	-

OPERAND USAGE:

_ZNn contains the value of the negative antifriction bias for the specified axis

RELATED COMMANDS:

ZP Positive antifriction bias

OF Offset

EXAMPLES:

```
ZNX=-1        ;'set negative antifriction bias on X to -1 volt
ZPX=1         ;'set positive antifriction bias on X to 1 volt
```


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ZP

FUNCTION: Positive antifriction bias

DESCRIPTION:

ZP adds a positive open loop voltage to the controller's command signal when the position error is positive.

ARGUMENTS: ZP n,n,n,n,n,n,n,n or ZPA=n where

n is a number in the range 0 to 9.999 volts with a resolution of 0.0003

n = ? Returns the value of the positive antifriction bias for the specified axis

USAGE: **DEFAULTS:**

While Moving	Yes	Default Value	0
In a Program	Yes	Default Format	-
Command Line	Yes		
Controller Usage	**ALL CONTROLLERS**		

OPERAND USAGE:

_ZPn contains the value of the positive antifriction bias for the specified axis

RELATED COMMANDS:

ZN Positive antifriction bias

OF Offset

EXAMPLES:

```
ZNX=-1          ;'set negative antifriction bias on X to -1 volt
ZPX=1           ;'set positive antifriction bias on X to 1 volt
```


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