Critical Factors in Sizing and Designing a Screw jack System

Abstract

At Motion Technologies we're not afraid to redesign customer concepts in order to increase system performance and save our customers money. From our experience in designing hundreds of screw jack systems we've found the largest misunderstanding in the linear motion industry is how critical factors such as linear guidance, screw end fixings and positioning of screw jacks in relation to loads are to system design. If these factors are adequately thought about at an early design concept stage it will benefit a thousand fold in system performance, ease of installation and ultimately cost.

This white paper details how these critical engineering factors should be addressed when designing and sizing a screw jack system.

System problem

Motion Technologies was approached by a local university to assist in optimizing the design of a screw jack system for the geo-technical laboratory. The concept design included a vertically mounted screw jack which needed to push and pull test plates into a soil sample providing speed and force feedback for experimental data. The system design parameters requested were as follows:

- Servo control with speed and travel adjustable.
- Push and pull capacity of up to 1 tonne
- Speed up to 25mm/s
- Screw jack travel distance is 500mm.

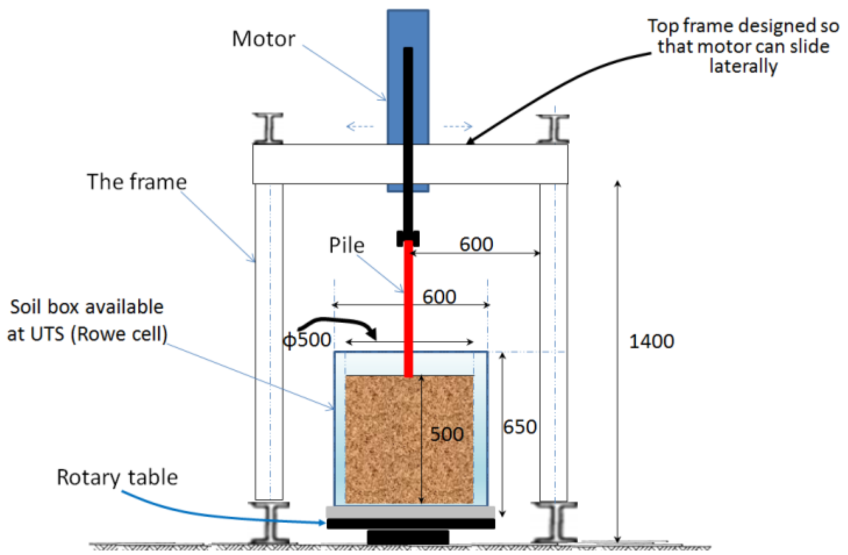


Figure 1 - Concept Design Configuration

Engineering Design

Initial engineering was conducted to check the required screw jack size for the specified scope of works. For screw jack systems trapezoidal screw is only applicable for required speeds up to 8mm/sec, therefore given the specified travel rate of 25mm/sec it was then known the system would require a ball screw.

Ball screw has a much higher efficiency than trapezoidal screw allowing you to reduce system friction and achieve higher travel rates. Given this; a ball screw column strength calculation was carried out to determine the required shaft diameter with a force of 1 tonne, total length of 1400mm (stroke plus the length of the test piece), with unsupported ends and holding the screw in compression.

Buckling Calculation:

$Fc\ [N] = Cs \times 9{,}687 \times 10^4 \times dr^4 / l^2$

Where: Fc = Critical bucking force (N)

Cs = End fixity factor based on following points:

End fixity, Cs:

- One end fixed, one end free 0.25
- Both ends supported 1.00
- One end fixed, one end supported 2.00
- Both ends fixed 4.00

dr = root diameter (mm)

l = unsupported length (mm)

In this case we checked for a screw size which will not buckle at 9806N, with one end free and one end fixed. In this case the unsupported length had to include the length of the test plate. The desired screw diameter was then determined through iterative calculations using data from the Nook Industries screw catalogue.

Once Motion Technologies knew the design required ball screw of roughly 40mm diameter this then determined the size of jack required. A 10 tonne ball screw jack was selected as it fits a 38.1mm diameter ball screw standard. It should be noted that system guidance is critical to design as at this stage for a simple 1 tonne push the project required a 10 tonne screw jack to withstand the column buckling forces.

Motion Technologies uses an in-house Power Screw calculator to size and design jacking systems. With the Ball screw diameter and screw jack size selected the data could then be input into the Power Screw calculator with two scenarios run. Two scenarios are generally run as each size of jack is available with two different worm gear ratio's, it's also important to check the effect of running a pre-reducer in the system. Worm gear screw jacks have a maximum input RPM of 1500; any RPM above this will be detrimental to the life of the box as the gearing cannot dissipate the heat.

Knowing the maximum RPM and the required travel rate then allowed us to determine the required lead on the ball screw by running iterations of screw size through the calculator. For this project a special high lead of 47.6mm was required.

Application and Design Requirements Per customer advise	Case 1	Case 2
Model or Description =	10BSJ	10BSJ
Screw OD, mm =	38.1	38.1
Lead, mm =	47.6	47.6
Number of screw thread starts	2	2
Stroke, mm =	500	500
Max. spindle length (stroke+boot+other allowances) mm =	1,400	1,400
Co-efficient of friction of screw =	0.002	0.002
Brg mount end fixity factor =	0.25	0.25
Total System Design Load (Kg) =	1,000	1,000
Total number of jacks sharing load PER MOTOR in the system =	1	1
Number of jacks for column strength calc's =	1	1
Required Travel rate (mm/sec) =	25.0	25.0
Jack worm ratio =	8.0	24.0
Jack Worm Gear efficiency % =	27.0%	19.0%
Total System Drag force (eg bearing preload, seals, cylinders) N =	30	30
Drag torque factor for anti-rotation device (if fitted) % =	5%	5%
Selected Jack Rating, kN =	25	25
Rated max. jack worm shaft torque, Nm =	18.0	18.0
Required Factor of Safety for compressive stength (3 recommended) =	3.0	3.0
Pre-reducer ratio at jack input =	5	1
Pre-reducer eff. at jack input =	100%	100%
Number of jacks driven by jack pre-reducer =	1	1
Nbr of jack worm shafts connected in series (1 for single jack sys.) =	1	1
Number of jack pre-reducer driven by gearmotor =	0	0
Gearmotor ratio (Typ. Used for bevel g'box systems) =	1	1
Gearmotor gear eff. (Typ. used for bevel g'box systems) =	100.0%	100.0%
Jack Inertia, kgcm^2 =	Reserved for future version	
Gear inertia, kgcm^2 =		
Rotating Nut or Screw? (N or S) =		
Compression or Tension =		

Edit default values as required

Typical Screw/Nut co-efficient of friction (approx only, choose value and insert)			
Nut Mtl	Dry	Middle	Lube'd
Cast Iron	0.180	0.150	0.120
Steel	0.150	0.125	0.100
Bronze	0.100	0.075	0.050
Plastic	0.100	0.075	0.050
Ball Screws ~ 0.002			

END FIXITY FACTOR:

NOTE: Factors below must be regarded as typical only and be chosen very carefully as they reflect the users factor of safety and assumes load is concentric to screw shaft.

a) For bearing mounted screws:

- 0.25 for one end fixed, other end free
- 1.00 for both ends supported
- 2.00 for one end fixed, one end simple
- 4.00 for both end rigid

NB: *Back to back bearings should be regarded as supported bearings. *Triplex or duplex with spacer can be regarded as a rigid support.

b) For screw jacks:

- 0.20 for rigid base, free rod clevis
- 0.60 for double clevis mount (vertical)
- 0.90 for rigid base, guided rod clevis
- 1.00 for rigid base, rigid guided structure

NOTES:

Figure 2 - Initial Power Screw Calculation Table

Given this input data into the power screw calculator the scenarios ran as follows:

SOLVE for CASE 1			
Rated power of selected motor =	1.00	kW	OK (sufficient power)
Speed of selected motor =	1,300	rpm	OK (sufficient motor speed)
Calculated motor output torque, running =	7.34	Nm	OK (sufficient motor run torque)
Calculated jack input worm shaft torque, running =	36.71	Nm	= 204% Fail (insufficient shaft strength)
Torque per jack input shaft at motor peak start torque =	80.77	Nm	Caution, limit motor start torque to <220%
Actual travel Rate =	25.8	mm/sec	OK (exceeds required travel rate)
	1.547	m/min	
Dynamic Available System Load = (limited by input power)	1,010	Kgf	OK for required load
	9,905	N	OK for Jack load rating
	1.0	Tonne	
Column strength F. of S. at Available Load =	0.00	at available load	Caution, F. of S. below default requirement!
Column strength F. of S. at Design load =	0.00	at design load	Caution, F. of S. below default requirement!
SOLVE for CASE 2			
Rated power of selected motor =	1.50	kW	OK (sufficient power)
Speed of selected motor =	800	rpm	OK (sufficient motor speed)
Calculated motor output torque, running =	17.90	Nm	OK (sufficient motor torque)
Calculated jack input worm shaft torque, running =	17.90	Nm	= 99% = OK (sufficient shaft strength)
Torque per jack input shaft at motor peak start torque =	39.37	Nm	Caution, limit motor start torque to <220%
Actual travel Rate =	26.4	mm/sec	OK (exceeds req'd travel rate)
	1.587	m/min	
Dynamic Available System Load = (limited by input power)	1,040	Kgf	OK for required load
	10,199	N	OK for jack load rating
	1.0	Tonne	
Column strength F. of S. at Available Load =	0.00	at available load	Caution, F. of S. below default requirement!
Column strength F. of S. at Design load =	0.00	at design load	Caution, F. of S. below default requirement!

Figure 3 - Power Screw Results

As can be seen the required motor torque to run these scenarios exceeded the worm box input torque and the factor of safety was below requirement. In order to make this design work a larger screw jack and motor would be required. Although this may work it would not be a cost effective solution to the design problem therefore Motion Technologies proposed a complete design change as follows:

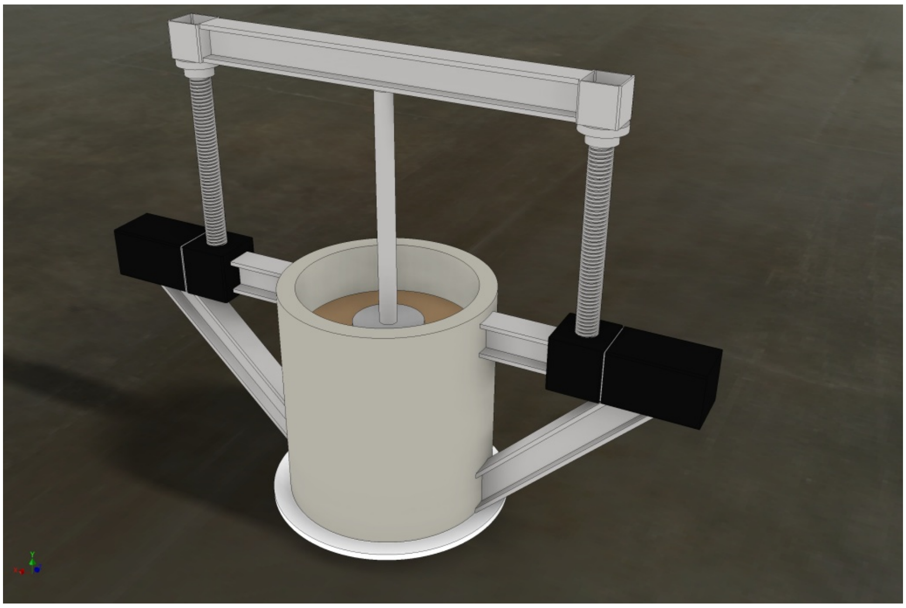


Figure 4 - MT Proposed Design

The proposed system design was advantageous as it allowed the following:

- Split load over two columns – 550kg per screw
- Allows complete support and guidance of ball screw against frame
- Reduces required motor size

As system was now a travelling nut with supported screw the screw size could drop to 1' inch diameter by 1' inch lead. This then meant a smaller worm gear box could be selected and tested in the power screw calculator.

Calculations were as follows:

Application and Design Requirements Per customer advise	Case 1		Case 2
Model or Description =	M4		M4
Screw OD, mm =	25.2		25.2
Lead, mm =	25.2		25.2
Number of screw thread starts	1		1
Stroke, mm =	500		500
Max. spindle length (stroke+boot+other allowances) mm =	500		500
Co-efficient of friction of screw =	0.15		0.15
Brg mount end fixity factor =	1.00		1.00
Total System Design Load (Kg) =	500		500
Total number of jacks sharing load PER MOTOR in the system =	1		1
Number of jacks for column strength calc's =	1		1
Required Travel rate (mm/sec) =	10.0		10.0
Jack worm ratio =	7.0		28.0
Jack Worm Gear efficiency % =	69.0%		69.0%
Total System Drag force (eg bearing preload, seals, cylinders) N =	30		30
Drag torque factor for anti-rotation device (if fitted) % =	5%		5%
Selected Jack Rating, kN =	50		50
Rated max. jack worm shaft torque, Nm =	38.0		38.0
Required Factor of Safety for compressive stength (3 recommended) =	3.0	Edit default values as required	3.0
Pre-reducer ratio at jack input =	1		1
Pre-reducer eff. at jack input =	100%		100%
Number of jacks driven by jack pre-reducer =	1		1
Nbr of jack worm shafts connected in series (1 for single jack sys.) =	1		1
Number of jack pre-reducer driven by gearmotor =	0		0
Gearmotor ratio (Typ. Used for bevel g'box systems) =	1		1
Gearmotor gear eff. (Typ. used for bevel g'box systems) =	100.0%		100.0%

Typical Screw/Nut co-efficient of friction (approx only, choose value and insert)			
Nut Mtl	Dry	Middle	Lube'd
Cast Iron	0.180	0.150	0.120
Steel	0.150	0.125	0.100
Bronze	0.100	0.075	0.050
Plastic	0.100	0.075	0.050
Ball Screws ~ 0.002			
END FIXITY FACTOR:			
NOTE: Factors below must be regarded as typical only and be chosen very carefully as they reflect the users factor of safety and assumes load is concentric to screw shaft.			
a) For bearing mounted screws:			
0.25 for one end fixed, other end free			
1.00 for both ends supported			
2.00 for one end fixed, one end simple			
4.00 for both end rigid			
NB: *Back to back bearings should be regarded as supported bearings.			
*Triplex or duplex with spacer can be regarded as a rigid support.			
b) For screw jacks:			
0.20 for rigid base, free rod clevis			
0.60 for double clevis mount (vertical)			
0.90 for rigid base, guided rod clevis			
1.00 for rigid base, rigid guided structure			

Figure 5 - Proposed Design Power Screw Calculation

As the system is not being operated by an AC motor it was not critical to check motor sizing at this point. The overall system calculations though needed to be checked for any potential concerns.

GLOBAL RESULTS			
Calculated screw efficiency =	81.1%	81.1%	
Jack worm torque input **per jack**, running =	5.27	1.32	Nm
Jack worm torque input **per jack at 220% Start** =	11.59	2.90	Nm
Pre-reducer **1** total torque output =	5.27	1.32	Nm
Reducer 1 input torque = Reducer 2 output torque =	5.27	1.32	Nm
Required motor output torque, excluding accell. torque =	5.27	1.32	Nm
Required motor speed =	167	667	rpm
Required motor power =	0.09	0.09	kW
Calculated spindle reaction torque =	3.64	3.64	Nm
Worm shaft rotations for stroke (for limit switch) =	139	556	turns
Calculated **System** screw compressive limit for Design Requirements =	0	0	N
Acceleration time =	Reserved for future version		secs.

Figure 6 - Global Results for Proposed Design

Engineering Design Results

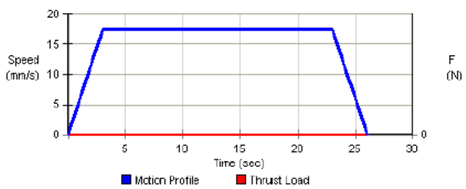
The proposed system redesign was proven through the screw selection process which showed the system would require much smaller ball screw and worm boxes than the initial concept design. This proves the importance of considering system guidance and orientation when putting forward concept designs. With the ball screw and worm box finalized the system required a servo motor selection to round out the system design

In order to size servo motors for engineered system Motion Technologies uses Kollmorgen software. Using the Lead Screw Mechanism tool all the system inputs could be entered into the software for analysis.

With the system data entered into Lead Screw mechanism within the sizing software a simple motion profile could be plotted. A simple trapezoidal move was selected to account for motor acceleration, dwell and deceleration time.

With the system and motion profile specified a servo motor can be selected based on allowable system inertia. For this scenario a Kollmorgen AKM 33C Servo Motor on 240 V AC was selected.

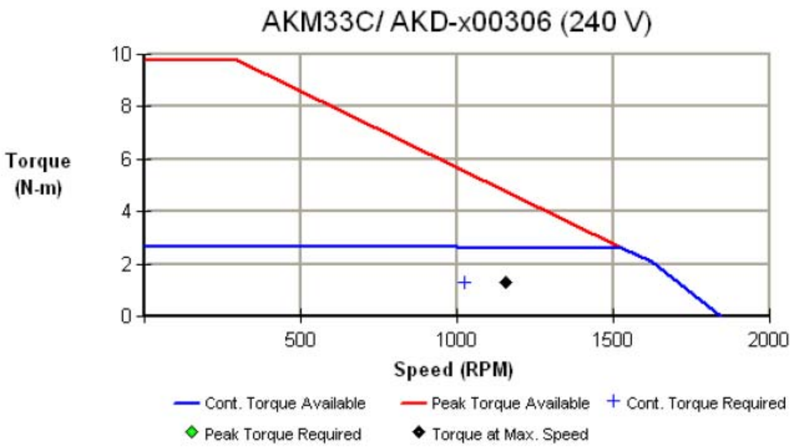
Profile Type: Custom
Selected system: AKM33C/ AKD-x00306 (240 V)



Time	Speed	Displacement	Acceleration	Torque
0.00 sec	0.00 mm/s	0.00 mm	0.00 m/s²	0.00 N-m
3.00 sec	17.50 mm/s	26.25 mm	0.01 m/s²	1.32 N-m
23.00 sec	17.50 mm/s	425.00 mm	0.00 m/s²	1.31 N-m*
26.00 sec	0.00 mm/s	37.50 mm	-0.01 m/s²	1.30 N-m

Figure 7 - Motion Profile for Kollmorgen AKM33C Servo Motor

As the motion profile checks out the required operating conditions are then checked against motor and drive available continuous torque and operating torque.



	Available	Required	% Margin
Continuous torque	2.65 N-m	1.31 N-m	102.8 %
Peak torque	4.75 N-m	1.32 N-m	260.3 %
Max. speed	1840 RPM	1157 RPM	59.0 %

Figure 8 - Kollmorgen AKM33C Motor Parameter Data

As can be seen the motor and drive combination is operating well within the continuous torque and speed available for the motor. It should be noted that the motor is capable of operating at a higher RPM than the maximum allowable input RPM of the worm box. As this is a servo motor system however the maximum torque and speed output of the motor can be entered into the drive in order to guarantee the worm box life.

Conclusion

Motion Technologies was able to redesign the customers proposed screw jack system in order to offer an engineered system with guaranteed performance within the customer’s budget. This design process highlights the importance of understanding the effects of linear guidance, force orientation and screw fixings when considering screw jack system design. When dealing with large system loads and high speeds these factors are critical to consider to ensure the system does not require an over engineered design.