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APPROPRIATE CHOOSING THE LINEAR MOTION GUIDE FOR ROBOTIC APPLICATIONS

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Abstract: The Linear Motion Guides (LM Guides) are provided with an ideal rolling mechanism capable of bearing vertical and horizontal loads. Therefore, the difference between dynamic and static friction is minimal and lost motion hardly occurs. The problem of choosing the appropriate type and size of the LM Guide is very important to obtain maximum performances of the mechanical systems guided by such mechanism. Based on the knowledge of operating conditions and data from the producer catalog, this paper provides a practical algorithm to support designer works.
Key words: linear motion, motion guides, robotics, machine design.

1. INTRODUCTION

The Linear Motion Guides (LM Guide) are the modern mechanical devices with a wide applicability in high precision machine-tools and industrial robots design. LM Guides demonstrates high performance in environments subject to vibrations and impact loads, where a high level of motion accuracy is required.

2. TECHNICAL DESCRIPTION

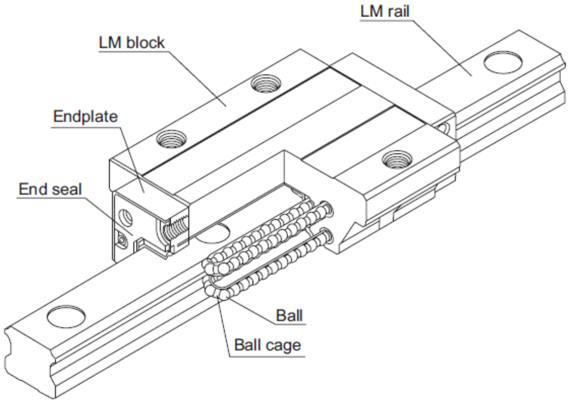


Fig.1. Structural Drawing of the Caged Ball LM Guide

Features of the LM Guide: -Large permissible load and high rigidity; -Accuracy averaging effect by absorbing mounting surface error; -Ideal four raceway, circular-arc groove, two point contact structure; -Low friction coefficient. As a result, the others following features are achieved: -Easy maintenance; -Improved productivity of the machine and robots speed; - Substantial energy savings; -Low total cost; - Higher accuracy of the motions; -Higher efficiency in robots and machine design.

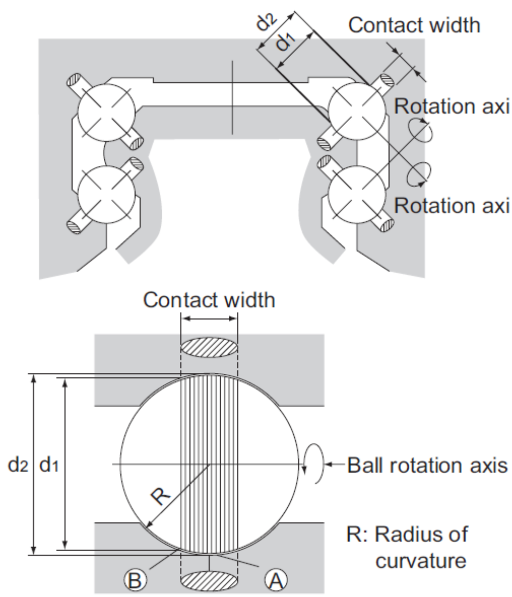


Fig. 2. LM Guide: Four Raceway, Circular-arc Groove, Two-point Contact Structure

In the ideal two-point contact structure (see figure 2), four rows of circular arc grooves are given appropriate contact angles. With this structure, a light distortion of the mounting surface would be absorbed within the LM block due to elastic deformation of the balls and moving of the contact points to allow unforced, smooth motion.

Figure 3 represent the flowchart as a measuring stick for selecting a LM Guide.

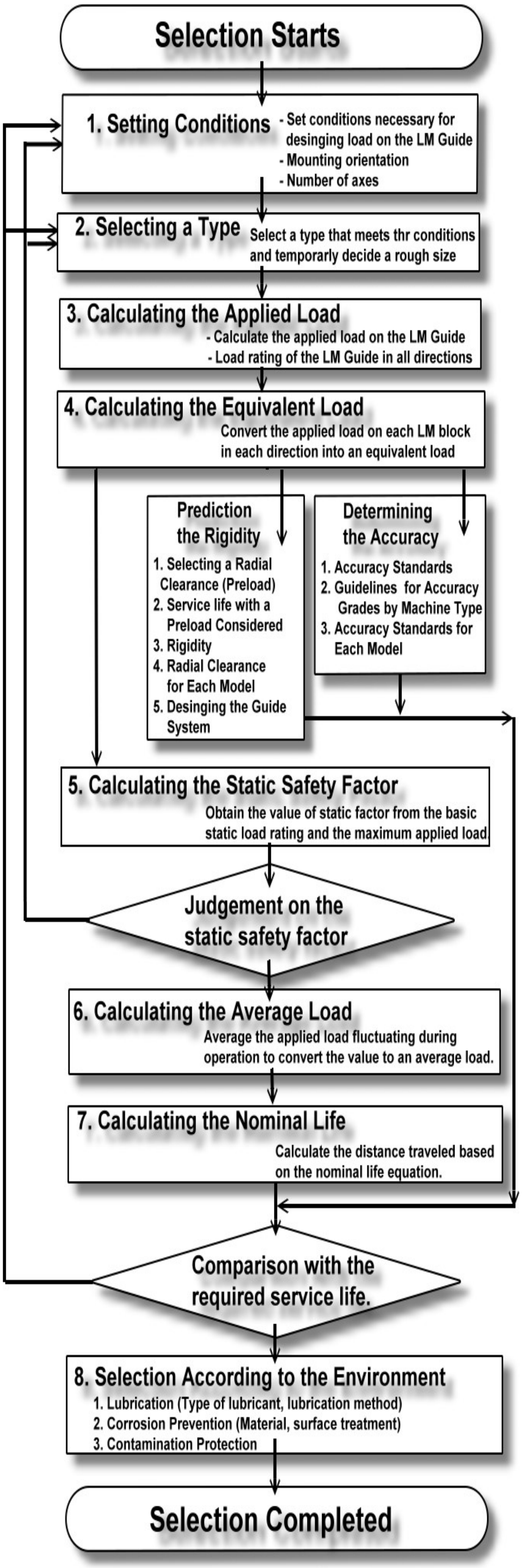


Fig. 3. The flowchart for selecting a LM Guide.

Appropriate selection of the LM Guide.

The LM Guide is capable of receiving loads and moments (figure 4) in all directions that are generated due to the mounting orientation, alignment, gravity center position of a traveling object, thrust position and cutting resistance.

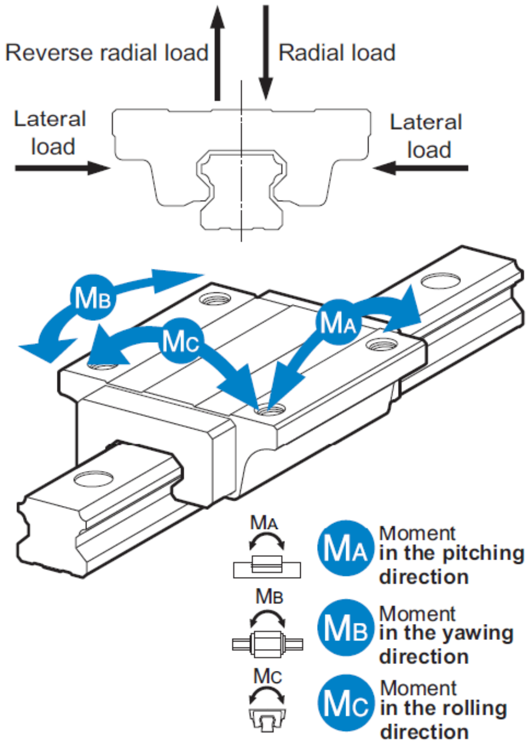


Fig. 4. Directions of the loads applied on the LM Guide

The LM Guide is categorized into roughly two types (figure 5): the 4-way equal load type, which has the same rated load in the *radial*, *reverse radial* and *lateral* directions, and the radial type, which has a large rated load in the *radial* direction.

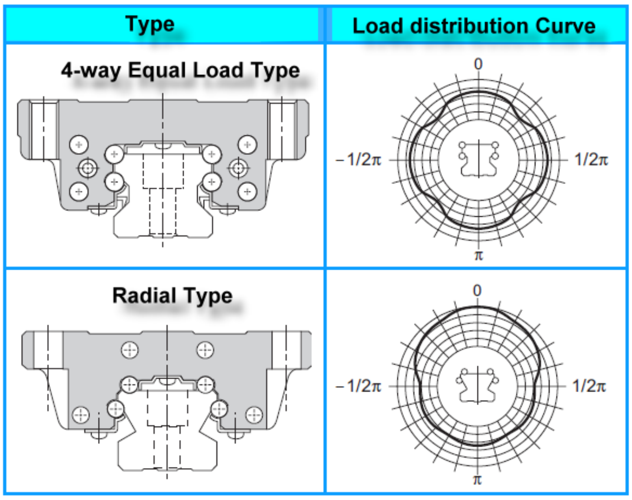


Fig. 5. The load distribution curve for the two main type of LM Guide.

With the radial type LM Guide, the rated load in the radial direction is different from that in the reverse radial and lateral directions. When such loads are applied, multiply the basic load rating by the corresponding factor. Those factors are specified in the manufacturer catalogue or technical sheet.

Calculating an Applied Load for a single-axis use

When the installation space for the LM Guide is limited, is possible to use only one LM block, or double LM blocks closely contacting with each other. In such a setting, the load distribution is not uniform and, as a result, an excessive load is applied in localized areas (i.e., both ends) as shown in Figure 6. Continued use under such conditions may result in flaking in those areas, consequently shortening the service life. In such a case, calculate the actual load by multiplying the moment value by any one of the equivalent-moment factors specified in manufacturer technical sheets/catalogue.

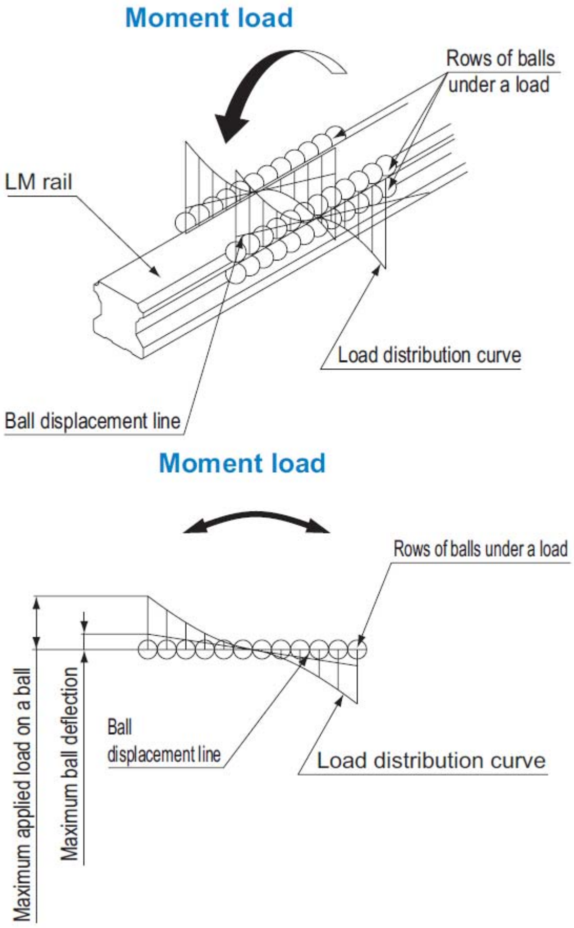


Fig. 6. The distribution of Ball Load when a moment is applied

- Moment Equivalence:

An equivalent-load equation applicable when a moment acts on an LM Guide is shown below.

$$P = K.M \qquad (1)$$

P : Equivalent load per LM Guide (N)
K : Equivalent moment factor
M : Applied moment load (N-mm)

Equivalent Factors

Since the rated load is equivalent to the permissible moment, the equivalent factor to be multiplied when equalizing the M_A, M_B and M_C moments to the applied load per block is obtained by dividing the rated loads in the corresponding directions. With those models other than 4-way equal load types, however, the load ratings in the 4 directions differ from each other. Therefore, the equivalent factor values for the M_A and M_C moments also differ depending on whether the direction is radial or reverse radial.

- Equivalent factors for the M_A moment

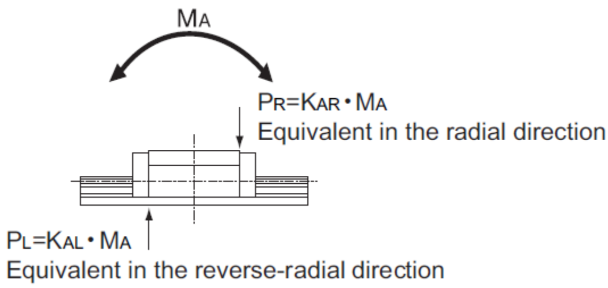


Fig.7. Equivalent Factors for the M_A Moment

-Equivalent factor in the radial direction:

$$K_{AR} = \frac{C_O}{M_A} \qquad (2)$$

-Equivalent factor in the reverse radial direction:

$$K_{AL} = \frac{C_{OL}}{M_A} \qquad (3)$$

- Equivalent factors for the M_B moment

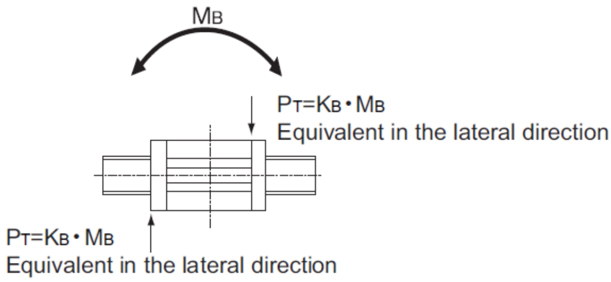


Fig.8. Equivalent Factors for the M_B Moment

- Equivalent factor in the lateral directions:

$$K_B = \frac{C_{OT}}{M_B} \qquad (4)$$

- <u>Equivalent Factors for the M_C moment</u>

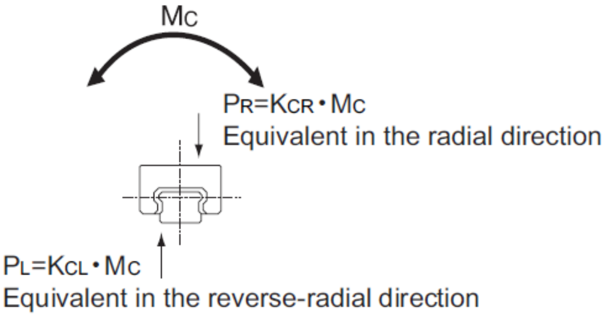


Fig.9. Equivalent Factors for the M_B Moment

- Equivalent factor in the radial direction:

$$K_{CR} = \frac{C_O}{M_C} \qquad (5)$$

-Equivalent factor in the reverse radial direction:

$$K_{CL} = \frac{C_{OL}}{M_C} \qquad (6)$$

P_R: Calculated load (radial direction),
P_L: Calculated load (reverse radial direction),
P_T: Calculated load (lateral direction),

C_0: Basic static load rating (radial direction),
C_{0L}: Basic static load rating (reverse radial dir.),
C_{0T}: Basic static load rating (lateral direction),

<u>Note:</u> *The above* ***C_0, C_{0L}, C_{0T}*** *and the below* ***Equivalent Factors*** *for each type of LM Guide are given in the manufacturer technical sheets/catalogue*

- K_{AR1}: Equivalent factor in the M_A radial direction when one LM block is used;
- K_{AL1}: Equivalent factor in the M_A reverse radial direction when one LM block is used;
- K_{AR2}: Equivalent factor in the M_A radial direction when two LM blocks are used in close contact with each other;
- K_{AL2}: Equivalent factor in the M_A reverse radial direction when two LM blocks are used in close contact with each other;
- K_{B1}: M_B Equivalent factor when one LM block is used;
- K_{B2} : M_B Equivalent factor when two LM blocks are used in close contact with each other;
- K_{CR}: Equivalent factor in the M_C radial direction;
- K_{CL}: Equivalent factor in the M_C reverse radial direction;

For example, the Equivalent Factors for a LM Guide (Model SR 25 M1VY – THK catalogue – SUA, see figure 10), are:

K_{AR1}=2.17x10^{-1}; K_{AL1}=1.09x10^{-1}
K_{AR2}=3.46x10^{-2}; K_{AL2}=1.73x10^{-2}
K_{B1}=1.51x10^{-1}; K_{B2}=2.35x10^{-2}
K_{CR}=1.11x10^{-1}; K_{CL}=5.55x10^{-2}

Model SR 25 M1VY

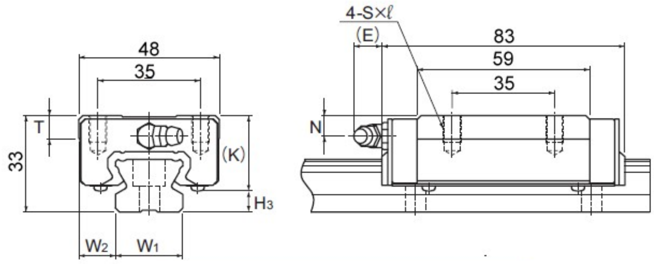


Fig. 10. Model SR 25 M1VY - LM Guide

<u>Example of calculation when one block is used:</u>

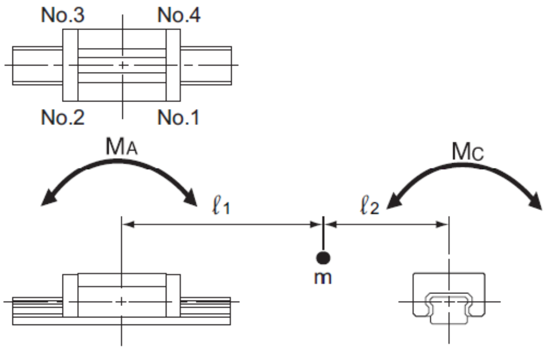


Fig. 11. LM Guide load when one block is used.

No.1: $P_1 = mg + K_{AR1} \cdot mg \cdot l_1 + K_{CR} \cdot mg \cdot l_2$ (7)
No.2: $P_2 = mg - K_{AL1} \cdot mg \cdot l_1 + K_{CR} \cdot mg \cdot l_2$ (8)
No.3: $P_3 = mg - K_{AL1} \cdot mg \cdot l_1 - K_{CL} \cdot mg \cdot l_2$ (9)
No.4: $P_4 = mg + K_{AR1} \cdot mg \cdot l_1 - K_{CL} \cdot mg \cdot l_2$ (10)

<u>Example of calculation when two LM blocks are used in close contact with each other:</u>

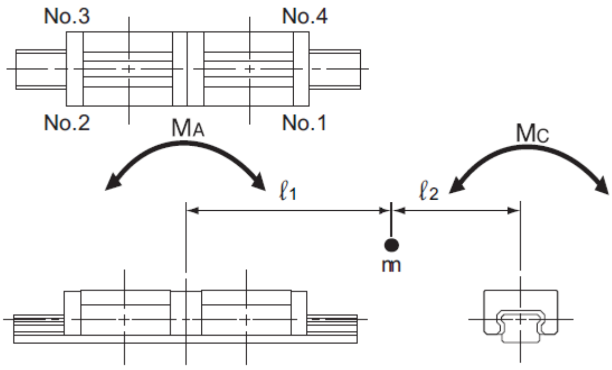


Fig. 12. LM Guide load when two blocks are used in close contact with each other.

$$\text{No.1}: P_1 = \frac{mg}{2} + K_{AR2} \cdot mg \cdot l_1 + K_{CR} \cdot \frac{mg \cdot l_2}{2} \quad (11)$$

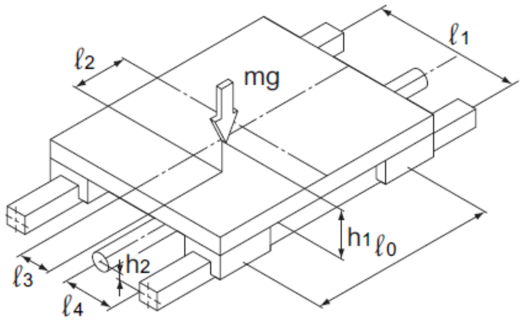
$$\text{No.2}: P_2 = \frac{mg}{2} - K_{AL2} \cdot mg \cdot l_1 + K_{CR} \cdot \frac{mg \cdot l_2}{2} \quad (12)$$

$$\text{No.3}: P_3 = \frac{mg}{2} - K_{AL2} \cdot mg \cdot l_1 - K_{CL} \cdot \frac{mg \cdot l_2}{2} \quad (13)$$

$$\text{No.4}: P_4 = \frac{mg}{2} + K_{AR2} \cdot mg \cdot l_1 - K_{CL} \cdot \frac{mg \cdot l_2}{2} \quad (14)$$

Calculating an Applied Load for double-axis use

Set the conditions needed to calculate the LM system's applied load and service life in hours.



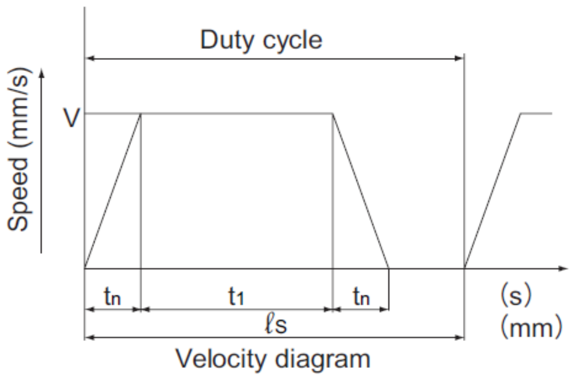


Fig. 13. Motion diagram of the LM Guide.

The conditions (see figure 13) consist of the following items:

(1) Mass: m (kg)
(2) Direction of the working load
(3) Position of the working point (e.g., center of gravity): l_2, l_3, h_1 (mm)
(4) Thrust position: l_4, h_2 (mm)
(5) LM system arrangement: l_0, l_1(mm) (No. of units and axes)
(6) Velocity diagram
  Speed: V (mm/s)
  Time constant: t_n (s)
  Acceleration: a_n (mm/s2)
(7) Duty cycle - Number of reciprocations per minute: N_1 (min-1)
(8) Stroke length: l_s (mm)
(9) Average speed: V_m (m/s)
(10)Required service life in hours: Lh (h)

Applied Load Equation

The load applied to the LM Guide varies with the external force, such as the position of the gravity center of an object, thrust position, inertia generated from acceleration/deceleration during start or stop, and cutting force.
In selecting an LM Guide, it is necessary to obtain the value of the applied load while taking into account these conditions.

m : Mass (kg)
l_n : Distance (mm)
F_n : External force (N)
P_n : Applied load (radial/reverse radial direction) (N)
P_{nT} : Applied load (lateral directions) (N)
g : Gravitational acceleration (m/s2)
V : Speed (m/s)
t_n : Time constant (s)
a_n : Acceleration (m/s2)

The next stage is the calculus of the load applied to the LM Guide in each particular case.
For example, below is sown the applied load equation for two particular cases (fig.14 &15).

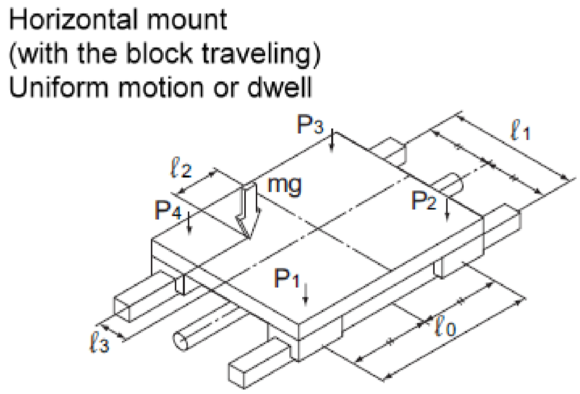


Fig. 14. Horizontal LM Guide traveling system

The applied load equation:

$$P_1 = \frac{mg}{2}\left(\frac{1}{2} + \frac{l_2}{l_0} - \frac{l_3}{l_1}\right); \quad (15)$$

$$P_2 = \frac{mg}{2}\left(\frac{1}{2} - \frac{l_2}{l_0} - \frac{l_3}{l_1}\right) \quad (16)$$

$$P_3 = \frac{mg}{2}\left(\frac{1}{2} - \frac{l_2}{l_0} + \frac{l_3}{l_1}\right); \quad (17)$$

$$P_4 = \frac{mg}{2}\left(\frac{1}{2} + \frac{l_2}{l_0} + \frac{l_3}{l_1}\right) \quad (18)$$

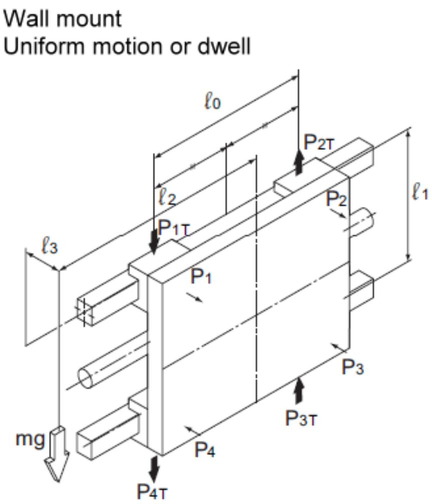


Fig. 15. Travel axis of cross-rail loader

The applied load equation:

$$P_1 = P_2 = P_3 = P_4 = \frac{mg \cdot l_3}{2 \cdot l_1} \quad (19)$$

$$P_{1T} = P_{4T} = \frac{mg}{4}(1 + \frac{2l_2}{l_0}) \quad (20)$$

$$P_{2T} = P_{3T} = \frac{mg}{4}(1 - \frac{2l_2}{l_0}) \quad (21)$$

Calculating the Equivalent Load

The LM Guide can bear loads and moments in all directions, including a radial load (P_R), reverse radial load (P_L) and lateral loads (P_T), simultaneously.

Applied loads include the following.

P_R: Radial load
P_L: Reverse-radial load
P_T: Lateral load

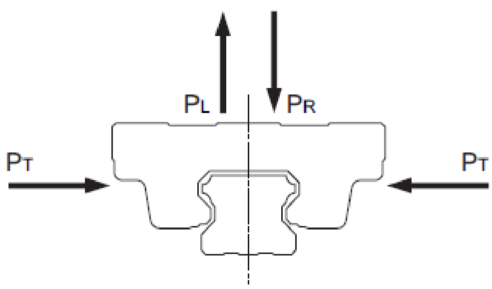


Fig. 16. Directions of the loads applied on the LM Guide

Equivalent Load P_E

When two or more loads (e.g., radial load and lateral load) are simultaneously applied to the LM Guide, the service life and the static safety factor are calculated using equivalent load values obtained by converting all the loads into radial, lateral and other loads.

The equivalent load equation for the LM Guide differs by model.

Example of equation for LM Guide model HSR (THK catalogue –USA).

The equivalent load when a radial load (P_R) and a lateral load (P_T) are applied simultaneously is obtained using the following equation:

P_E (equivalent load)=P_R+P_T
P_R: Radial load
P_T: Lateral load

Calculating the Static Safety Factor

To calculate a load applied to the LM Guide, the average load required for calculating the service life and the maximum load needed for calculating the static safety factor must be obtained first. In a system subject to frequent starts and stops, placed under cutting forces or under a large moment caused by an overhang load, an excessively large load may apply to the LM Guide. When selecting a model number, make sure that the desired model is capable of receiving the required maximum load (whether stationary or in motion).

Table 1. Standard values for the static safety factor.

Machine using the LM Guide	Load conditions	Lower limit of f_S
General industrial machinery	Without vibration or impact	1 to 1.3
	With vibration or impact	2 to 3
Machine tool	Without vibration or impact	1 to 1.5
	With vibration or impact	2.5 to 7

When the radial load is large	$\frac{f_H \cdot f_T \cdot f_C \cdot C_0}{P_R} \geq f_S$
When the reverse radial load is large	$\frac{f_H \cdot f_T \cdot f_C \cdot C_{0L}}{P_L} \geq f_S$
When the lateral loads are large	$\frac{f_H \cdot f_T \cdot f_C \cdot C_{0T}}{P_T} \geq f_S$

f_S : Static safety factor
C_0 : Basic static load rating (rad. dir.) (N)
C_{0L} : Basic static load rating (rev.rad. dir.) (N)
C_{0T} : Basic static load rating (lat.dir.) (N)
P_R : Calculated load (rad. dir.) (N)
P_L : Calculated load (rev.rad.dir.) (N)

P_T : Calculated load (lat.dir.) (N)
f_H : Hardness factor (see Fig.17).
f_T : Temperature factor (see Fig.18)
f_C : Contact factor (see Table 2)

Calculating the Average Load

In cases where the load applied to each LM block fluctuates under different conditions, such as an industrial robot holding a work with its arm as it advances and receding with its arm empty, and a machine tool handling various work pieces, it is necessary to calculate the service life of the LM Block while taking into account such fluctuating loading conditions.

The average load (P_m) is the load under which the service life of the LM Guide is equivalent to that under varying loads applied to the LM blocks.

$$P_m = \sqrt[3]{\frac{1}{L} \cdot \sum_{n=1}^{n} \left(P_n^{\,3} \cdot L_n\right)} \qquad (22)$$

Pm : Average load (N)
Pn : Varying load (N)
L : Total travel distance (mm)
Ln : Distance traveled under load Pn (mm)

Note) The above equation or the equation (23) below applies when the rolling elements are balls.

Calculating the Nominal Life

The service life of an LM Guide is subject to variations even under the same operational conditions. Therefore, it is necessary to use the nominal life defined below as a reference value for obtaining the service life of the LM Guide. The nominal life means the total travel distance that 90% of a group of units of the same LM Guide model can achieve without flaking (scale-like pieces on the metal surface) after individually running under the same conditions.

- Nominal Life Equation for an LM Guide Using Balls:

$$L = \left(\frac{f_H \cdot f_T \cdot f_C}{f_W} \cdot \frac{C}{P_C}\right)^3 \cdot 50 \qquad (23)$$

- Rated Life Equation for an LM Guide Using Rollers:

$$L = \left(\frac{f_H \cdot f_T \cdot f_C}{f_W} \cdot \frac{C}{P_C}\right)^{\frac{10}{3}} \cdot 100 \qquad (24)$$

L : Nominal life (km)
C : Basic dynamic load rating (N)
P_C : Calculated load (N)
f_W : Load factor (see Table 3)

Once the nominal life (L) has been obtained, the service life time can be obtained using the following equation if the stroke length and the number reciprocations are constant.

$$L_h = \frac{L \cdot 10^6}{2 \cdot l_s \cdot n_1 \cdot 60} \qquad (25)$$

L_h : Service life time (h)
l_s : Stroke length (mm)
n_1 : Number of reciprocations per minute (min-1)

f_H: Hardness Factor.

To ensure the achievement of the optimum load capacity of the LM Guide, the raceway hardness must be between 58 and 64 HRC. If the hardness is lower than this range, the basic dynamic load rating and the basic static load rating decrease (see figure 17). Therefore, it is necessary to multiply each rating by the respective hardness factor (f_H).

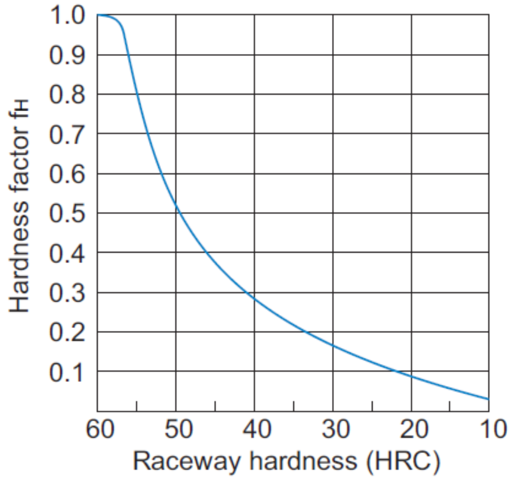


Fig. 17. The Hardness factor

f_T:Temperature Factor

If the temperature of the environment surrounding the operating LM Guide exceeds 100°C take into account the adverse effect of the high temperature and multiply the basic load ratings by the temperature factor indicated in Figure 17.

Note: The LM Guide is designed to normally be used at environment temperature of 80°C or less.

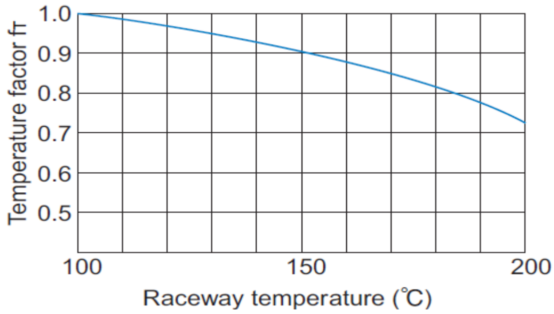


Fig. 18. Temperature factor

f_C: Contact Factor. When multiple LM blocks are used in close contact with each other, it is difficult to achieve uniform load distribution due to moment loads and mounting-surface accuracy. When using multiple blocks in close contact with each other, also, if uneven load distribution is expected in a large machine, multiply the basic load rating (C or C_0) by the corresponding contact factor indicated in Tab. 2.

Table 2. Contact factor

Number of blocks used in close contact	Contact factor f_C
2	0.81
3	0.72
4	0.66
5	0.61
6 or greater	0.6
Normal use	1

f_W: Load Factor. In general, reciprocating machines tend to involve vibrations or impact during operation. It is extremely difficult to accurately determine vibrations generated during high-speed operation and impact during frequent start and stop. Therefore, where the effects of speed and vibration are estimated to be significant, divide the basic dynamic load rating (C) by a load factor selected from Table 3, which contains empirically obtained data.

Table 3. Load factor

Vibrations/ impact	Speed(V)	f_W
Faint	Very low V≦0.25m/s	1 to 1.2
Weak	Slow 0.25<V≦1m/s	1.2 to 1.5
Medium	Medium 1<V≦2m/s	1.5 to 2
Strong	High V>2m/s	2 to 3.5

3. CONCLUSIONS

The problem of choosing the appropriate type and size of the LM Guide is very important to obtain maximum performances of the mechanical systems guided by such mechanism. The proposed method for appropriate choosing of the linear motion guides and checking of its nominal life and service life time is an important tool for designers of industrial robots and high precision machine-tool.

The calculation and validation methods are based on manufacturer's technical sheets /catalogue data and takes into account all static and dynamic loading conditions of the LM Guide.

4. REFERENCES

[1]. Yoshimi Ito. *Modular Design for Machine Tools*. McGraw-Hill Comp. New York, 2008.

[2]. Collins, J., A. Busby, H.,R. Staab, G.H. *Mechanical Design of Machine Elements and Machines;* John Wiley & Sons Inc. 2010.

[3]. THK - General Catalogue; Linear Motion Systems

[4] www.thk.com/us

Alegerea adecvata a ghidajelor liniare de rulare pentru aplicatii robotice.

Rezumat: Lucrarea prezintă premisele teoretice necesare si algoritmul alegerii optime a tipului şi mărimii ghidajelor de rulare cu bile ce intră în structura mecanica a sistemelor de ghidare liniara, caz specific roboţilor industriali şi masinilor-unelte moderne, de precizie ridicata. Lucrarea se bazeaza pe condiţiile reale de încărcare statică şi dinamică ale sistemului de ghidaje, precum si pe datele de catalog ale unor firme producatoare de prestigiu (exemplu THK-SUA).

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