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Study of Stiffness of a Linear Guideway by FEA and Experiment

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Abstract: Linear rolling ball guideway is a key component of many machines. However, due to the point contact between the ball and the groove, stiffness of linear guideway is the major factor which affects the rigidity and precision of machines. Preload in the guideway can increase the stiffness of linear guideway and thus reduces the position deviation under an external load. The purpose of this study is to develop FEA and compare the results with experimental results to prove the correctness of the FEA model. This model can be used to predict the stiffness of linear guideway with 4 rows of rolling ball, face–to-face arrangement and 45 degrees angular-contact for different preload. The results of this study are (1) set up numerical simulation model (2) carry out an experiment to measure the stiffness and compare it with the numerical result (3) stiffness that provide by upper of 2 rows of rolling ball under downward load, not distributed from 4 rows equally (4) deflection and contact angle change induced by ball rotating and compression under downward load. This study is useful for establishing the stiffness on different sizes and arrangement of linear guideway.

Keywords: Linear gudieway, Stiffness, FEA method, Experimental method.

1 Introduction

A linear rolling ball guideway is a key component of many high speed machines. It can achieve high positioning accuracy (μm order) and reduce the friction force effectively. However, due to the point contact between the rolling balls and the grooves, which is not only lower the rigidity of a linear rolling ball guideway, but also higher the contact stress than sliding guideway. The elastic deflection δ in direction of loading come from applied variable load F [AG (2007)], as shown in Fig.1.

In linear components, rolling interface between the rolling elements and grooves, which exhibit nonlinear contact characteristics of Hertzian theory.[Johnson (1985)]

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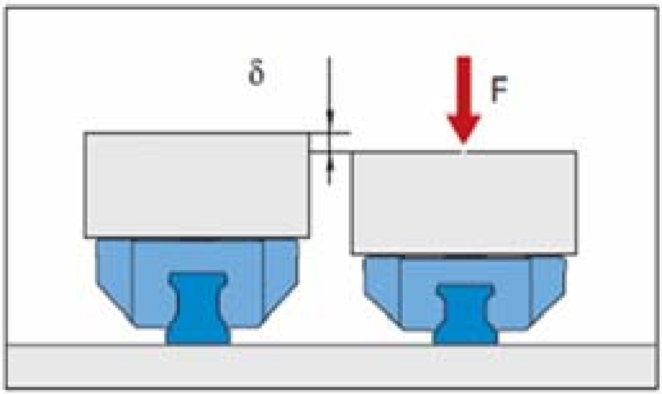

Figure 1: Downward load and elastic deflection of linear guideway

For linear rolling ball guideway, an oversized rolling ball is usually employed to produce adequate preload to increase the structural rigidity. Definition of stiffness value K can be expressed as follows:

$$K = \frac{dF}{d\delta} \tag{1}$$

The study [Ohta (1999)] had shown that a rolling ball guide exhibit different vibration characteristics when the preload is set to different magnitudes. An investigation [Hung (2009)] also verified that the external load acting on the positioning stage caused a variation in structure stiffness of linear guideway, and hence, brought the stage to vibrate at different frequencies. Although a large number of studies have been done on dynamic and static characteristics of linear guideway under different stiffness classification, little is know about contact stiffness of linear gudieway on simulation and elastic deflection investigation. This research is intended as an investigation of stiffness by FEA and experimental method. The system stiffness of numerical simulation was predicted and validated with the experimental measurements performed. The object of study focuses on system with 4 rows of rolling ball, 45 degrees angular contact, face-to-face arrangement type and different preload classes, such as shown in Fig.2.

2 Description of methodology

In order to present the investigation of stiffness for linear guideway system under variable downward load, FEA model [Altair (2009)] and experimental setup described in next two section.

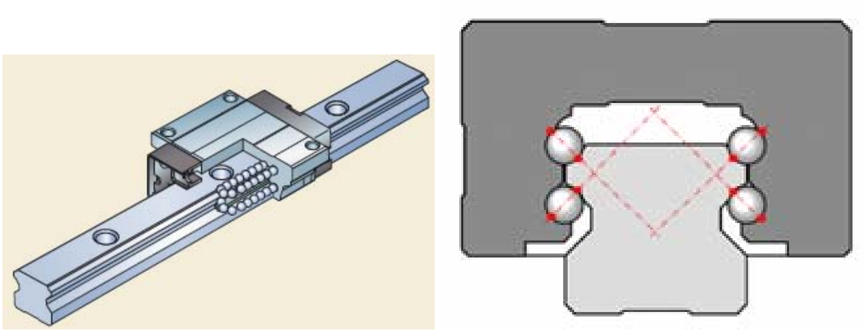

Figure 2: Schematic illustration of face-to-face arrangement 2

2.1 3D modeling preparing for finite element analysis of stiffness

The procedures of the finite element analysis are as follows:

(A) Pre-process performed:

Step 1: Set up CAD model from the dimensional data into STEP format by Soildworks. To simplify the analysis, only one rolling ball diameter of length of the guideway is used in modeling. (1/12 length of the guideway and thickness is 5.55625mm).The geometric for linear gudeway is shown in Fig. 3 and Table 1.

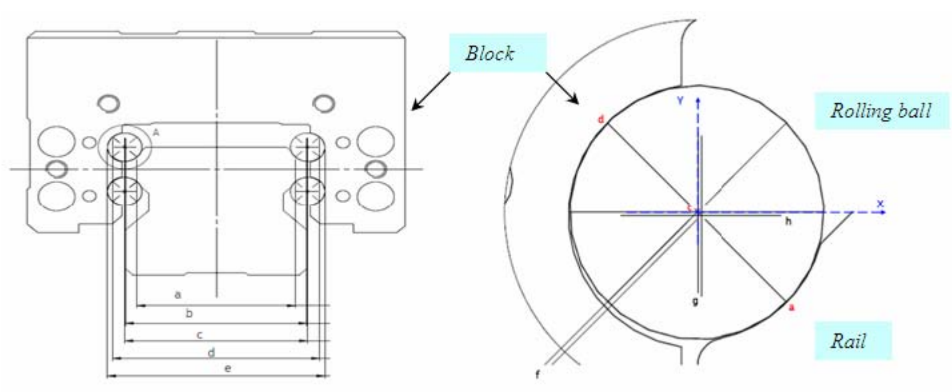

Figure 3: Schematic illustration of cross section

Step 2: Input CAD model into HyperMesh. Then, set up proper element, mesh density, constraint condition, loading steps, point contact links and material property for analysis. Major parameters of setting in HyperMesh are listed on Table 2. Fig.4 shows the meshed geometry and constrain of degree of freedom for linear

Table 1: Specification of dimension in linar guideway system

Item	Description	Size (mm)
a	Rail 45^{o} contact point distance	24.0711
b	Block raceway center distance	27.8428
c	Steel ball center distance	28
d	Block 45^{o} contact point distance	31.9289
e	Block raceway top-end point distance	33.6213
f	Distance between curvature center at block and center at ball	0.1111
g	Distance between curvature center at block and center at ball (X vector)	0.0786
h	Distance between curvature center at block and center at ball (Y vector)	0.0786

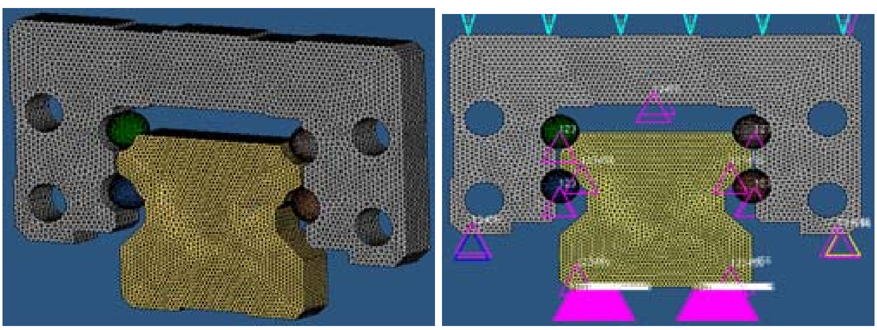

Figure 4: Geometry of mesh density and constraints setting

Table 2: Specification of mesh setting and property in linar guideway system

Meshing			
Components	Block X 1	Rail X1	Steel Balls X 4
Element Type	3D Tetra		
Elements	120894		
Aspect ratio	< 3.5		
Warpage	<1.25		
Jacobian	< 0.7		

Components	Position	Constraints
Rail	Bottom	dof 1,2,3,4,5,6
	Front	dof 1,2,3,4,5,6
Block	Front	dof 1,3,4,5,6
Steel Ball	Center	dof 1,2,3
Material property		
Young's modulus E	206 Gpa	
	0.3	
	7800 kg/m^3	

guideway.

The simulation of interface of ball and groove by using single rigid element was positioned at 45 degrees contact point between groove and ball and referred to as 1D two-point link mode. Equivalent downward load distributed on the top of block equally, such as shown in Fig.5.

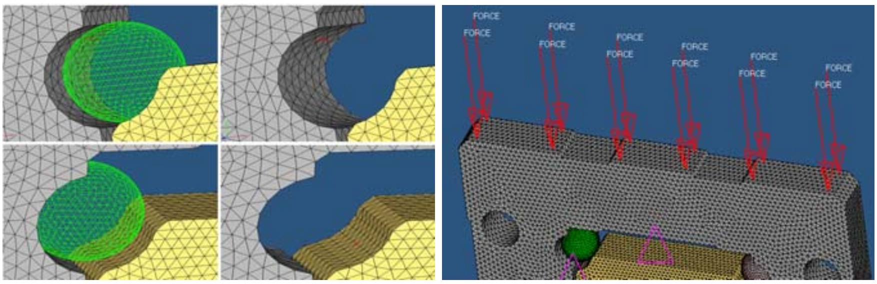

Figure 5: (a) Rigid links between grooves and ball (b) downward load applied on the block

(B) Solving process performed:

Input the FE modeling from HyperMesh to RADIOSS and solved by linear static load mode.

(C) Post process performed:

After solving process for FE model was finished, the graphic results of deflection and modal animation of guideway were preformed by HyperView. The measurement results of deflection can compare with the displacement of the node at the central of block.

2.2 Experimental setup for linear guideway

In order to measure deflection of guideway in micrometer order, experimental fixture was equipped high rigidity frame to avoid deformation when downward load applied. Experimental setup is shown in Fig.6. A load cell, model no.UWD-25klb, was used to measure load on block. A trapezoidal screw rod provided the downward force that increased by torque wrench step by step. The deflection of δ are obtain by LVTD, lever probe with TESATONIC length measuring instrument, model no. TT10. The probe was equipped with 0.1 micrometer and 1 micrometer division within +/-5 micrometer and +/-50 micrometer measuring range respectively. The lever probe was positioned on the top of central of block and the position of measurement was measured same as FEA model.

Figure 6: Experimental apparatus setup and enlargement right

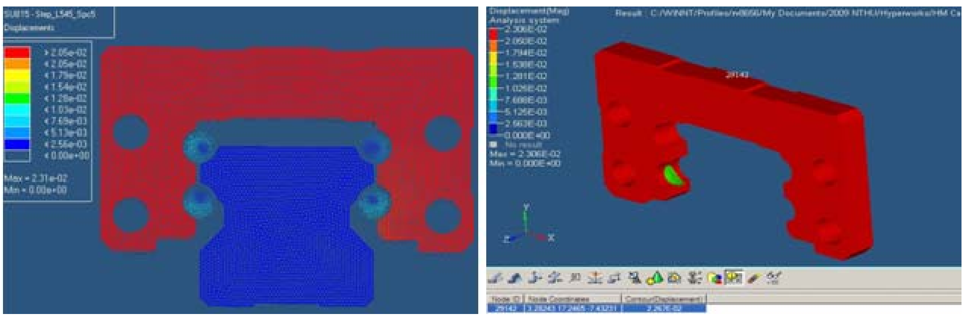

Figure 7: FEA result of deflection on block

3 Description of result

3.1 Analytical results

The 3D models of linear guideway were analyzed that the deflection on top of block are shown in Fig.7. System is assumed to be elastic to satisfy actually material property under zero preload. The relative motion between block, rail and ball was considered. Variable downward load and deflection listed on Table 3. According to analysis result of deflection, stiffness value can be expressed as follows:

$$K_{T0}^{f} = \frac{dF}{d\delta} \cong 24.08(N/\mu m) \tag{2}$$

The prediction the kinemics of linear guideway by FEA was further shows in Fig. 8. After compression the movements of upper ball of 2 rows between no load and loaded, it was observed that point to point contact on the ball with rigid links combined rolling motion when the guideway applied load. Original 45 degree contact had been changed on compressive rows with rotating motion of ball. Lower ball of

Table 3: Deflection of FEA model under variabel load

Step	#1	#2	#3	#4	#5	#6	#7	#8
Load (N)	88	162	200	286	360	456	546	595
	3.7	6.7	9.7	12.8	14.9	18.9	22.6	24.7

2 rows were separated without point contact and force transfer.

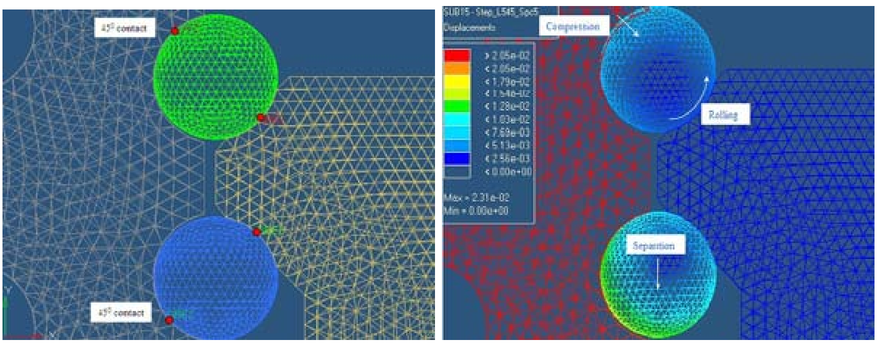

Figure 8: Comparisons of kinemics rolling motion on the balls and grooves (a) without load.(b) downward load applied.

3.2 Experimental results

For investigating the preload effects and further comparison with numerical analysis, linear guideway with different preload setting were employed. (T0 class for zero preload and T1 class for 0.02 of dynamic preload C) In experiment, preload in the block was determined by the diameter of the balls. The use of balls with a defined larger diameter generates a preload in the same block. Variable downward load and deflection measurement listed on Table 4.

According to analysis result of deflection, stiffness value of T0 preload setting can be expressed as follows:

$$K^{e}_{T0} = \frac{dF}{d\delta} \cong 224.54(N/\mu m) \tag{3}$$

Stiffness value of T1 preload setting can be expressed as follows:

$$K^{e}_{T1} = \frac{dF}{d\delta} \cong 411.66(N/\mu m) \tag{4}$$

The results are also plot in Fig.9.

Table 4: Deflection of experimental measurement depend on variabel load (a) T0 preload setting (b) T1 preload seeting

(a) LLTH 30U T0 (0μm ball employed)														
Step	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
Load (N)	627	1058	1509	1940	2470	2920	3430	3920	4449	4880	5468	5998	6546	7134
Deflection(μm)	3.9	6	7	9	11	12	14	16	17	19	20	22	23	25

(b) LLTH 30U T1(+8μm ball employed)														
Step	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
Load (N)	510	980	1470	1960	2470	3018	3528	3900	4430	4900	5390	5880	6370	6899
Deflection(μm)	1.4	2.4	3.6	5	6	8	9	10	11	12	13	15	16	17

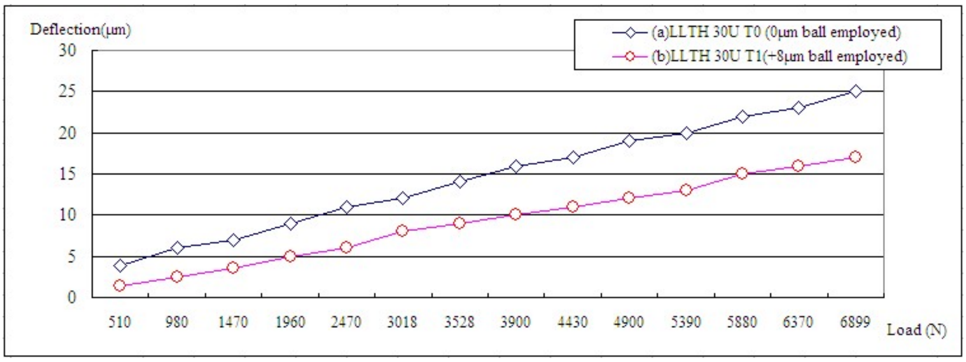

Figure 9: Experimental results comparison under different preload block

3.3 Comparison between experimental and analytical results

In order to compare the stiffness obtained from finite element simulation and experiment. The calculated experimental stiffness the guideway has 12 balls on each row of groove, therefore, the load should be 12 times the load applied in FEA model. The Fig. 10 seeks to capture the fact that the similar trends of stiffness value between experiment and numerical analysis under T0 preload.

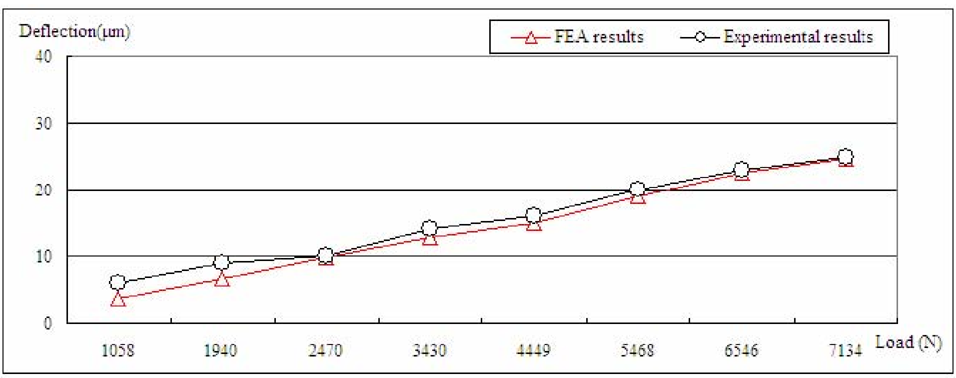

Figure 10: Deflection versus load of the results of FEA and experiment

4 Conclusions

In this study, the stiffness of numerical analysis results and experimental results of a linear guideway were obtained. The comparison shows that the numerical model is reasonable correct. The study has following conclusions:

(1)The FEA provide good consistencies in the prediction of the dynamic behaviors of the liner guideway comparing with experimental results.

(2)Preload increases the stiffness of the overall system. It anticipates the ball has elastic compressive deformation and rotating motion when the guideway under loading.

(3)Contact stiffness that support by upper 2 rows of balls under downward load, not equally distributed on 4 rows of balls.

(4) FEA results show that contact angle between grooves and ball is changed.

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