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Test and Evaluation of Stiffness of a Pin Turning Device for Large Marine Engine Crankshafts

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ABSTRACT

In order to prevent unwanted excited vibrations and to secure better machining precision in large size heavy duty machine tools dynamic stiffness is one of the most desirable and critical properties. In the past decades, many researches on machine tool stiffness test and evaluation methodology have been made. However any methodology for a Pin Turning Device (PTD), which is a special kind of turning lathe for machining big size crankshaft pins, is rarely found among them. This study proposes a test and evaluation process of stiffness of a PTD by measuring frequency response function at the tool center point (TCP). For conformance proving for the proposed methodology, stiffness of a PTD obtained by the proposed method with impact hammer test (IHT) has been compared with that determined by FEM.

Keywords: Pin Turning Device (PTD); Machine Tool Stiffness; Compliance Response Function; Impact Hammer Test

1. Introduction

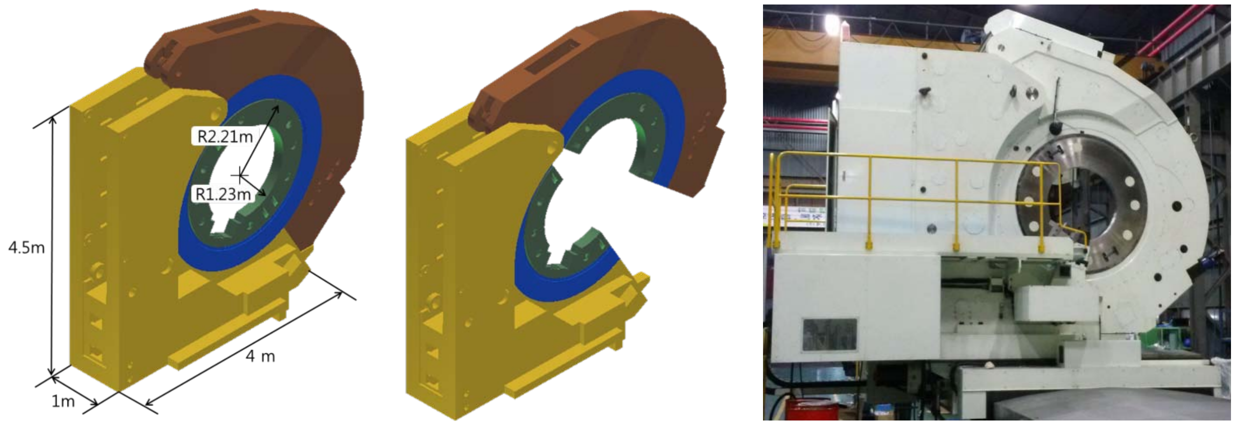
Recently there is an increasing demand for large scale machine tools for large and precision parts for several high growth industry fields like; conventional and renewable energy power plants, airplane structures, offshore platforms, ships and marine engines, etc. [1,9,10]. For large size machine tool, reduced structural stiffness compared to smaller machine tool is one of problems to be resolved because deflection of a machine structure rises as an exponential function of its dimension while the allowable deflection increases linearly [9]. In the past decades, many researchers have studied machine tool stiffness evaluation methodologies and design optimization for high structural rigidity and lightweight [2-8]. Machine tool stiffness evaluation method [3,4] by determining the compliance frequency response function at TCP is a more economical and analytical way than that by a direct cutting test. Thus, this method has been broadly applied to obtaining machine tool stiffness. Typical stiffness evaluation methodologies for many different types of machine tools have been studied by M. Weck and K. Teipel [4] except that for a special purpose lathe like a PTD for machining crankshaft pins as shown **Figure 1**. The PTD has volumetric dimension of $4\times1\times4.5$ (m^3).

For turning operation of the PTD, a revolving ring built in tool post rotates around a fixed workpiece differed from a general lathe, in which a workpiece is rotating and tool is moved (indexed) by a tool post. The tool post of the PTD can be indexed in the radial direction only. Thus cutting forces correspondingly occur in the radial and tangential directions. Moreover there is a strong possibility that the PTD does not show uniform stiffness in the radial and tangential directions along the circumference because the PTD has an asymmetric structure and open and close type revolving ring as illustrated in **Figure 1**. Therefore stiffness in the radial and tangential directions is a critical influential parameter upon dynamic behavior and machining accuracy of the PTD. Thus this study proposes a proper test and evaluation methodology of stiffness of a PTD.

2. Test and Evaluation of a PTD Stiffness

2.1. Test Methodology and Process

According to M. Weck and K. Teipel [4], stiffness of a machine tool can be determined from reciprocal of the compliance measured at TCP as shown in **Figure 2**. From the view point of theoretical basis, the PTD stiffness evaluation methodology in this study is almost the same as theirs [4]. However there is not specified any method or process for a PTD in [4], so we propose a test and evaluation methodology of a PTD stiffness as illustrated in **Figure 3**. The static stiffness k_s and dynamic stiffness k_d are defined by Equation (1) and Equation



(a) Open & close type PTD (b) Prototype PTD

Figure 1. Solid model and prototype of a PTD.

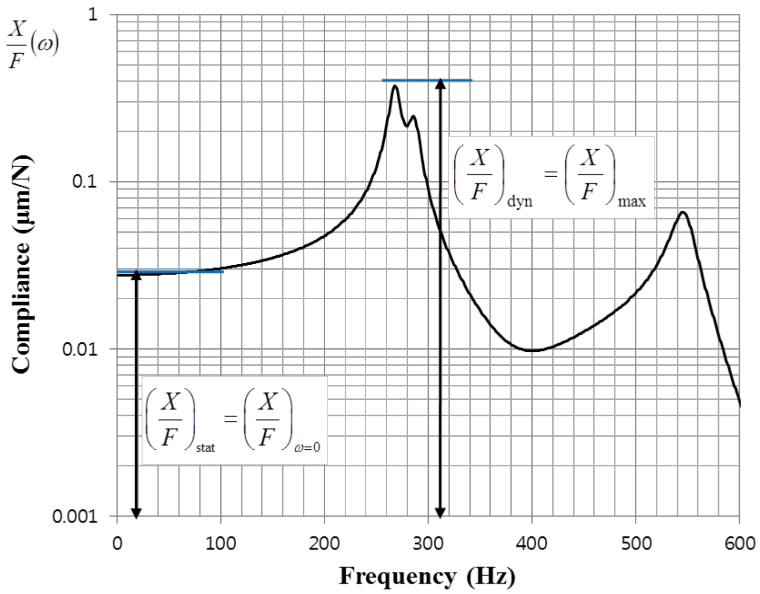


Figure 2. A typical sample of measured compliance at TCP.

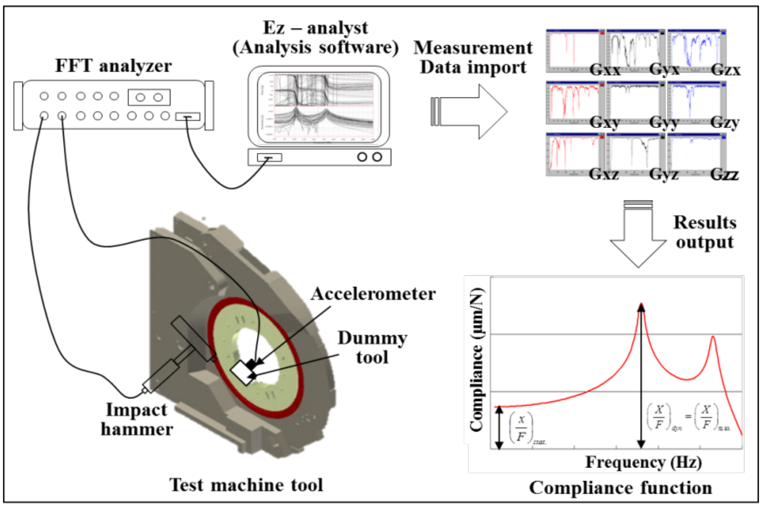


Figure 3. An explanatory flow of the proposed PTD stiffness test methodology.

(2), respectively. For a PTD, static and stiffness deviations Δk_s and Δk_d defined by Equations (3) and (4), of course, will be reasonable and useful criteria considering that the PTD has asymmetric structure and its tool post with the revolving ring turns around a work piece in the vertical plane.

$$k_s = 1 \Big/ \left(\frac{X}{F} \right)_{\omega \approx 0} \tag{1}$$

$$k_d = 1 \Big/ \left(\frac{X}{F} \right)_{\max} \tag{2}$$

$$\Delta k_s = \left. k_s \right)_{\max} - \left. k_s \right)_{\min} \tag{3}$$

$$\Delta k_d = \left. k_d \right)_{\max} - \left. k_d \right)_{\min} \tag{4}$$

Where F and X are excitation force and displacement at TCP of the machine tool, respectively.

The coordinate systems and parameters for measurement position are defined as shown in **Figure 4(a)**. Cartesian coordinate system is used for defining global coordinates of the PTD structure and a local polar coordinate system is used for defining coordinates of the circular parts and revolving motions. The parameters M, R_R, R_M represent the measurement position, the radius of revolving ring, the radial distance of the measurement position (the distance between the position M and the revolving ring center), respectively. A dummy tool shown in **Figure 4(b)** is installed into the tool post of the PTD and a tri-axial accelerometer is attached on it. The radial distance of measurement point R_M is apparently decided as following equation.

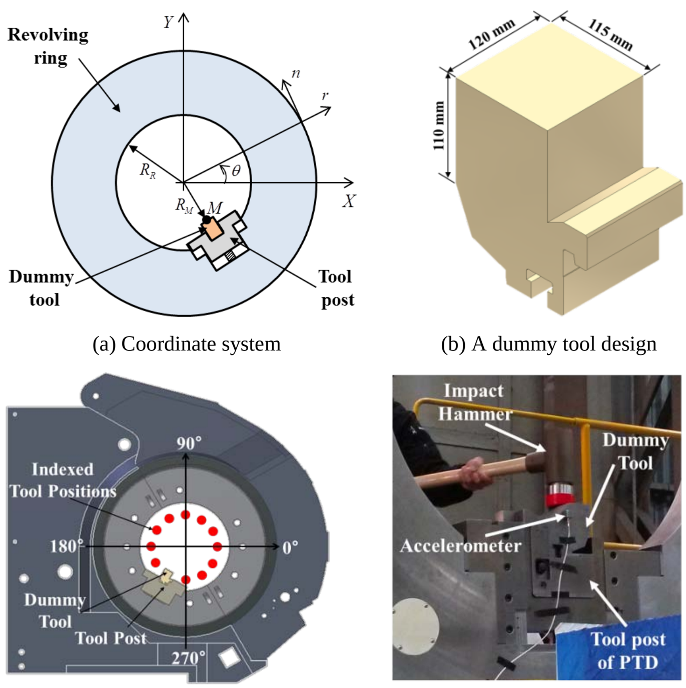
$$R_M = R_R - \left(r_{TP}/2 + h_{DT} \right) \tag{3}$$

Where r_{TP} and h_{DT} are the feed of tool post in the radial axis and the dummy tool height, respectively.

Compliance due to applied impulse force or random excitation has been measured at 12 evenly indexed TCPs as shown in **Figures 4(c)** and **(d)**. Consequently stiffness has been obtained from the measured compliance. For measuring compliance of the PTD, some measuring devices were used as; FFT analyzer (ZonicBook 618E), impact hammer (PCB Model 086D50), tri-axial accelerometer (Kistler Type 8795A50).

2.2. FEM Analysis of PTD Stiffness

In order to predict the compliance of the PTD analytically and to compare with test results, in this study, harmonic response analysis also has been carried out. FEM model of the PTD for the harmonic response analysis is shown in **Figure 5**. The modeling data and applied force are given in **Table 1**. Compliance frequency responses were analyzed in each case of harmonic excitation applied to the evenly indexed 12 different TCPs as shown in **Figure 4(c)**. As the result, the static and dynamic compliances at each of the 12 different TCPs were obtained and consequently the corresponding static and dynamic stiffness and their deviations were computed by using Equations (1)-(4).



(a) Coordinate system (b) A dummy tool design

(c) Measuring positions (d) Impact hammer & pickup

Figure 4. Coordinate system, measuring positions, and equipment for the PTD stiffness test methodology.

Table 1. Modeling data for FEM analysis of the PTD.

FEM modeling	*Element type*	*No. of nodes*		*No. of elements*
	SHEL 63	10,439		11,031
Material property	*Material*	*Elasticity* (***GPa***)	*Poisson's ratio*	*Density*
	GCD 500	172	0.275	7200
	SCM 440	205	0.29	7850
Applied force at spindles	*Direction*	*Radial dir.*		*Tangential dir.*
	Force (*N*)	3623		13,523
Boundary conditions	4 supporting nodes at the bottom are fixed			

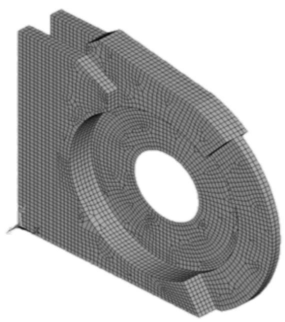


Figure 5. FEM model of the PTD.

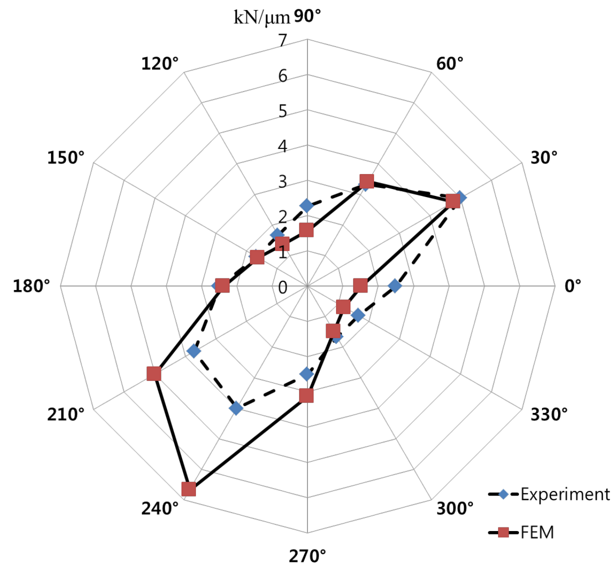
3. Results and Discussion

For verifying conformance of the proposed methodology, both measured and computed stiffness at 12 evenly indexed TCPs have been compared with each other and they look alike as observed in **Figures 6** and **7** and **Tables 2** and **3**.

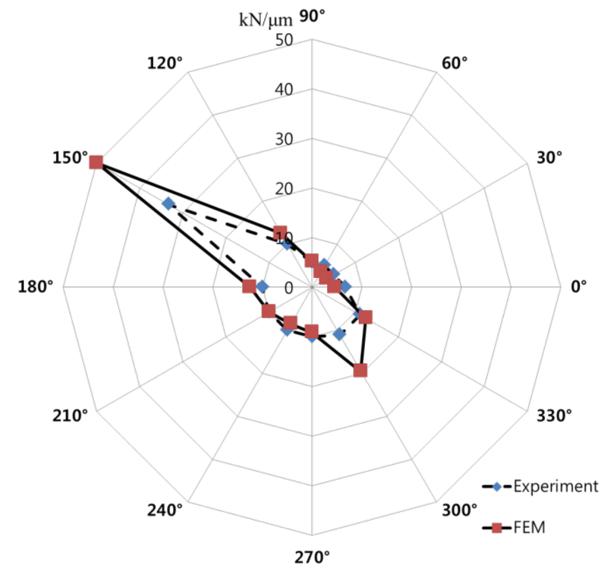
As seen in **Table 2**, measured static stiffness (minimum stiffness value) of the PTD was 1.666 kN/μm in the radial direction and 5.000 kN/μm in the tangential direction, respectively. Computed static stiffness was 1.370 kN/μm in the radial direction and 3.367 kN/μm in the tangential direction, respectively.

Similarly as seen in **Table 3**, measured dynamic stiffness of the PTD was 54.1 N/μm in the radial direction and 111.1 N/μm in the tangential direction, respectively. And the computed dynamic stiffness was 39.1 N/μm in the radial direction and 100 N/μm in the tangential direction, respectively

Judged by the test results, static stiffness deviation was 3.334 kN/μm in the radial direction and 28.333 kN/μm in the tangential direction, respectively. And also dynamic stiffness deviation was 173.2 N/μm in the radial direction and 297.1 N/μm in the tangential direction, respectively. So, the proposed PTD stiffness test methodology has been proven to be valid for determining real stiffness of a PTD.



(a) In the radial direction

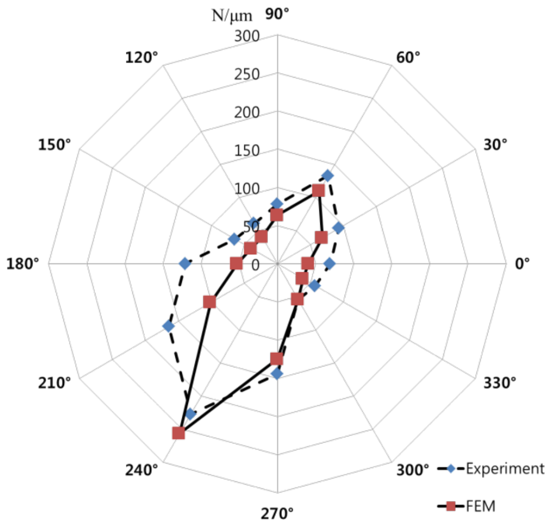


(b) In the radial direction

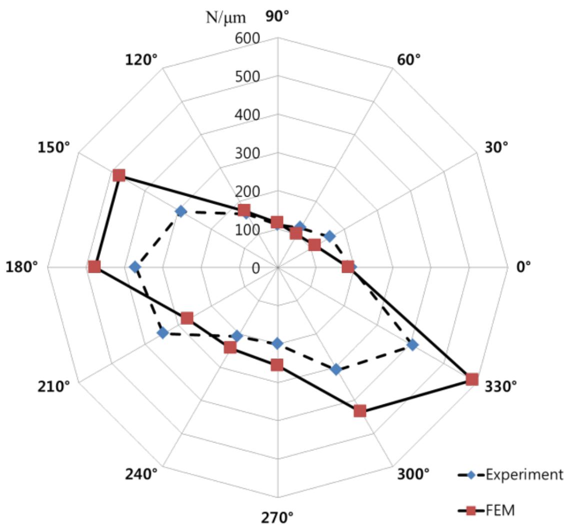
Figure 6. Comparison of measured and computed static stiffness of the PTD at 12 evenly indexed TCPs.

4. Concluding Remarks

In this study, a test and evaluation methodology of stiffness of a PTD, which is special purpose turning lathe for large marine engine crankshafts, has been proposed. The proposed methodology can obtain machine tool stiffness



(a) In the radial direction



(b) In the tangential direction

Figure 7. Comparison of measured and computed dynamic stiffness of the PTD at 12 evenly indexed TCPs.

Table 2. Comparison of static stiffness of the PTD.

Position (˚)	Static stiffness (kN/μm)			
	Radial direction		Tangential direction	
	Measured	*Computed*	*Measured*	*Computed*
0	2.500	1.522	6.666	4.545
30	5.000	4.784	5.000	3.367
60	3.333	3.413	5.000	3.546
90	2.272	1.574	5.000	5.154
120	1.666	1.370	10.000	12.500
150	1.666	1.613	33.333	50.000
180	2.500	2.381	10.000	12.500
210	3.703	5.000	10.000	10.000
240	4.000	6.666	10.000	8.547
270	2.500	3.125	10.000	9.091
300	1.666	1.490	11.111	19.607
330	1.666	1.197	11.111	12.500

Table 3. Comparison of dynamic stiffness of the PTD.

Position (˚)	Dynamic stiffness (N/μm)			
	Radial direction		Tangential direction	
	Measured	*Computed*	*Measured*	*Computed*
0	69.4	40.7	192.3	185.2
30	93.5	68.0	158.7	113.6
60	133.3	109.9	119.0	100.0
90	78.1	63.7	111.1	116.3
120	61.0	40.3	161.3	169.5
150	64.1	39.5	289.9	476.2
180	120.5	52.6	370.4	476.2
210	163.9	101.0	344.8	270.3
240	227.3	256.4	208.3	243.9
270	144.2	125.0	200.0	256.4
300	54.1	54.3	309.3	434.8
330	57.5	39.1	408.2	588.2

from measured compliance response by impact hammer test or random excitation test. Following the proposed method and process, PTD compliance was measured at 12 evenly indexed TCPs and then the corresponding stiffness was determined. For verifying conformance of the proposed methodology, measured stiffness has been compared with FEM analysis results. Thus the proposed methodology is proven to be appropriate for evaluating real stiffness of a PTD.

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