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A STUDY ON TRANSMISSION RATIO DISTORTION OF LEVER-TYPE FORCE STANDARD MACHINE USING FINITE ELEMENT METHOD

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Abstract – A study on transmission ratio distortion of 1 MN lever-type force standard machine has been performed using finite element method (FEM). The study involves the determination of deformation that occurs in the arms due to loading calculated using a software-based finite element method. The dimensions of the arms are taken from the manufacturing data. For verification purposes, the transmission ratio distortion resulted from the finite element modeling is compared to the linearity error calculated from results of a series of calibration using load cells as force transfer standards. The finite element simulation results show that the transmission ratio distortion is linear and amounted to approximately 270 ppm at maximum capacity. In addition, the study also concludes that the transmission ratio decreases with increasing forces. These results are in agreement with previous calibration performed by KRISS, Korea and acceptance test results from PTB Germany.

Keywords: transmission ratio distortion, force standard machine, lever-type force standard machine, finite element method, finite element modelling

1. INTRODUCTION

1 MN Lever-type force standard machine at Research Centre for Metrology-Indonesian Institute of Sciences (Puslit Metrologi-LIPI) is used as a reference on calibration of force measuring instruments with measuring range 2 kN - 1 MN. The force standard machine can be seen on Figure 1. Based on the previous calibration, the deviation of force value is up to 300 ppm and the deviation value is different with different loading capacity. Transmission ratio distortion of lever-type force standard machine will affect the value of force. Therefore, it is deemed necessary to study on the transmission ratio distortion to explain the calibration results of the machine and also purpose to reverse engineering.

Fig. 1. 1 MN Lever-Type Force Standard Machine, Puslit Metrologi LIPI, Indonesia

1 MN Lever-type force standard machine uses 5-level of comparisons of the lever arms and has 4 types of transmission ratios of 1: 200, 1: 500, 1: 800 and 1: 1000 [1]. This machine uses comparisons of lever arms to produce high capacity of force, by using input mass *m* produces output force *F* (Figure 2).

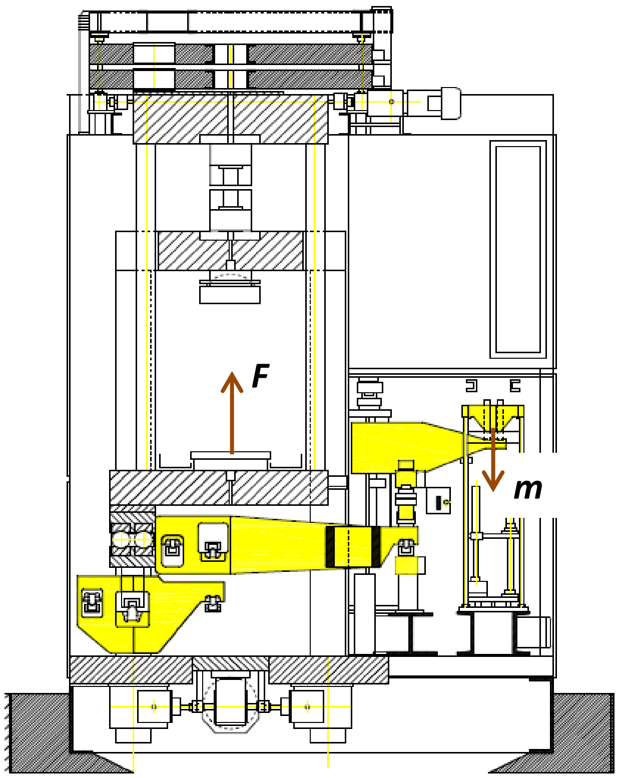

Fig. 2. 1 MN Lever-Type Force Standard Machine, amplification system

2. TRANSMISSION RATIO DISTORTION USING FINITE ELEMENT METHODE

Finite element analysis was performed using ANSYS 13.0 software with static structural analysis. Geometry modeling using CAD software based on manufacturing data and direct measurements. The geometry modeling for all arm of force standard machine can be seen in Fig. 3.

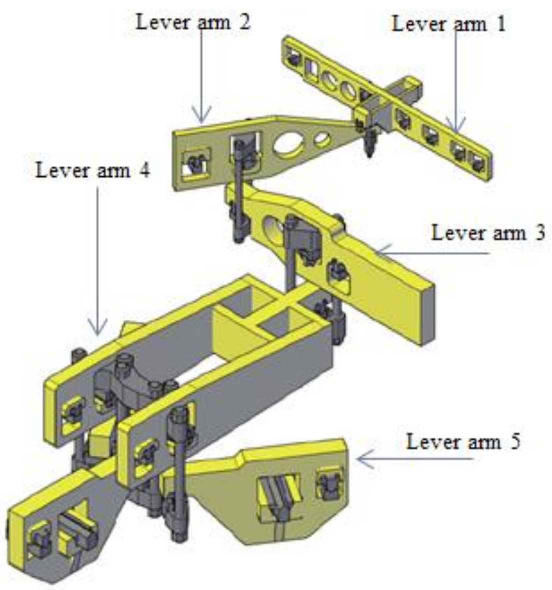

Fig. 3. Geometry modeling of lever system of 1 MN Lever-Type Force Standard Machine

The model geometry used in solid form. The analysis was performed for each lever arms. The material properties are used with modulus elasticity are (200 ± 10) GPa.

The boundary conditions on the input force F is given as a force at the knife-edge, on the support of lever arm using the displacement with direction of X, Y and Z = 0 and on the reaction force use the displacement with direction of the Z = 0, X and Y are free. The boundary condition is at knife-edge on Lever arm 1 see Fig. 4.

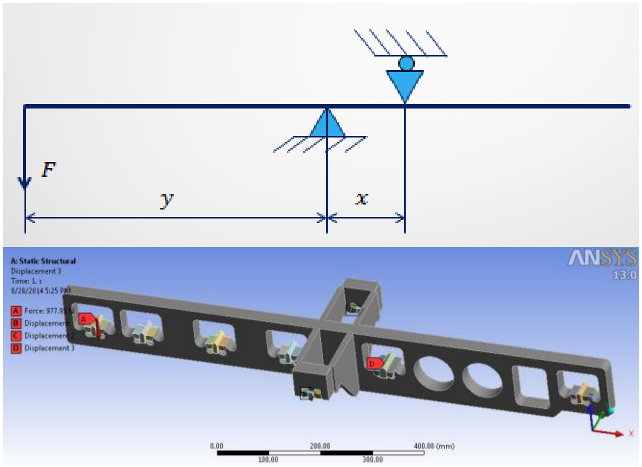

Fig. 4. Boundary condition at the knife-edge on Lever arm 1

The boundary conditions for Lever arm 2, Lever arm 3, Lever arm 4 and Lever arm 5 use the same principle with Lever arm 1. The different is the support position of the lever arm. The boundary condition is at knife-edge on Lever arm 2 see Figure 5.

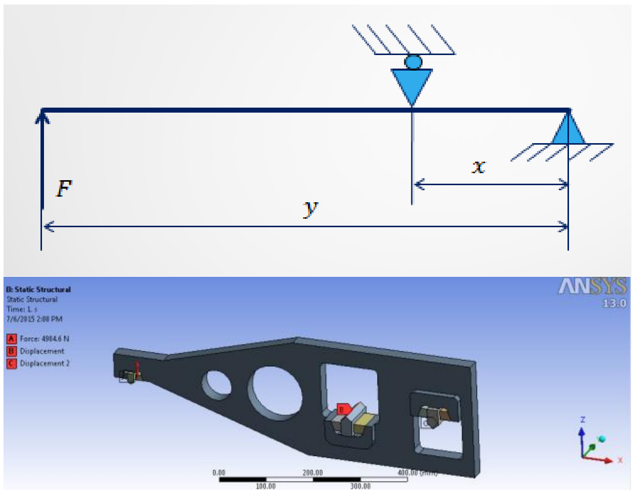

Fig. 5. Boundary condition at the knife-edge on Lever arm 2

The lever arm length directly influences the lever amplification ratio [2]. Therefore, the solution are required from finite element simulation is lever arm deformation in the X-direction (horizontal direction). This deformation results are then used to calculate the transmission ratio distortion of each lever arms. Deformation probe is at a knife edge. The transmission ratio distortion is described as in Fig. 6.

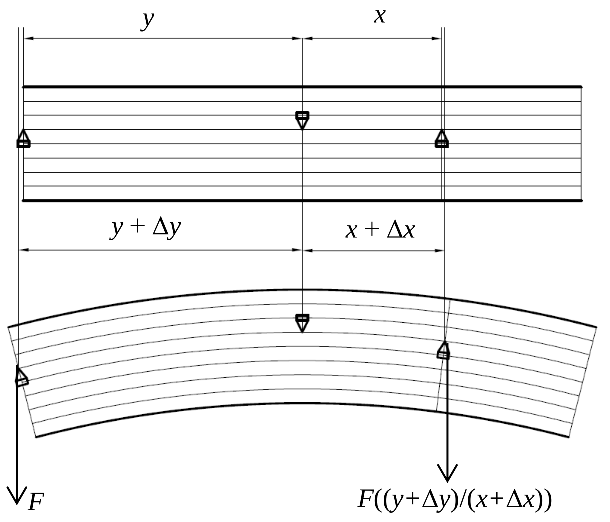

Fig. 6. Transmission ratio distortion on lever arm due to loading

Transmission ratio distortion is determined by the different between the transmission ratio after loading with before loading and calculated using Equation (1) is given as follows:

$$\Delta R_i = \frac{(y_i + \Delta y_i)}{(x_i + \Delta x_i)} - \frac{y_i}{x_i} \qquad (1)$$

With:

ΔR_i = transmission ratio distortion (arm-i)

y_i = long lever arm (arm-i)

x_i = short lever arm (arm-i)

Δy_i = deformation of long lever arm (arm-i)

Δx_i = deformation of short lever arm (arm-i)

By using the Equation (1), it can be determined transmission ratio distortion in Lever arm 1, ΔR_1, Lever arm 2, ΔR_2, Lever arm 3, ΔR_3, Lever arm 4, ΔR_4 and Lever arm 5, ΔR_5.

Total transmission ratio has been calculated by multiplication of the transmission ratio of each lever arms, using Equation (2) as follows:

$$R = R_1 . R_2 . R_3 . R_4 . R_5 \qquad (2)$$

With:

R = Total transmission ratio

Total transmission ratio distortion has been calculated using the propagation error equation, as Equation (3) as follows:

$$\Delta R = \sum_{i=1}^{5} \frac{\partial R}{\partial R_i} \Delta R_i \qquad (3)$$

From the finite element simulation gets information of the deformation in the X-direction (Δx and Δy). The contour of X-deformation is shown in Fig. 7 and Fig.8.

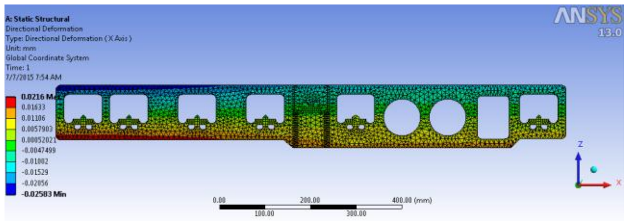

Fig. 7. Contour of deformation in the X-direction on Lever arm 1

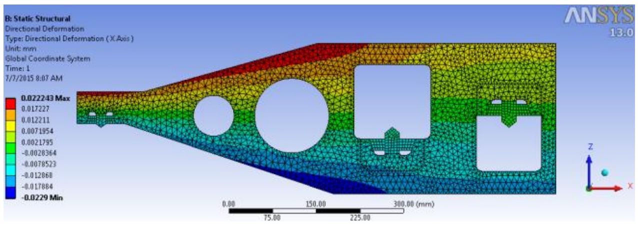

Fig. 8. Contour of deformation in the X-direction on Lever arm 2

From the software information the deformation is on the line at the top of knife-edge. The results of finite element simulation to determine the transmission ratio distortion can be seen in Table 1 below.

Table 1. Transmission ratio distortion at 1 MN force

Lever arm No.	Manufacturing Data		Transmission Ratio R_i	FEM		Transmission Ratio Distortion ΔR_i
	x_i	y_i		Δx_i	Δy_i	
	mm	mm		µm	µm	
1	98.1	500	5.097	3.57	3.30	-0.00015
2	200	700	3.5	5.77	15.5	-2.3E-05
3	170.8	560.8	3.283	5.99	11.3	-4.9E-05
4	200	1160	5.8	32.4	39.1	-0.00074
5	200	600	3	37.1	55.6	-0.00028
		R =	1019.15		ΔR =	-0.27814
					$\Delta R/R$=	-0.00027

3. EXPERIMENTAL VERIFICATION

For verification purposes, the transmission ratio distortion resulted from the finite element modeling is compared to the linearity error calculated from results of a series of calibration using load cells as force transfer standards. The calibration results are come from PTB Germany in 1986 and come from KRISS Korea in 2006. While, in 2014 the calibration by Puslit Metrologi-LIPI using calibrated load cell from PTB. The comparison of linearity error can be seen in Fig. 9.

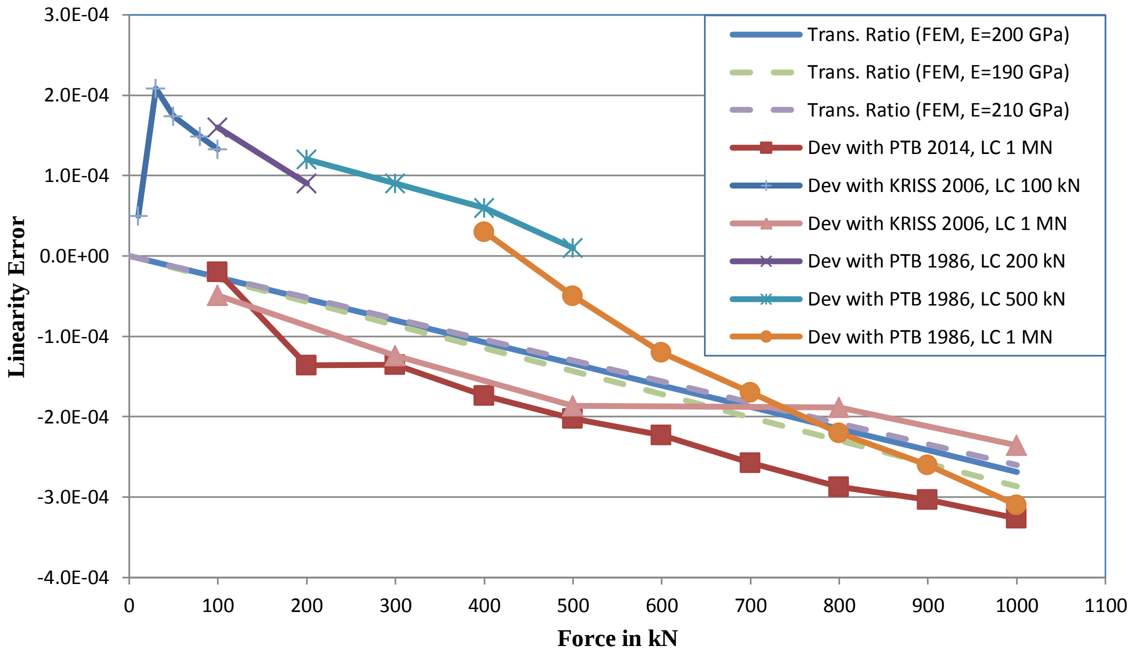

Fig.9. Linearity error of 1 MN Lever-Type Force Standard Machine

In Fig. 9, the transmission ratio distortion from the finite element simulation results is linear from zero to the maximum capacity, with transmission ratio distortion at 1 MN force is about 270 ppm. By using variation of modulus elasticity 190 GPa, 200 GPa and 210 GPa, the variation of the transmission ratio distortion is about 25 ppm at 1 MN force, therefore the mistaken of materials properties of the modulus elasticity ± 10 GPa will have effect to the results transmission ratio distortion about 25 ppm at the maximum capacity.

4. DISCUSSIONS

The simulation results of transmission ratio distortion give information the prediction of force value using finite element method with different loading capacity.

The results of finite element simulation also have similar trend of linearity error with the calibration results. These results indicate that the possibility of finite element simulation can be used to design lever arm of lever-type force standard machine to produce smaller transmission ratio distortion (possibility by performing an optimization of geometry and optimization of knife-edge position in the vertical direction [3]).

5. CONCLUTIONS

The finite element simulation results show that the transmission ratio distortion is linear and amounted to approximately 270 ppm at force value 1 MN and the transmission ratio decreases with increasing forces. These results are in agreement with previous calibration performed by KRISS, Korea and acceptance test results from PTB Germany.

The results linearity error of transmission ratio from finite element simulation is not significantly different when compared with the linearity error force value from calibration result, especially at high capacity. It suggests that the effect of bending the lever arms is the dominant source of the linearity error of this 1 MN lever-type force standard machine.

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