Research Article

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Experimental assessment of the static stiffness of machine parts and structures by changing the magnitude of the hysteresis as a function of loading

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Abstract: Static stiffness is determined by one-sided loading and unloading of machine parts relative to the selected base. For each structure, there will be some loss of potential energy due to the dissipative forces that occur during the loading inside the structure. This loss is manifested in hysteresis in the stiffness diagram. A new approach to the assessment of static stiffness consists in gradual, bilateral loading and unloading of the structure through the effect of static forces of different magnitude. In this process, the stiffness hysteresis varies, depending on the intrinsic nature of the dissipative forces, a specific property suitable for assessing the condition of machines.

Keywords: Static stiffness, laser interferometer, hysteresis

1 Introduction

Nowadays, not much attention is paid to the issue of stiffness. For example, with the production machines, the priority is given to the issue of thermal stability and the issue of component accuracy [1–5]. Of course, the stiffness is also an important property and it is investigated along with damping properties. The issue of machine stiffness comes to the forefront especially when equipment is being developed. Portable stiffness diagnostic devices have not yet been developed. The issue of measuring the static stiffness of machines is dealt with in works [6–8]. There are relatively few research papers on the stiffness measurement methodology. Basic papers in this area deal only with the form of direct loading, and do not evaluate dynamic changes during static measurements [9, 10].

Mathematical processing of experimental data is presented in [11]. The progressiveness of the stiffness trend under dynamic conditions is investigated in the work [12]. The influence of the structure layout on the machine stiffness is discussed in the works [13, 14].

In this paper, the authors focused on examining a new methodology of stiffness measurement or hysteresis of the loading process, which is experimentally verified on a test stand.

2 Experiment layout

The aim of the measurement was to verify the static stiffness of the beam clamped in a mechanical vise. The beam with the vise and the supporting metal structure form one assembly, where different clamping connections were used to ensure stiffness. Each joint determines the resulting stiffness of the system relative to the loading base.

The force applied to the beam was provided by an independent load-bearing system by means of a rope transmission and weights. The size of deflection was measured at the site of load application, using a laser interferometer. The overall measurement stand assembly is shown in Figure 1. The schematic layout of the measurement is shown in Figure 2.
3 Means used

- 100-gram weights were used for application of the force (precision ± 1 gram). The maximum load was 20N (2000 gram).
- A Renishaw XL80 laser interferometer was used to measure deflection. The recording accuracy was 0.1 micrometer.
- The beam to which the load was applied is made of structural steel 180×50×5 (mm)
- Cast Iron Small Bench Vise - revolving mini vise (weight 2.2 kg)

4 Measurement procedure

In contrast to the classical stiffness measurement, where the load is gradually added and subsequently gradually removed, both sides of the beam were alternately loaded in this experiment. After each pair of bidirectional load, the weight was increased by 100 grams. This process continued until the maximum load (2000 g) was reached. 4 values were recorded for each load cycle. Alternately, the left and right sides of the beam were loaded. The residual hysteresis value was recorded after each unloading. Table 1 shows an example of a measurement record.

The measurements were set up in three experiments.

4.1 The first experiment

In the first experiment, both sides of the beam were alternately loaded. The beam was firmly clamped into the vise. The part most affected by loading is the jaw area. The maximum load moment (3.2 Nm) was applied to the 160 mm beam arm. The magnitude of hysteresis was determined by subtracting the residual load value from the maximum value. The load deflection record is shown in Figure 3, with the sides indicated.

The lightweight, no-load condition was not recorded. As seen from the graph (Figure 3) hysteresis increases due to the magnitude of the load force. The maximum hysteresis value is 1.344 mm. Other important information that can be read from the graph are sudden stiff-
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Sudden step changes were caused by the release of dissipative forces on the prestressed contact surfaces. In both cases of the step, the original state was reset after the load change. Static force loading was performed by slowly increasing the load. The effect of dynamic forces and vibrations has been minimized. Nevertheless, there are some instabilities in the prestressed part of the contact surfaces. In this case, however, they were reversible. There are several prestressed contact surfaces on the visé. Due to the nature of the load, the jaw contact surfaces are most stressed. There is probably a slight micro-movement in this section, which is reflected in the graph by a step change.

An interesting factor is the non-linearity of stiffness which, in this case, is of a regressive nature. On devices with a backlash and moving parts, the stiffness change is generally progressive. The level of non-linearity is mathematically and graphically expressed in Figure 4.

Step changes must be omitted to correctly translate the trend curve. A polynomial regression curve was then used. The right side corresponds to the third order polynomial.

\[ y = -52.16x^3 - 96.67x^2 - 71.48x - 0.54 \]  
(1)

The left side has a slight curvature and corresponds to a second order polynomial.

\[ y = -19.69x^2 + 44.05x - 0.11 \]  
(2)

The change in initial stiffness is expressed in Table 2. The percentage change in stiffness can be expressed by the formula (3)

\[ S = \frac{S_A - S_B}{S_A} \times 100 \% \]  
(3)

Table 2: Change of initial stiffness.

| Side | Stiffness [N/m] |
|------|----------------|
| A    | 0.073          |
| B    | 0.019          |
| L    | 0.041          |
| R    | 0.038          |

From the result of the experiment, the relative change in stiffness for the right side is 73%, while the change for the left side is only 5%.

The stiffness asymmetricity is related to dissipative forces that are released to different degrees in different directions. The degree to which the dissipative bonding forces were released is best seen in residual deflection after loading (Figure 5). At points C, a disruption in the deflection process occurs. Initially at low loads, the residual deflection is of the same nature on both sides of the load. At breakpoints, the system becomes unstable. This is also reflected in the deflection measurement, when the values cease to be static and change slowly over time due to the load. The graph shows that the left side is more stable than the right side.

4.2 Second experiment

During the second experiment the measurement conditions did not change. The first experiment was formally repeated except that the system was reset to the last beam load position. At the beginning of the experiment, the beam had considerable residual deflection after the load application to its right side (0.8 mm) which was carried out in the first experiment.

Figure 6 shows an increase in hysteresis. As you can see, a step change on the right side occurred during load-
ing. Since the system had not been in the central position to start with, the same load on the left side also caused a step change, but of an irreversible nature. The system maintained its stiffness unchanged. The step change occurred only on the left side, indicating that different contact surfaces are loaded when the force orientation changes.

The trend of residual deflection after loading is shown in Figure 7. Changes are also visible in this representation. As you can see, deflection values show only positive values. This is due to the initial prestress. The residual deflection step change occurred under the same load as in the first experiment.

### 4.3 Third experiment

In the third experiment, two metal bolsters were added to the vise clamping jaws (Figure 8). Adding bolsters is actually adding a resilient element. It can be assumed that the stiffness, as well as the nature of hysteresis, will change.

Figure 9 shows increase in hysteresis. The graph shows unambiguous changes upon load application to the right side of the beam. First, the stiffness has become linear throughout the loading.

Compared to the first experiment, the stiffness value on the right side decreased (Table 2 and Table 3). The stiffness value on the left side increased by 50%. This figure is only approximate, as the clamping forces were not measured. The stiffness trend on the left side is progressive.

The graph of residual deflection (Figure 10) does not show breakpoints in this case. However, some degree of non-linearity can be observed. At higher loads, the resid-
ual deflection intensively increased, as the static process changed to dynamic. Deflection values did not stabilize during loading. There was a slow increase in deflection. Duration of the load application during the experiment never exceeded five seconds. After that time, the system was unloaded.

5 Conclusion

The main benefit of the results of the stiffness measurement experiments of a complicated structure is to point out the stiffness variability at grip joints. As the experiments show, stiffness may also have a regressive trend under certain conditions. The proposed stiffness and hysteresis measurement methodology provides more comprehensive information about the structure of the devices than does conventional measurement and has general application in machine diagnostics and machinery development. Machine tools can only produce accurately under appropriate stiffness conditions of machine components, including the workpiece. The outlined stiffness measurement study is also important for the assessment of the clamping forces. Strong clamping ensures high rigidity but also causes local undesirable deformations of the workpiece. The new stiffness measurement approach makes it possible to optimize production practice requirements.

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Figure 10: Residual deflection disruption after unloading. Source: Own study.