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Research on Gentle Loosening of Solidified Bolted Joints for Complex Capital Goods

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Abstract

The consideration of sustainability is increasingly becoming a focus in research and production. For example, the recycling process for products that are no longer usable should be optimally prepared by separating materials by type as far as possible. In addition, products should be made usable again by repair or replacement if only sub-components fail. In the case of complex capital goods, like aircraft engines, it is mandatory to preserve the product since damage to the joining partners can lead to immense costs. A decisive factor in this context are assembly connections, which have a major influence on the complexity of disassembly. Concerning this matter, detachable connections, like screwed joints, have many advantages for service, repair and recycling compared with permanent fixing solutions. They can reduce assembly time, simplify maintenance processes, and greatly reduce maintenance time and costs. However, during a product's life cycle, threaded connections can corrode, leading to damage or even failure of the bolted joints. Beyond that, they can solidify and often only be disassembled destructively. In this article, we present an approach to improve the loosening of operational solidified screwed connections. It is well known that vibrations during operation can reduce the preload force of the connections. We exploit this aspect by inducing vibrations through micro impacts to alleviate the loosening torque of the solidified bolted connection. Depending on the direction of the vibration (torsional or axial), that can ensure a gentle and component-friendly disassembly to a greater or lesser extent in contrast to destroying the screw by drilling or shearing and splitting with the risk of damaging the product being maintained. The designed experimental setup with a piezo actuator allows us to investigate the amplitude and frequency of the induced vibrations for the required disassembly force. The results show that our approach enables component-conserving disassembly, as the forces can be significantly reduced.

Keywords: Disassembly; Regeneration; Bolt Connections; Vibration; Solidification

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1. Introduction

Disassembly is necessary for the regeneration of a product and therefore a central element of a sustainable cycle economy [1]. During operational use, the product underlies wear, like physical and thermal stress and corrosion, which changes its properties and characteristics. That leads to an unknown condition and increased disassembly effort with initially detachable joints solidifying and even becoming non-detachable. Therefore, the product should not be subjected to additional and avoidable stress caused by the disassembly process. Thus, manual labor often characterizes disassembly processes as it is possible to adapt tools to the product's condition. Nevertheless, worn parts can often only be taken apart with high effort and oversized tools and forces, which is contrary to a gentle disassembly.

Generally, in terms of sustainability, detachable joints simplify the product's regeneration, since they can easily be removed and replaced. In the subproject, ”Adaptive and Component-friendly Disassembly in the Regeneration Process”, of the Collaborative Research Centre (CRC) 871, ”Regeneration of Complex Capital Goods”, we aim to develop a scientific method for gentle disassembly strategies in maintenance, repair and overhaul (MRO). By this, it becomes possible to reduce parts replacement by reusing regenerated products. The focus of this work are threaded fasteners that, for instance, connect the aircraft engine's main modules. Caused by the aforementioned influences such as thermal stress or corrosion, the joints solidify. That generates the risk of destroying the fasteners during disassembly, causing extensive financial and economic damage to the module or, at worst, making it unusable. We present our research of an approach for a gentle disassembly, using vibrations induced by a piezo stack actua-

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tor to tackle this challenge. That makes it possible to reduce the needed loosening torque and minimize the risk of breaking the fasteners. In addition, we consider the application of this method as a manual or automated disassembly tool.

Section 2 will give a short overview of related work. After the presentation of the methodology and approach for our research in section 3, we will show the first part of our experimental investigation, using design of experiment to plan the investigation and the response surface method to analyze the results in section 4. In section 5 we present the second part of our experiments to show the possibility of vibrations to reduce the loosening torque. The last chapter will present the conclusion and give an outlook for further research.

2. Related work

The design of bolted joints is still a complex engineering task and is supported by guidelines such as VDI 2230 [2]. According to it, a bolted joint is a detachable connection between two or more parts by one or more bolts. In addition, it presents an overview of how to calculate bolted joints. Some of the important parameters discussed in this paper are the tightening torque, which builds the assembly preload. Due to the bolted joint's embedding, it does drop for a certain amount after tightening the bolt. Thus, the loosening torque will be lower than the tightening torque. VDI 2230 also shows that the self-loosening is caused by the neutralization of the bolt's self-locking. The causes are the reduction in the thread coefficient of friction, dynamically acting transverse loads, or dynamically acting moments around the bolt axis. Therefore, bolted joints are designed, so that self-loosening is prevented. However, they also can solidify during operation, as summarized in the following section.

2.1. Disassembly of solidified bolted joints

As detailed above, caused by wear of the product, bolted joints corrode, leading to a solidification of the joint. Therefore, the disassembly of bolted joints depends on their condition and the degree of solidification. To choose the right tool, it is necessary to know if the joint is still detachable or if it has become non-detachable. For detachable bolts, usually, hand tools, like wrenches, are used. Tighter fitting bolts require more loosening torque, applied by electric or pneumatic impact wrenches or impact drivers to loosen the bolts. Depending on the condition of the bolt, these types can be gentle but can also damage the bolt and even the base part's material. Destructive methods are, for example, destroying the screw by drilling, which also removes the bolt. Methods to just open the connection are shearing tools that only remove the bolt's head [1].

Gentle disassembly methods are currently the focus of our research. Shuvaev et al., for example, present a tool for assembly and disassembly of screws as an approach for a gentle disassembly of bolted joints [3]. It uses ultrasonic vibrations, inducing both inverse and torsion vibrations. The inverse vibration interacts directly on the bolt, whereas the torsion vibration is induced to the nut. The tool's resonance frequency is specified as 16,750 Hz, but no other specification is detailed. However, according to the notes from a personal interview with an expert from the disassembly department of an aviation MRO company, ultrasonic waves caused irreversible damage to the parts. These were traced back to an oscillation close to the part's resonance frequency, changing the microstructure of the surface zone. However, the experiment demonstrated that vibrations can ensure gentle disassembly of solidified assembly connections like aircraft engine's turbine blades since dynamic load has been researched to loosen threaded fasteners, described in the next section.

2.2. Self-loosening of bolted joints

Vibrations are known in engineering research and application to loosen threaded fasteners. Junker established in 1969 an essential contribution on the loosening of bolted joints by vibration [4]. This work elaborates that axial dynamic load induced only a partially loosening. In comparison, transverse dynamic load led to a full loosening of the joint. Junker's method is today known as the junker vibration test, standardized as an application for the aerospace sector in [5]. It mechanically measures when a bolted joint loses its preload during transverse vibration. Gong et al. give an overview over various external loads which can result in rotational and non-rotational self-loosening of the bolted joint [6]. Altogether, it can be said that, additionally to junker's results, in different simulations and experimental investigations over the last decades, both loosening and no loosening occurred while inducing axial vibration. However, torsional vibration led to a self-loosening under certain conditions. Jiang et al. showed in their research that loosening by vibration can be divided into two steps [7]. The first step is material deformation, where there is no relative motion between the bolt and the nut, causing a reduction of the preload force. The second step is the rotation of the nut causing a further rapid reduction of the preload force and loosening torque.

The presented research observes the self-loosening caused by vibration during operation. In contrast to e.g. the junker vibration test, we plan to exploit the effects of vibration to support the disassembly of solidified bolted joints. In this work, we investigate a method for a gentle disassembly by inducing focused external vibration to loosen the bolted joint, since the joint's solidification increases the needed loosening torque. Consequently, we research the solidification of aircraft engine's bolted joints and the reduction of disassembly torques. We do not aim at a self-loosening or complete self-disassembly of the joint. Our goal is to weaken the solidified joint to decrease the loosening torque that tools can be used with minimal physical effort for maximal gentle but time-sensitive disassembly.

3. Test preparation and methodical approach

In order to set up the investigation of the reduction of the loosening torque of bolted joints, we designed samples, as seen in Figure 1. The joints consist of two plates, which are screwed

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together by a bolt and a nut. Since we are using metric M8 screws, the needed tightening torque will be 25 Nm, according to a german machinery's handbook [8].

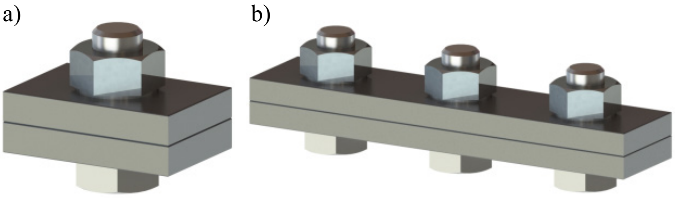

Fig. 1. (a) Single bolted joint, (b) Triple bolted joint.

We will artificially age the bolted joints to reproduce a lifecycle of the product. For this purpose, we will use an accelerated corrosion test method. In this work, we use the salt mist environment, according to DIN EN 60068-1-11:2000-02 [9]. The samples will be kept in the environment at 35 °C for 168 hours. For the post-treatment, we will wash the samples under desalinated water, dry and store them for one-and-a-half hour under ambient conditions before further experimental investigations, according to the standard. The plates are made of mild steel (S235JR) for rapid corrosion. The bolts and nuts are stock engineering screws made of electro-galvanized steel.

The experiments will be executed using our previously designed and developed disassembly test rig [10]. The test rig contains a piezo-stack-actuator connected to a pushing rod which can induce micro impacts with known frequency and amplitude on the bolt. The pushing rod will perform a preload to ensure full and even contact. The loosening torque will be measured using a digital torque wrench, that shows the maximum value for each loosening run. Its measurement tolerance is specified as ±3 %, additional to the potential deviation by manual unscrewing.

As summarized of Gong et al. in several studies, depending on the researcher team and method, both self-loosening and no self-loosening occurred in simulation and experimental investigation [6]. Therefore, we investigate the influence of axial vibration on solidified bolts. We assume that axial vibration cause least damage to the base material, which we need to confirm in future work. Also, the application of axial vibration appears practical for the implementation in a manual or automated disassembly tool. The experimental procedure will be described in the next section.

4. Reduction of the loosening torque by axial vibration

To investigate and analyze the possibility of decreasing the loosening torque of artificially aged bolts by axial vibration, the response surface methodology (RSM) is used. It is an often-used tool to model and optimize original chemical processes and is widely applied for engineering studies. RSM includes several mathematical and statistical techniques to model and analyze a system influenced by independent variables with the objective to optimize the response [11]. The usage includes the experimental design and procedure and a data fitting model followed by the verification of the model using the analysis of variances (ANOVA) [12]. The experimental plan, run order and following evaluation is determined and calculated using the software MATLAB.

4.1. Design of experiments

The design of experiment (DoE) is a reliable technique to detailed plan experimental investigation. It maximizes the amount of information at a given amount of experimental effort and shows the effect of each input individually and their interactions on the output [13]. The face-centered composite design (CCF) is used, since it provides great predictions of linear and also quadratic influential parameters and interaction effects [12]. The output variable will be the loosening torque T in Nm, as the objective is to investigate its reduction. Table 1 shows the inputs and their levels.

Table 1. Levels of influential parameters in CCF.

Factor	-1	0	1
Piezo's amplitude (û), µm	10	55	100
Piezo's frequency (f), Hz	4	31.5	59
Actuation time (t), s	5	12.5	20
piezo's waveform	Sin	Saw	Tri

The piezo's amplitude, frequency, and the actuation time are continuous variables, meaning they can have any value between the higher and lower level. However, the piezo's waveform is a nominal categorical variable, meaning it can only take on its limited values and has no natural order. Therefore, it can't be sorted into levels. Instead, the CCF is repeated for each waveform. The upper limits of the piezo's amplitude and frequency are chosen according to the manufacturer's specifications, whereas the lower limits are set to be practical. The levels of the actuation time are chosen regarding plausible process times for manual disassembly. Too long preparation time would be contrary to an economic process. The mentioned piezo's waveforms in Table 1 are all options that can be selected. To ensure even contact between bolt and piezo-actuator, a preload of 100 N will be applied directly and colinear on the bolt for every run.

4.2. Experimental procedure

We split the experimental investigation in six steps (see Table 2). The first step will be the investigation of new joints. In order to get the condition of a new condition, we assemble single bolts (Figure 1(a)), let them embed and rest, before we loosen them (#1). After the treatment according to the standard detailed in section 3, we loosen the artificially aged joints ”single bolt” as the second step (#2). The result will show the change of the loosening torque caused by accelerated aging. The third step will be the investigation following the CCF-plan using the artificially aged ”single bolts” (#3). After performing the RSM investigation, we use it’s potentional optimized parameters to induce vibration on the first bolt (step #4) of the ”triple bolted joints” (Figure 1(b)). We then measure the loosening torque from left to right, to get the maximum reduction of the torque (steps #5 and #6). Additional, we want to investigate if there is a transmission of the vibration to the adjacent bolts. Table 2 lists the experimental procedure.

Table 2. Experimental Procedure.

Experiment Step	Joint Design	Treatment
#1	Single	Embedded and no vibration
#2	Single	Salt Mist and no vibration
#3	Single	Salt Mist and entire CCF-plan
#4	Triple: 1st Bolt	Salt Mist ($\hat{u}$ = 100 µm, f = 4 Hz, t = 5 s, SAW)
#5	Triple: 2nd Bolt	Salt Mist and transmitted vibration of #4
#6	Triple: 3rd Bolt	Salt Mist and transmitted vibration of #4

4.3. Data fitting and verification

In order to fit the data, an approximation for the relationship between the input (x_k) and response (y) variables must be calculated. Depending on the data, either a first-order model or a polynomial of higher degree must be used for the data fitting [11]. Equation 1 shows an exemplary polynomial containing linear, two-factor interactions and quadratic terms.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \epsilon \qquad (1)$$

The calculation of the polynomial is executed by Matlab. Using only the two-factor interaction, we got the best fitting model. That excludes the term $\sum_{i=1}^{k} \beta_{ii} x_i^2$ from Equation 1. Using the analysis of variance (ANOVA), we can investigate whether to accept or to reject the hypothesis of no differences in mean values (null hypothesis), assuming that the residuals are normally distributed [11]. However, as seen in Table 3, the results p-value is at 0.233 which means the model is not significant. In order to be significant, it must be less than 0.05. The model’s calculated R^2 is 0.29, and the adjusted R^2 is 0.07, indicating a bad fit of the model. A bad fit and non-significant p-value lead into accepting the null hypothesis, stating no difference in mean values, and imply that the model’s prediction is no improvement over using the dependent variable’s mean value. Therefore, the RSM’s model has no predictive power to analyze and optimize the data. Instead, the CCF result is the calculated mean value of μ = 30.9 Nm with a standard deviation of σ = 5.6 Nm, shown as #3 in Figure 2.

Table 3. ANOVA table.

Model	Sum of Squares	df	Mean Square	F	p
Regression	547.612	14	39.115	1.321	0.233
Residual	1332.765	45	29.617		
Total	1880.377	59			

4.4. Results and discussion

Figure 2 shows the loosening torque result’s box plot. Each test was conducted five times, except the RSM consisting of 60 runs in randomized order. We see an increase of 10.9 Nm caused by the rusting when comparing step #2 with #1. Due to the analysis’ result, we summarized the RSM outcome as seen in the box-plot of step #3. It becomes more visible, that the variation is due to noise, when comparing with the box plot of step #2. We see a slight difference of the mean and median values caused by outliers. Since our model doesn’t fit, the calculation of optimal parameters does not lead to a meaningful result. To confirm, we use the calculated pseudo optimal parameters to treat the triple bolt samples. As expected, we do not see a noticeable reduction in the loosening torque when comparing steps #4 and #6 with steps #2 and #3, but a huge outlier at step #5, probably due to error in measurement or unequal artificially aging. Yet, the results are within the Min/Max interval of step #3.

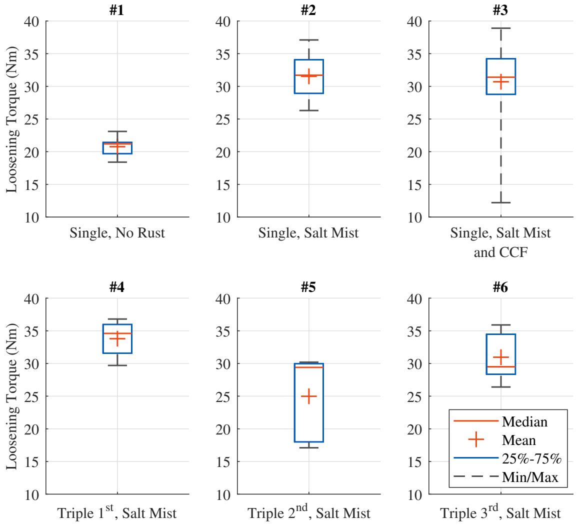

Fig. 2. Box Plot of Loosening Torque: Axial Vibration (see experimental conditions in Table 2).

As a result, we can point out that axial vibration has no recognizable impact on the loosening torque of solidified bolted joints. Therefore, we assume that there is also no reduction of the preload force due to axial vibration, neither by material deformation nor by rotational movement, according to the assumption of loosening in two steps, as detailed in subsection 2.2. Furthermore, we suspect the result’s deviation is dependent on the vast difference of the artificially and accelerated aged bolted joints. Figure 3 shows five samples that were in the salt mist for 168 h (b-f), compared to one that wasn’t (a). There is strongly varying markedness of rust and corrosion. For example, (d) shows only traces of rust, whereas (c) is nearly covered. Sample (b) and (e) have, beyond that, remains of salt, as seen on the white deposit, despite thorough washing after the removal out the salt mist.

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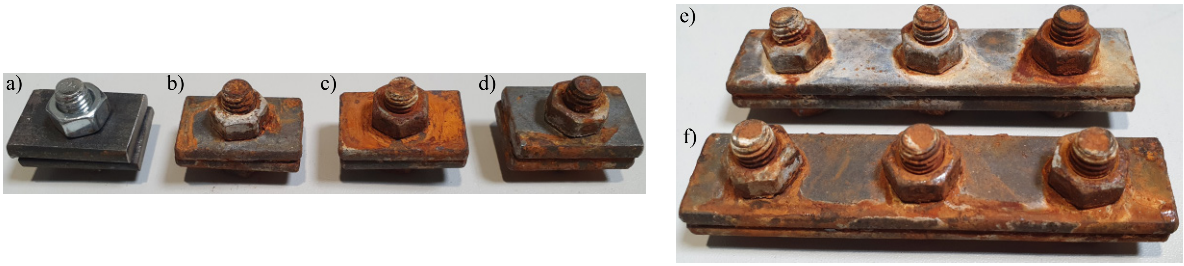

Fig. 3. Bolted Joints: (a) Single, before in salt mist, (b)-(d) Single, after 168 h in salt mist, (e)-(f) triple, after 168 h in salt mist.

5. Reduction of the loosening torque by torsional vibration

Based on the results of Gong et al., we expand our investigation on reducing the loosening torque by vibration to torsional vibration [6]. We assume that this method will also be suitable for loosening solidified joints. Although, implementation in a manual or automatic disassembly tool will be more challenging. For the experiments, we induce torsional force on the nut. In its current stage, the disassembly test rig is not capable in its current condition of testing the samples of Figure 1 by torsional vibration. We adapt the disassembly test rig that we can exert the loosening moment through a lever (Figure 4). Since a modification of the rest rig is not possible at the current stage of the project, we use slightly modified samples without salt mist treatment. However, the fasteners have been in the salt mist for 168 h, but tightened before each run. Hence, we will address the investigation on solidified bolted joints in future research. Nevertheless, the adaption of samples will not affect the experimental results since we want to investigate feasibility. In addition, the artificially aging process lacks reproducibility that no qualitative evaluation is possible.

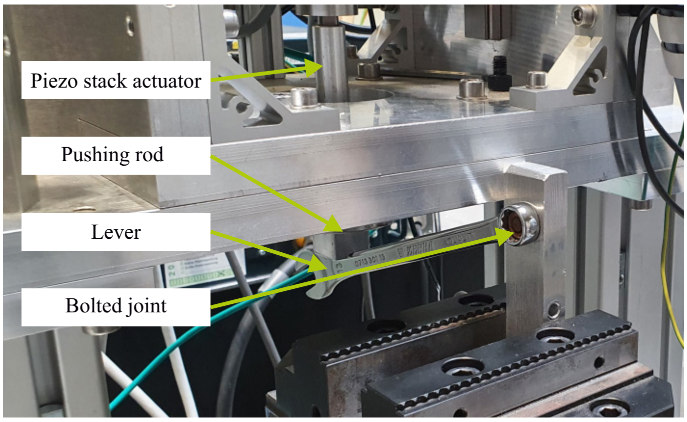

Fig. 4. Test rig adjustment for torsional vibration.

The test rig moves the nut with a constant speed of 0.0086 rad/s, measuring the force with a load cell. The experiment was conducted on two days with five runs each without and with superimposed vibration. The piezo parameters were û = 100 µm, f = 59 Hz and triangle waveform. Figure 5 shows the box plots of the loosening moment's maximum values by multiplying the maximum forces by the lever arm's length for without and with piezo vibrations.

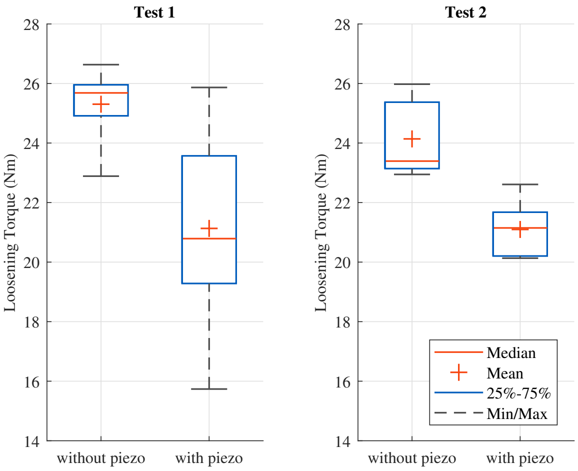

Fig. 5. Box Plot of Loosening Torque: Torsional Vibration at 59 Hz without pretreatment.

Assessing the results of the first test, the runs without vibration show low deviation, except for one outlier downwards. Also the mean and median values are very close to each other. However, the difference between the maximum values, when using vibration, varies strongly. Still, the mean and median values are close to each other, despite the outliers down and up. After a repetition of the experiments for the second test, the trend was almost the same, yet they show less deviation. The range of outliers has become less, the mean values of the samples without vibrations have decreased, but the mean values of the samples with vibrations are nearly identical. The average reduction is 12.6 % for the first test, and 16.4 % for the second one.

In further experiments, we also considered a pre-treatment. Similar to the axial investigation, we set up a preload moment of 1.6 Nm on the nut. While the moment is applied, we switch on the piezo actuator for 5 s. The piezo parameters were û = 100 µm, f = 59 Hz and triangle waveform. After the pretreatment, we increase the frequency to 100 Hz but still with the same constant speed of 0.0086 rad/s. In contrast to the 59 Hz, the increased frequency can only be set for a short interval without damaging the piezo stack actuator. Figure 6 shows the results, comparing the loosening torque's maximum values. For

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comparison, we split the experiment in thirds: tests without any vibration (none), test with superimposed vibration at 100 Hz (piezo) and, as described above, pre-treatment and superimposed vibration at 100 Hz (pretreatment), five repetitions each. As a result, we see that increasing the frequency causes a reduction of the loosening torque by 13.6 % and is in between the previous tests. With an pre-treatment the reduction raises to 26.6 %.

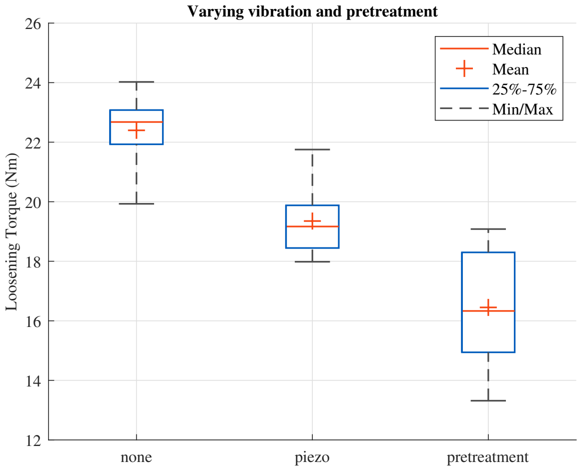

Fig. 6. Box Plot of Loosening Torque: Torsional Vibration at 100 Hz and pretreatment.

6. Conclusion and outlook

In terms of sustainability, the disassembly of products into their individual parts for reuse after overhaul or recycling, plays an important role. Threaded fasteners are ideal for this purpose, due to their interchangeability, easy installation and disassembly [6]. If disassembled as gently as possible, products can be restored with minimal repair effort, and the remaining service life is not prematurely terminated. That is particularly important for complex capital goods, where there is a high financial loss in addition to the environmental loss. However, if these joints solidify, the effort required for disassembly demands an even gentler process when process forces increase. In order to enable a gentle disassembly, we investigated methods that allow minimization of the loosening torque using vibration. For this purpose we used a piezo stack actuator, which can apply vibrations with a frequency up to 59 Hz for long-term use and up to 100 Hz for short-term use.

In summary, we have shown that vibrations can be used to reduce the loosening torque. Although axial vibrations did not prove to be effective, the result was more successful with torsional vibrations. In our first experiments using superimposed torsional vibration, the loosening torque could be reduced on an average of 12.6 % to 16.4 %. Further experiments using torsional vibration with a preload of about 1.2 Nm showed a vast decrease of the loosening torque just by inducing vibration without a simultaneous movement. After a pre-treatment and increasing of the frequency, the loosening torque was reduced by 26.6 %. We assume that these procedures and induced vibration will cause the least damage to the base material. However, we need to confirm our assumption in future investigations. For this purpose, we plan a more detailed examination of the condition of a solidified joint, including material scientific studies. Also, we must perform further RSM analysis with artificially aged samples for torsional vibration to obtain the optimal parameters.

Although axial vibration to loosen solidified bolted joints was not promising for time-sensitive disassembly tasks, it might be usable for tasks unaffected by time. Junker summarized in his work that a loosening by axial vibration was recorded with a higher number of cycles [4]. However, experiments with torsional vibration show a reduction of loosening torques. With that, researchers can use the results to develop strategies and tools for gentle disassembly. Nevertheless, future work will have to elaborate on the aspect of component protection.

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