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Design of a piezo-actuated disassembly tool for seized threaded fastenersRichard Blümel^{a,*}, Lars Aschermann^b, Lukas Lachmayer^a, Annika Raatz^a*a Institute of Assembly Technology and Robotics, Leibniz University Hannover, An der Universität 2, 30823 Garbsen, Germany**b MTU Maintenance Hannover GmbH, Münchner Straße 31, 30855 Langenhagen, Germany*** Corresponding author. Tel.: +49-511-762-18248. E-mail address: bluemel@match.uni-hannover.de***Abstract**

Disassembly is the first and thus crucial step in remanufacturing, maintaining and repairing products. Due to varying product conditions, disassembly requires manual tools. An example of this is the loosening of threaded fasteners used in aircraft engines. These fasteners, connecting its parts, seize during the usage, i.e., the harsh thermal and mechanical conditions to an unknown extend. Inappropriate loosening strategies can cause these to break off, leading to further unplanned tasks, wasting time, labor and capital. In this article, we present a piezo-actuated hand-held tool which enables an adaptable and non-destructive disassembly of seized threaded fasteners. Monitoring the actual torque during disassembly ensures that material limits are maintained. Based on the measured torque, vibrations are actively applied to the bolted joint, adapted to the joint's condition. The use of multivariate vibrations breaks up seizure and reduces friction during unscrewing. This prevents damage, such as screws breaking off, saving valuable resources such as materials and labor time. This article outlines the developed design and control of the handheld vibration assisted disassembly tool.

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1. Introduction

The disassembly of aircraft engines is a complex task that requires specific expertise, thoroughly planned processes, and the use of specialized tools. The complexity of the disassembly task is further increased by the stringent safety controls, legal requirements, and quality requirements of the aviation industry. A flawless disassembly process is critical, as even the slightest deviation can have a lasting impact on the integrity and reliability of engine components.

For regular, extensive checks, inspections and repairs, aircraft engines are brought into maintenance, repair and overhaul (MRO) shops [1]. Following an initial pre-assessment and planning of the necessary procedures, the engines are disassembled before being passed on for subsequent assessment, repair and reassembly steps. As with any disassembly operation, aircraft disassembly is characterized by

uncertainty and unknown product conditions [2]. In addition, disassembly procedures may differ depending on the manufacturer, type, model or age of the engine. Although the task may be similar, each process is performed individually. For this reason, aircraft engines are often disassembled manually in order to adapt to individual conditions.

Aircraft engines are exposed to harsh environmental conditions, especially in the hot gas area of the engine, combustion chamber and turbine. These conditions expose the components to extreme stress resulting in significant wear over time. This article focuses specifically on threaded fasteners in the engine's hot gas section, e.g., to secure turbine blades. A variety of factors can lead to seizure of fasteners, making disassembly challenging. On the one hand, factors that can influence and vary the condition of the joint are known prior to the disassembly, like flight hours, cycles; or hours since last shop visit. On the other hand, the engines are exposed to

influences that are not known and their impact on seizure during disassembly, such as sodium substances in sea salt when flying over oceans [3], volcanic ashes [4] as part of the intake air or combustion residues. In Fig. 1 typical debris on the parts in an engine's hot section is shown. Although the aim is non-destructive disassembly, even with the utmost care, damage can occur, which can result in broken bolts leading to longer repair times or the need for spare parts.



Fig. 1 Hot gas section of a PT6A-65AG engine [5]

Based on our previous work, this article presents the design and the development of a novel handheld disassembly tool to aid in the disassembly of seized bolted joints. By using vibration and taking advantage of self-loosening effects, loosening torques of bolted joints are reduced to enable damage-free disassembly.

Section 2 provides a brief overview of related work and tools in the field of disassembly. In Section 3, initial design considerations are discussed, followed by derived technical implementation and realization in Section 4. In Section 5, a functional model of the tool in the actual state is described. A conclusion and outlook for future work is given in Section 6.

2. Related work

As introduced, the disassembly of threaded fasteners, such as bolted joints, is characterized by complexities. In order to withstand the stresses of flight operation, aircraft engine's threaded fasteners are made of, e.g., nickel-based alloys, which offer high resistance to creep or corrosion, but are characterized by a high coefficient of friction [6]. Due to the high coefficient of friction, the engine's operation and resulting wear, the joints seize or solidify resulting in increased loosening torques during disassembly. Despite greatest care when unscrewing, damage may occur, which can result in broken bolts requiring subsequent rework.

As detailed in previous work, the present state of the assembly and disassembly of aircraft engine threaded fasteners follows strict specifications in the manuals of engine manufacturers. In order to prevent seizure, special thread coatings, such as graphite or silver, are applied [6]. Nevertheless, seizure in the joint occurs. For disassembly, only

tools approved by manufacturers are allowed, e.g., long-lever breaker bars. Also, the procedures are defined incrementally. Before the unscrewing attempt, the threaded fasteners are treated with penetrating oils and left sit to penetrate for a predetermined period. Subsequently, technicians perform the unscrewing, using their comprehensive training and experience to adaptively loosen the bolts. However, bolts can be stuck that they are damaged unpredictably or can only be removed destructively.

In order to achieve a non-destructive and damage-free disassembly, a concept for a disassembly tool was developed in previous work [7]. It utilized the effect of vibration to loosen threaded fasteners by decreasing the preload force and torque. As known from the literature, threaded fasteners self-loosen under vibration [8]. The effect of self-loosening of bolted connections due to vibrations is related to friction. Littmann et al. demonstrated a reduction of friction, when superimposing vibration on a movement [9]. The effect of vibration on bolted joints was also described in Junker's research. In particular, radial vibration reduces the clamp load of the bolt and can lead to self-loosening [10].

Similar approaches using vibration to assist disassembly were developed by Shuvaev et al. [11] and Ward et al. [12]. The developed tool of Shuvaev et al. utilizes axial and torsional ultrasonic vibration, to assist assembly and disassembly by reducing the coefficient of friction. Ward et al. also utilize an ultrasonic oscillating actuator, to assist the assembly and disassembly of stuck threaded fasteners. However, in consultation with MRO experts, externally induced ultrasonic vibration may not be feasible on some threaded fasteners in aircraft engines. In certain instances, bolts installed in the aircraft engine are reused for a second flight interval, extending their operational lifespan until the next scheduled service interval. According to MRO experts, these screw connections must not be disassembled with vibration at high frequencies or ultrasonic vibration, as they would no longer be approved for flight operations. Consequently, the disassembly process would no longer be damage-free. In addition, the two aforementioned approaches lack the ability to lower the frequency. Also, they do not individually adapt to the disassembly task and the actual condition of the joint by assessing the intensity of the vibration.

Recently, a US company has developed and launched a similar method that utilizes ultrasonic impacts to lower the breakaway torque needed for disassembly [14]. The company asserts that their tool cuts the required breakaway torque by half. Nonetheless, concerns have been raised by MRO experts during interviews regarding the use of ultrasonics, as aforementioned.

The developed design in this work aims to amend on previous designs by focusing on two main considerations, in order to remain as damage-free as possible: First, the individual condition of the joint must be observed by monitoring the loosening torque. Second, vibration must be induced only as much as necessary, but as little as possible. For this purpose, the following section summarizes the developed concept and initial design considerations.

3. Initial design considerations

For the design of the disassembly tool, the main task and subfunctions were defined. In accordance to previous work, the main task of the disassembly tool is to gently and damage-free disassemble seized threaded fasteners [7]. As described in the previous section, seized and solidified bolted joints impede the disassembly. To prevent the damage of broken bolts, it is essential to adhere to the maximum torque specifications without exceeding the material limits. Therefore, the maximum torque of the bolt must be known and the actual torque during the disassembly process observed. The measured value of the torque can be used to infer different disassembly processes, i.e., the screw being turned or not being turned, as presented by Apley et al. [13]. Thus, the first subfunction is the observation of the actual torque.

In order to break up any seizure and further reduce the loosening torque below the maximum torque, external vibrations are utilized. In preliminary and ongoing experiments, the influence of vibration setting parameters on the loosening torque is investigated. According to Gong et al. [15], different directions for the externally induced vibration are examined: axial and radial to the bolt axis, and torsional around the bolt axis. For each direction, amplitude, frequency and waveform is investigated. The results so far show that increasing amplitude and frequency decreases the loosening torque needed to unfasten the bolt. Also, using a triangle waveform seemed to be more effective in decreasing the loosening torque than using a sawtooth or a sine wave. Concerning the direction of vibration, radial vibration shows better results in reducing the loosening torque than torsional or axial vibration, with torsional and axial vibration being almost equal. Thus, the second subfunction is the induction of vibration, to allow a reduction of friction and seizure effects and to support the disassembly.

A tool control is required to integrate the subfunctions into the main task. The control monitors the actual torque and adjusts the vibration accordingly to reduce the loosening torque. It is placed in an external housing so that the disassembly tool can be used as a hand tool. The hand tool will be designed similar to a wrench. A more detailed description of the subfunction's combination and the technical realization is given in the following section.

4. Technical realization

The disassembly tool consists of the main wrench body and an electrical cabinet containing the tool control, shown in Fig. 2. As described in the previous section, the tool's function is divided into the following subfunctions: Measurement of the actual torque, inducing of vibration to reduce the loosening torque. To combine these subfunctions, a central data processing by the tool control is implemented for choosing optimized process parameters. The subfunctions torque measurement and vibration actuation are part of the wrench body, while the central data processing takes part in an electric cabinet. A cable connects the hand-held wrench with the electric cabinet. The following subsections describe the setup of the individual subfunctions.

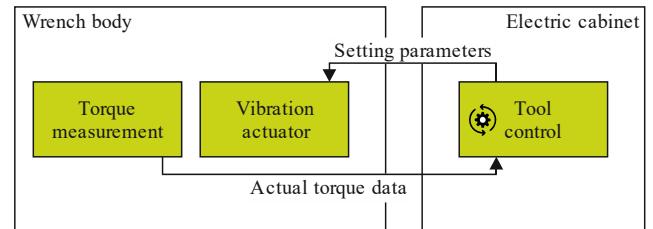


Fig. 2 The disassembly tool's subfunctions

With the subfunctions defined, the next sections illustrate the design and development of the subfunctions torque measurement, induction of vibration and tool control.

4.1. Torque measurement

As aforementioned, the intention and purpose of the designed disassembly tool is to achieve non-destructive disassembly. Threaded fasteners like bolted joints are damaged, when torques are exceeding the material's stress limits, resulting in, e.g., torn off screw heads. In order to prevent damage, the torque applied to the connection by the wrench must be measured and monitored. A simple and reliable method for torque measurement is the use of strain gauges. Mounted on a shaft under torque, its torsional deformation can be detected and converted into a measurement of the applied torque.

The investigations concluded that two strain gauges, each positioned at 45° to the shaft axis and at 90° to each other are able to detect the applied torque with sufficient accuracy. Configured in a Wheatstone half-bridge ensuring temperature compensation, the measured values are calibrated to a torque value.

4.2. Induction of vibration

For the induction of vibration into the bolted connection, piezo actuators are used. Using the inverse piezoelectric effect, a voltage applied to the crystal leads to a change in length [16]. Due to its fast response behavior, the change in length is highly dynamic. They have demonstrated their reliability for use in disassembly tasks. Additionally, their compact dimensions allow for integration into a hand-guided tool.

In order to select the appropriate actuator size, it was necessary to consider a number of key factors related to the disassembly process, in addition to the findings of previous research. It was observed that as the frequency of the vibration increased, the performance in reducing the loosening torque improved. However, as described in Section 2, high-frequency settings, even extending into the ultrasonic range, can have a significant impact on the bolts, excluding ultrasonic vibration for external induction. Since increasing amplitude also improves the performance in decreasing the loosening torque, it can be used to balance the overall performance. Nevertheless, further investigation is required to determine the impact of vibration amplitude on material integrity. However, the selection of the maximum amplitude is also constrained by the specified frequency, as the amplitude cannot be traveled at a rapid pace. In order to resolve the conflict of objectives, an

actuator with the following specifications was selected: a maximum amplitude of 90 μm and a maximum frequency of 800 – 1,000 Hz. Two actuators were selected to induce vibrations to the bolted joint in both the axial and radial directions. The actual vibration's parameters are selected by the tool control, which is described in the following section.

4.3. Tool control

As indicated in Fig. 2, the tool control receives the sensor data from the strain gauges and controls the vibration actuation. The preliminary tests were conducted to ascertain the relationship between the loosening torque (M_L) of a bolted joint and its potentially influencing parameters, including amplitude (A_v), frequency (f_v), waveform (wf_v), and direction of vibration (d_v). The results allowed the formulation of a mathematical model that allows us to describe the relationship, as illustrated by the following Eq. 1:

$$M_L = f(A_v, f_v, wf_v, d_v) \quad (1)$$

In the process of disassembling bolted joints, parameters from flight characteristics, such as flight hours or engine type, are also taken into account as influential parameters. Therefore, further studies were performed to artificially age the connection using a salt mist environment, since no experiments can be performed on engine parts that are authorized for flight operation. The use of artificial data as a substitution of real flight characteristics allows for the identification of their influence. The deduction to the substitute data and integration of real flight and engine data is planned for future studies.

To integrate the results from the experimental studies into the tool control, they were used to teach a learning model. When disassembling a certain bolted joint, process data needs to be entered into the learning model, like bolt type or size. Based on previously specified values as well as experiments, the learning model limits the maximum torque that can be applied to avoid the bolt breakage. By entering flight characteristics, the learning model calculates and predicts an expectable breakaway torque to initially loosen the joint. Utilizing the estimated breakaway torque, the learning model inverses the mathematical model of vibration parameters that influence the torque and sets optimized parameters with the objective of achieving a breakaway torque that is smaller than the maximum torque that can be applied. During the actual disassembly process, i.e., when the worker uses the wrench and applies the torque to unfasten the bolt, the measured value of the actual torque is used, to actively adapt the vibration parameters. This ensures that the bolt's maximum torque threshold is not exceeded, both during the initial breakaway torque and the subsequent unscrewing.

In order to process and calculate the torque from the data of the strain gauge and to move and control the vibration actuators, a programmable logic controller (PLC) with an integrated industrial PC (IPC) from *Beckhoff Automation* is used as the central processing unit. It allows the output signals for the actuators to be generated and the analog signal from the strain gauges to be detected and converted into the corresponding torque value. The learning model has been

implemented in a *Python* program, which is run directly on the IPC. On a touch display, a graphic user interface (GUI) shows the currently measured torque. Additionally, data related to the disassembly process, including flight characteristics, engine and bolt specifications, can be input. Furthermore, the option to enable or disable vibration support can be selected. An LED indicator and a switch are attached to the wrench body. The button can be used to enable and disable the functionality in the same way as the GUI button. The LED indicator in a stoplight arrangement signals the torque status. It is divided into green, yellow and red and indicates the range from the actual measured torque to the maximum loosening torque. The exact values will be determined in future test series.

Compared to other existing tools, the presented disassembly tool's torque measurement during unscrewing offers a decisive advantage. Since the torque is actively monitored during the loosening process, the effect of vibration on the loosening torque can be directly registered. During the loosening attempt, as the effect is registered, the change or decrease in the actual torque can be assessed and actively readjusted if insufficient. By actively adjusting the vibration parameters as a function of the measured torque and the offset from the maximum torque that can be applied, it is possible not only to respond to uncertainties and variations caused by different degrees of seizure. The system can also respond to and disassemble different types or sizes of bolted joints. The mounting for exchangeable bit sockets, as described in the previously developed concept [7], allows the tool to be quickly retooled for further threaded fasteners. Following the technical details, the functional model of the tool is presented in the next section.

5. Functional model

Once the technical concept and realization was determined, the design concept was developed with consideration of the predefined requirements list [7]. A housing is designed to accommodate the shaft for torque measurement, the piezo actuators, and other electrical components such as the push-button and LED indicator (Fig. 3). The radial actuator is located in the housing along the direction of the lever arm, which is extended to a total length of approximately 470 mm. The second actuator for inducing the axial vibration is aligned axially with the shaft, protruding from the housing. To mount and secure the axial actuator, a second housing part housing is added to act as a second handle. As a result, the tool can be operated manually and has a long lever arm for applying torque. The lever arm is screwable and therefore interchangeable, allowing the length to be varied. The second axial handle can be used as a guide for more comfortable positioning of the tool on the bolted joint. Both handles are encased in a soft material to provide vibration damping. A return spring opposite the radial piezo actuator ensures contact with the actuator. Contact with the axial piezo actuator is ensured by the weight of the tool itself when placing the tool bit on the screw to be loosened during disassembly. To demonstrate the prototypical implementation of tool bit interchangeability, three 1/4" sockets were machined and fitted with an external thread to be screwed into the torque measuring shaft. In the following, the 3D CAD model, the functional build

and the tool control using a graphical user interface (GUI) is detailed.

5.1. 3D model of the disassembly tool

An isometric view and a sectional view of the design concept created in SolidWorks is illustrated in Fig. 3. The main functional parts are highlighted: 1) LED indicator, 2) switch for enabling or disabling the wrench and vibration support, 3) secondary handle, 4) main handle, 5) piezo actuator for axial vibration, 6) return spring for radial vibration, 7) interchangeable threaded socket, 8) shaft with mounted strain gauges and 9) piezo actuator for radial vibration. The internal electrical wiring has been excluded for the sketch, only the connection to the electrical cabinet has been indicated.

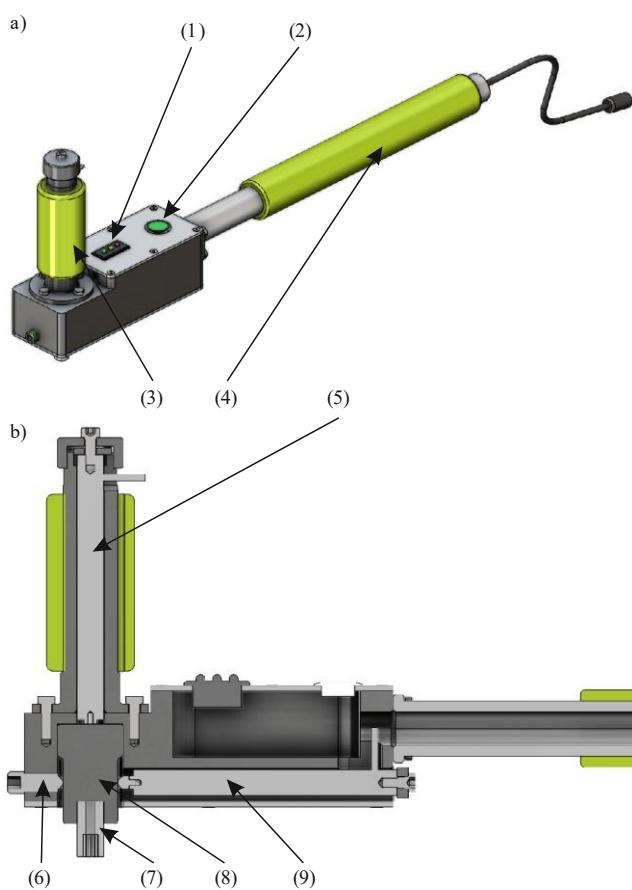


Fig. 3 SolidWorks design of the functional model: a) Isometric view, b) Sectional view

5.2. Functional build

Fig. 4 shows the functional build of the developed tool. Some parts, such as the cover caps of the main body, are currently 3D printed, as the final position of, e.g., the switch is not yet finalized. Furthermore, the control cables of the piezo actuators are currently being routed outside the wrench body to enable changes to the actuators during the test phase.



Fig. 4 Functional build of the disassembly tool

For the tool control a GUI is developed, as shown in the next section.

5.3. Graphical user interface for tool control

In order to control the tool, disassembly task data needs to be specified for the tool control to work. The worker can choose the type of screw, which is to be disassembled. Thereby, the value of the maximum torque that can be applied is taken from the database and shown in the GUI. In the next textbox, the operator is shown the currently measured applied torque, which is also used to control the LED indicator. Buttons on the display are provided for activating and deactivating the tool and thus for switching the vibration on and off. The right side shows the parameters selected by the tool control. The initial version of the GUI is shown in Fig. 5. However, further work is necessary to develop its application, like further testing and training of the tool control. The next chapter provides a conclusion and outlook for future work.

Piezo actuators control	
Torque	Current parameters
Skrew type Skrew 2 (20Nm)	Signal type axial: Triangle waveform
UPDATE SCREW TYPE	Frequency axial: 43.83
max_torque 20	Amplitude axial: 52.23
Current torque: 17	Signal type radial: Sine waveform
START	Amplitude radial: 43.52
STOP	Frequency radial: 40.16
	Error: -

Fig. 5 Example GUI for tool setup

6. Conclusion and future work

In this article, a design of a piezo-actuated disassembly tool to damage-free disassemble seized threaded fasteners was presented. A torque measurement option allows the disassembly progress to be monitored. The active vibration control takes advantage of the self-loosening effect of threaded fasteners, using vibration to break seizure and allow damage-free disassembly.

As aforementioned, substitute data obtained on a test rig was used to train the tool control model, to calculate and estimate the optimized vibration setting parameters. Using the finalized functional build, unscrewing experiments will be performed in future work, in order to obtain data for training the tool control.

Future work must also include an investigation and assessment of ergonomics. In particular, the effects of vibrations on the human body, such as wrists, arms or body joints, must be investigated. Xu et al. conducted experiments and research to study the behavior of impact wrenches and the effects of vibration on the human arm [17]. They used a setup consisting of two accelerometers attached to the wrist and elbow and an accelerometer attached to the tool handle to record the transmitted vibrations. In order to comply with ergonomic limits and ensure the health of workers, a similar study must be carried out with the tool presented in this article. The effects on the human body and the limits of vibrations are also defined in relevant ISO standards, which will be consulted in the evaluation. Furthermore, approaches to minimize vibrations should be integrated into the concept. In their work, Ehlers et al. present a design and guidelines to significantly reduce vibration using particle damping, leaving unmelted powder inside an additive manufactured beam [18, 19]. This method might, for example, be refined and implemented into the handle of the wrench in order to reduce vibration amplitudes on the operator's wrist and elbow.

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