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ACTIVE WASHER FOR SMART MECHANICAL LINKAGE

CHRISTIAN BELLY*, ADRIEN GUIGNABERT, AURELIEN RIQUER, GAËL CHEVALLIER†, PAULINE BUTAUD, GAËL MATTEN AND NICOLAS PEYRET∞

* Cedrat Technologies
59 Chemin du Vieux Chêne 38246 Meylan Cedex, France
e-mail: {christian.belly}{adrien.guignabert}{aurelien.riquer}@cedrat-tec.com, web page: http://www.cedrat-technologies.com

† FEMTO-ST Institute, Applied Mechanics Dpt.
Université de Bourgogne Franche-Comté 25000 Besançon, France
e-mail: {gael.chevallier}{pauline.butaud}{gael.matten}@femto-st.fr

∞ Laboratoire QUARTZ - SUPMECA – EA7393
3 rue Fernand Hainaut 93407 Saint-Ouen Cedex – France
e-mail: nicolas.peyret@supmeca.fr

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Abstract. Bolted connection is the most common way to assemble mechanism. It is widely used in transport domains, such as aerospace, rail, aircrafts… Ensuring that the minimum torque value is always present in the assembly is one of the main maintenance tasks for those components. A possible way to carry out those actions is to implement active component in the bolted assembly. A solution is proposed in this document. Construction, potentialities, performances (based on lap-joint demonstrator) and limitations are identified and confronted to other techniques.

1 INTRODUCTION

Control of the tightening tension in critical bolted connections (rotor - blade or undercarriage - hub - wheel links, gearbox, motor group ...) is a niche market but is a real need for maintenance, which essentially consists in ensuring that the minimum torque value is always present in the assembly. Without this maintenance, carried out at regular intervals, the risks are significant for structures (fatigue, corrosion and crack occurrence). For example, maintenance operations for torque verification on a helicopter requires up to sixty hours every 1000 flight hours (400 concerned linkages). Moreover, several theoretical works have been performed in order to improve the vibration damping by semi-active control of the tightening load [1][2][3].

Uncertainties and dynamic problems of bolted joints are widely treated in the literature [4]. Farther than detecting and monitoring the screw tension [5], the present paper proposes to counteract the preload loose using active components placed either under screw head or nut. This active washer component allows targeting several techniques, such as:

- Keeping constant preload within bolted assembly and make it stable through time,
- Act on linkage damping of mechanical linkage due to dry friction and/or as a complement to damping elastomer,

- Low frequencies protocol for structural decoupling.

The paper is composed of four parts. Firstly, for helping the reader to identify awaited benefits, the interest of actively controlled bolted assembly tension is shown. Secondly, a configurations trade-off is detailed, allowing catching advantages and intrinsic limitations of several concepts. Thirdly, experimental results are given on a single active washer and also on a lab user case, in order to compare with uncontrolled behaviour. Different techniques as described previously are considered in this experimental part. Finally, application fields and potentialities are pointed out introducing real user cases.

2 ABOUT THE INTEREST TO CONTROL BOLT TENSION

From Festjens H. [7] work, it has been shown that both the natural frequency and the damping ratio depends on the clamping torque and the vibration amplitude, see Figure 1. According to vibration amplitudes, the natural frequency is decreasing whereas the damping increases up to a maximum reached near the total sliding threshold and decreases after this limit. The clamping torque allows to tune these evolutions making the threshold shifting.

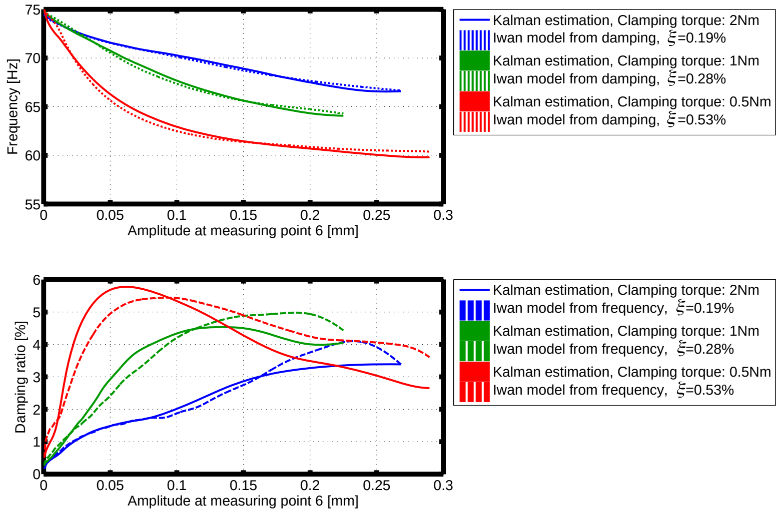

Figure 1: Natural frequency and Damping ratio according to several clamping torque and vibration amplitudes [7]

This result brings out the opportunity to adapt the value of the natural frequencies and the amplitude of the damping. In order to get interesting vibration control performances, our goal is to tune the natural frequency in order to prevent resonances. This idea is inspired from the work of Guyomar et al. [8] on the continuous switching of a piezoelectric device. Here the switching can occur between two extreme tightening torques in order to modify the resonance frequency continuously, see [3] for more explanations.

3 CONFIGURATIONS OF ACTIVE WASHER

The proposed technique is to integrate piezo active material in the bolted assembly. This leads to a few control strategies. Firstly, as long as the tension in the bolt is able to be monitored, compensation can be performed using the actuator. In that case, correct correlation in stiffness and stroke of the active component has to be found. Secondly, a strategy consisting in creating discontinuity in boundary condition can be implemented, using the actuator close to its border between free and hard stop conditions. Thirdly, impact on displacement transfer function can be established in order to get experimental determination of behaviour.

Stiffness adaptation

The stiffness adaptation consists in making efficient adaptation between stiffness of the bolt assembly and the stiffness and stroke of the active component. Figure 2 is presenting the link between the behaviour coming from bolt stiffness (two cases: soft and stiff bolts) and the behaviour coming from the actuator (two cases: strong and long stroke actuators).

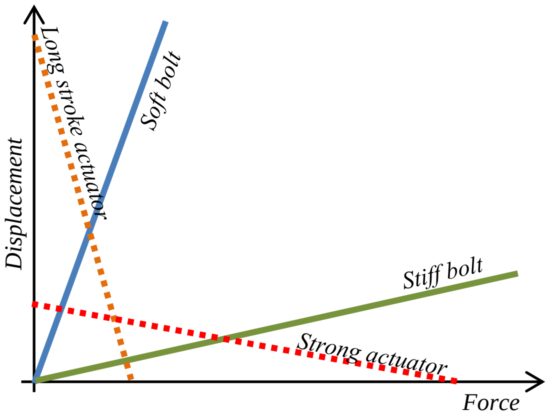

Figure 2: Force/displacement relation between bolt and actuator

Main limitation is coming from bolt, which is typically long, so elastic (see Figure 3). A M4 screw, admitting 20mm free length admits a 130N/µm stiffness. As a comparison, 10mm piezo stack made from rings (diam 8mm) admits typically a 130N/µm stiffness for 12µm free stroke. Therefore, useful stroke and force is intrinsically halved. Additionally, part of displacement is lost in contact stiffness's. Therefore, true contribution of actuator is limited. It can be also noticed that, increasing stroke using longer piezo stack requires also to increase length of bolt. So benefits is not linear.

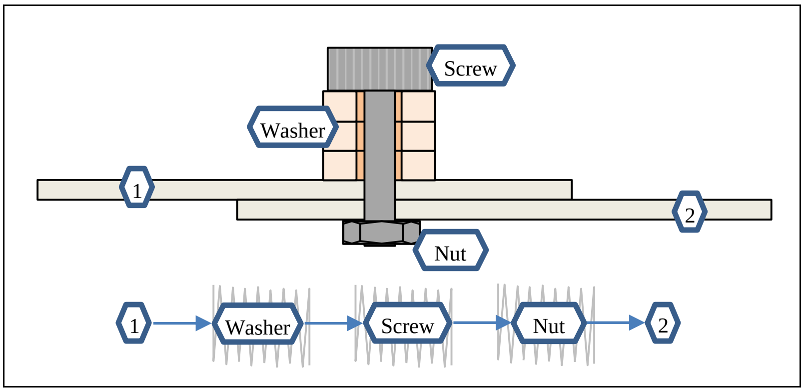

Figure 3: Bolted assembly and force path

Another contributor to small stiffness is potential soft material (visco-elastic) between the two layers of lap-joint. This additional layer can allow target damping characteristics. The axial stiffness is strongly lowered, making necessary to be able to perform longer stroke.

Actuator selection

Possibility to reach longer stroke, able to adapt to mechanism uncertainties and local parasitic stiffness's appears to be interesting. In that case, because of limits in volume, especially length) and costs, it is necessary to consider amplification. Proposed solution consists in mechanical amplification is the frame of APA® (Amplified Piezo Actuators).

Amplified Piezo Actuators APA® have already been considered in damping strategies [6]. Those kind of actuators offer larger strokes than direct actuators by amplifying displacement due to its shape. The flattest the actuator is, the more amplified the displacement is. In return, stiffness of the actuator is reduced. Typically, mechanical amplification being ruled by a factor α, stiffness is divided by $2\alpha^2$.

Figure 4: APA95-PTW-MD actuator, from [6]

The actuator (Figure 4) can generate up to 8.5kN of blocked force for 100µm free stroke. The support with additional viscoelastic material is able to improve the mechanical parameters of actuator, with changes the stiffness and damping characteristics. Application targeted by this application is machining and cancellation of chatter. Its relatively large size (approx. $100x100x100mm^3$) makes it not relevant for targeted application.

Available volume is roughly a few centimetre square. This size makes eligible use of standard $5x5x20mm^3$ piezoelectric stack within elliptical shape. Standard APA40SM actuator, creating 200N blocked force and 50µm free stroke is chosen. In lap-joint configuration, structural strength is performed using standard bolt linkage. Parallel active bolt are then used to adapt overall damping behaviour. The proposed design is integrating a central stiffener, non-linear, which is creating possible discontinuity in contact of internal surfaces of actuator (see Figure 5). Typically, when force going through actuator is rather low, actuator stiffness is taken in consideration. As a contrary, when force applied is high, either by external preload or by actuator self-force, the actuator stiffness is short-circuited, leading to a standard nut behaviour. Discontinuity between both states is considered as possibly beneficial for damping issues. In further part of the document, this component is called active washer.

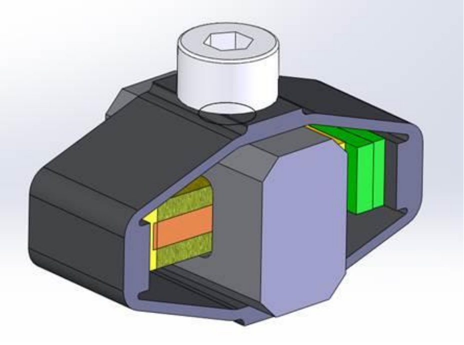

Figure 5: CAD view of active washer/nut.

4 ACTIVE WASHER PROTOTYPE AND APPLICATION IN LAP-JOINT

4.1 Active washer performance

Experimental trials of the proposed prototypes (see Figure 6) has been carried out. Aim of the characterization is to determine the possibility to place actuators is such a position that its own stiffness changes with input voltage.

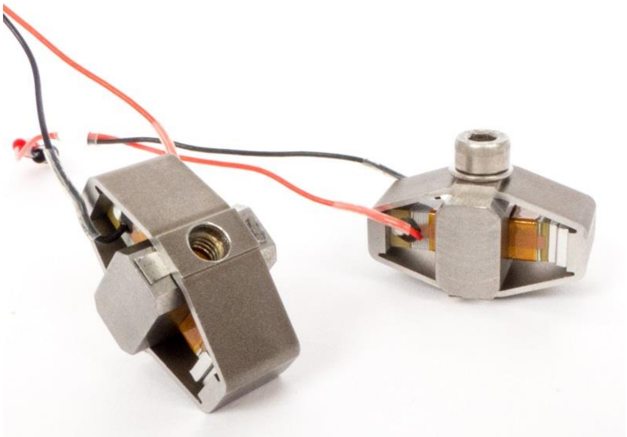

Figure 6 : Two active washer prototypes

Comparison between standard actuator and central ring configuration is presented in Figure 7. Actuator is powered using National Instruments board, driven by Signal Express software and associated with linear amplifier LA75 from Cedrat Technologies. Polytec laser is used, with 8µm/V gain in measurement. Generation and Acquisition are done simultaneously, with 10Hz sine 8.5Vpp signal. This corresponds to 170Vpp piezo actuator voltage. Applied voltage is within the range [-20:+150V]. Overall pattern is showing a hysteresis loop, classical in piezoelectric actuator response. Discontinuity coming from central ring is visible on the slope.

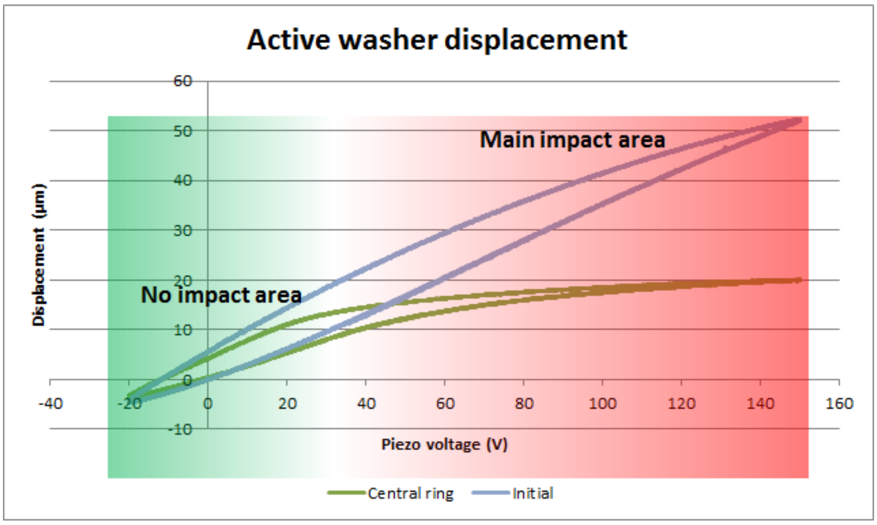

Figure 7 : Behaviour difference in standard condition or with internal stiffener

On the previous figure, displacement remains almost unchanged for input voltage from -20V to 20V, above this voltage, slope of the displacement curves changes. This is result of change in stiffness placed in parallel to the piezo actuator. This stiffness is a combination of contact stiffness and ring part stiffness. Numerical values are visible on Figure 8.

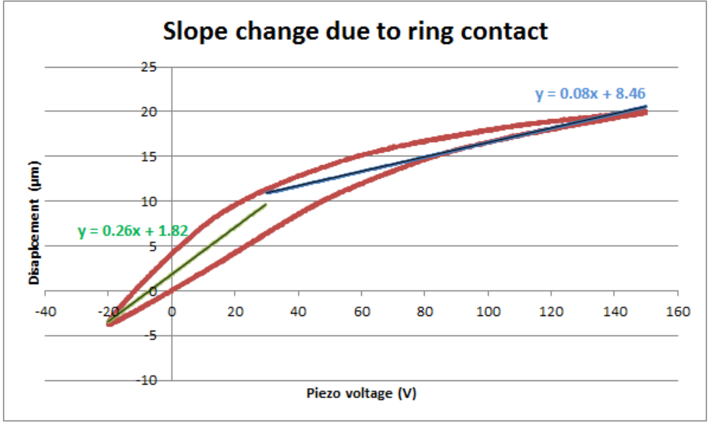

Figure 8 : Slope change in displacement

Standard stiffness of actuator is 3.7N/µm. This corresponds to blocked force (i.e. 194N is APA40SM) divided by free displacement 52µm. The slope in free displacement is 0.30µm/V. On active washer, initial slope is close to standard one, with 0.26µm/V. High voltage slope is smaller (0.08µm/V). This value allows to estimate equivalent stiffness of the actuator to be close to 14.1N/µm, revealing a 3 or 4 times increase in stiffness. Such kind of stiffness evolution will create a 1.7 to 2 factor in normal mode frequency, giving potential adaptation of modal landscape of structure. Integration onto standard user case lap-joint is presented in further part.

4.2 Integration on Lap-joint and experimental benefits.

The prototypes have been integrated in a lap-joint constituted with two plates linked by three screws, see Figure 9. The central screw is a passive one strongly tightened in order to ensure the reliability of the structure. The external screws are less tightened in order to provide damping. The smart washers are integrated in these joints. In order to evaluate their efficiency, the lap joint has been tested in a vibration set-up constituted with a clamp, a shaker and a 3D laser vibrometer.

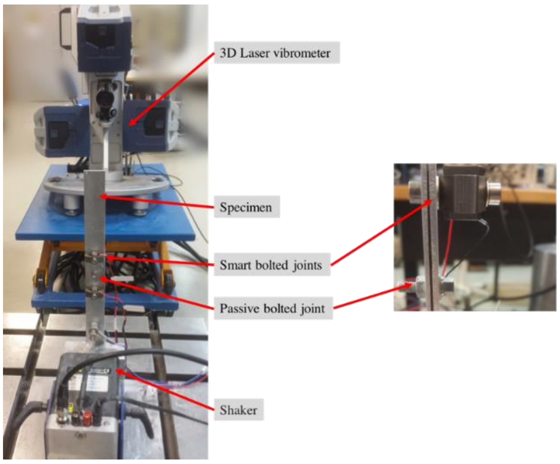

Figure 9: Vibration setup

The lap-joint is excited in the [0-2000] Hz frequency range with the shaker driven by a random signal. The signal is measured all over the surface of the setup in three directions thanks to the Polytec 3D Vibrometer. Then, we integrate the velocity over the surface in order to get a single scalar measure according to the frequency. This measured is weighted by the excitation level to build the Frequency Response Function, see Figure 10. This FRF exhibits several resonance frequencies. To evaluate the effect of the active washer, we build the FRF for three different voltages applied to the piezo actuators from -20V to + 145V. -20V corresponds to a 16cNm tightening torque whereas +145V corresponds to a 11cNm. From a vibration point of view, this means that the resonance frequencies are lower when the voltage is high and greater when the voltage is low. Obviously, the frequency shift depends on the Eigen mode we observe. The second Eigen mode is the most energetically coupled and the frequency shift is equal to 5%. These first results allow to expect an interesting vibration mitigation. Further investigations will focus on the control law that allows to maximize the efficiency.

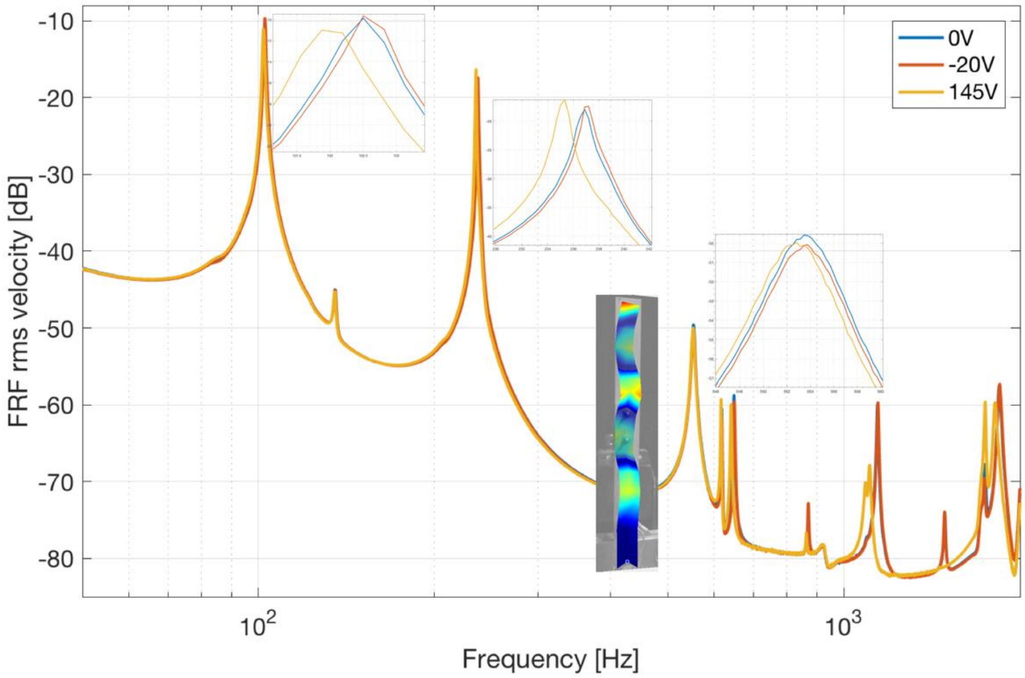

Figure 10: Frequency Response Functions according to several voltages.

5 IDENTIFIED LIMITS AND FUTURE WORK

To achieve the goal of this work, several technical developments are still in progress. The most important technical limit to overcome is to get the highest tightening load variation as possible. To improve the prototype, one has to manage the kinematic amplification thanks to an optimized design of the actuator. Secondly, we have to find the optimal placement for the active bolted connections. To get it, the setup has to be simulated numerically in order to compute the placement that allows to get the best energy coupling.

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