Clamp Force based Control for the Tightening Processes of Threaded Fasteners

Simulation based studies and experimental verification

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Abstract

Clamp force-based tightening control has been of interest for a long time in both industry and research. No significant breakthroughs have been made in this area when it comes to the control of dynamic processes. Advances in sensors and signal processing and the development in model-based control enable new approaches for clamp force-based control for tightening processes. A detailed model of the threaded fastener joint mechanics enables studies on tightening results' parameters. The project's goal is to develop new control strategies based on clamp force as a control objective.

Introduction

A threaded fastener joint's objective is to keep the joint together when an external force is applied to it. This is done via the clamp force generated during the tightening of the fastener (see Figure 1). In the most common tightening strategies used today, torque, torque plus angle, and material yielding are used to estimate clamp force.
Usually, the reference values are determined through look-up tables from various industry norms or a joint analysis. The tightening result is subjected to a large scatter due to variations in friction, speed dependency, mechanical influences, and other disturbances.
These shortcomings and the attempts to achieve a better process control originate from the idea of developing tightening strategies based on clamp force or which use more accurate clamp force estimators.

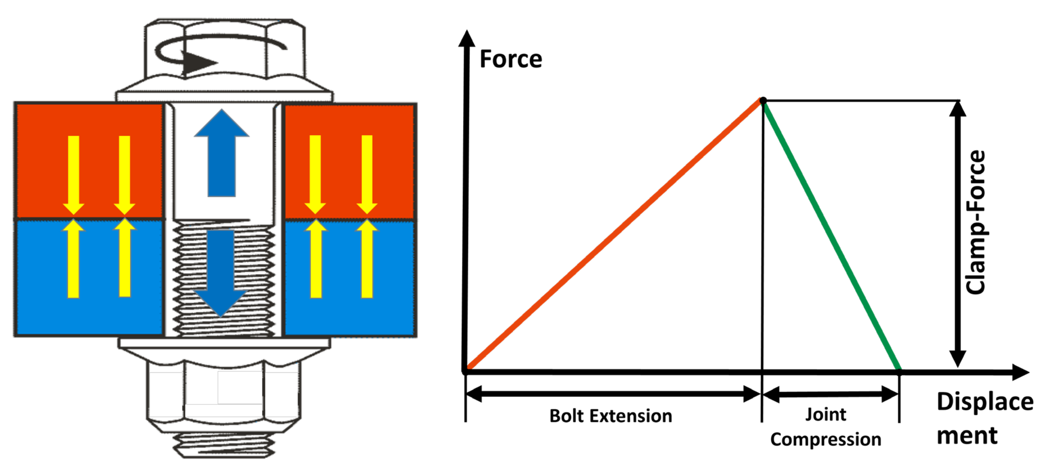

Figure 1. Forces and displacements in a typical bolted joint [from internal presentation] / [from boltscience.com]

Problem Formulation

The achieved clamp force in a tightening process is subject to scatter to a large extent. Therefore, many threaded fastener joints are over-dimensioned, and the actual clamp force in a joint is seldom known.
Hence there is a need for more accurate clamp force control in tightening processes.
A target is to develop tightening strategies that use better models for clamp force estimation or measure clamp force directly.

State of the Art Tightening Strategies

State of the art in the tightening industry are cascaded control loops with P and PI-control.
The most common tightening strategies are:
a) **Torque tightening** runs with a defined speed until the shut-off torque is reached.
b) **Torque plus angle tightening** works with a defined angle as a shut-off parameter.
c) **Yield tightening** works with a change in the torque rate as shut off parameter.

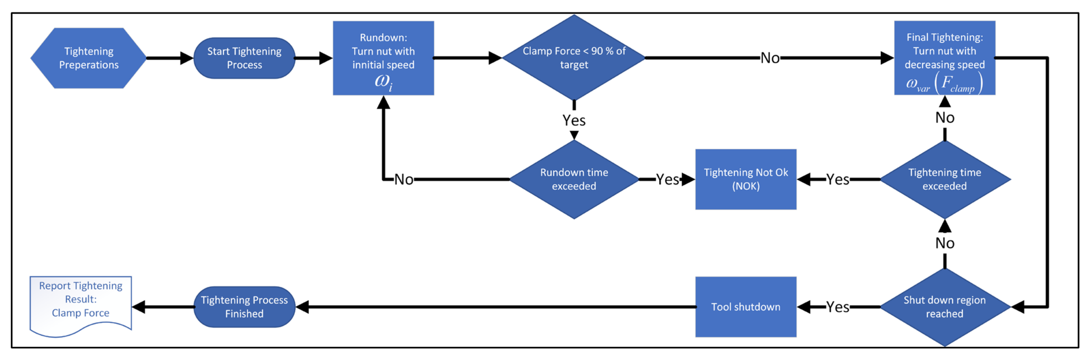

Figure 2. Novel tightening strategy with clamp force as a control parameter

Challenges

It is necessary to develop further methods for clamp force measurements or estimation methods to use them in tightening tools. The tightening strategies must be simulated, evaluated, and system parameters must be identified. For doing that, models of the tool and joint are needed, and methods for parameter identification or system identification can be used.

Clamp Force based Tightening Strategies

In contrast to the tightening strategies described in the state of the art, shall new control strategies be based on the desired clamp force. Achieving that will lead to a paradigm shift for technical documentation standards, while it enables to express the direct functional requirement for a threaded fastener joint. An example of such a strategy can be seen in figure 2.

Modeling

The driveline of a tightening tool with the typical components: electrical motor, gearbox, and transmission is like the driveline of electric vehicles and can be modeled in a similar fashion. The threaded fastener joint is modeled as two spring system, with friction losses that depend on the spring load. The current modeling approach is a system of DAEs that are molded in OpenModelica, as seen in figure 3.

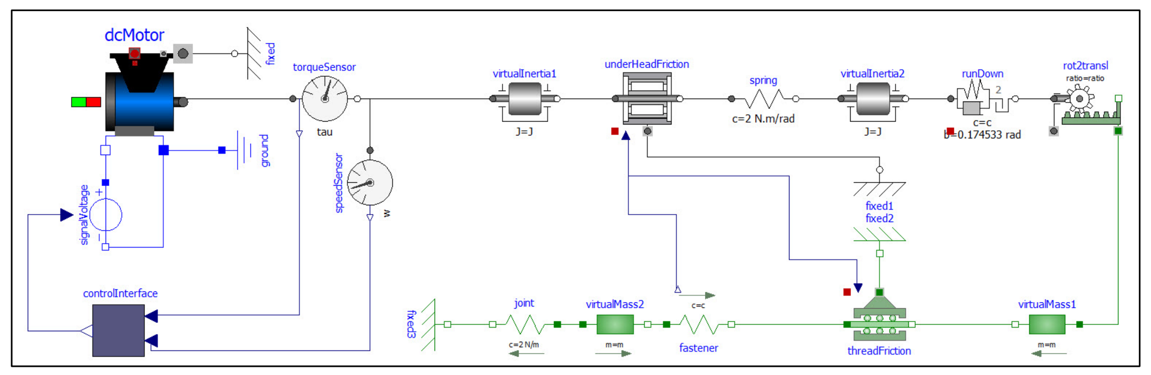

Figure 3. Model of a tightening system. Including the threaded fastener joint. Modeled in OpenModelica

Planned model-based studies

<u>The influence of friction variations on tool control</u>: That friction is challenging to determine precisely is well known. However, it is not studied how much tool control would improve with better knowledge about friction. It is planned to investigate that fact with the abovementioned joint model.
<u>Speed dependence of reaction forces on highly dynamic tightenings</u>. Empirically it is known that the reaction forces reduce with higher tightening speeds. A simulation study is planned to investigate the parameters that influence the decrease of reaction forces.

Test Rig for Control Experiments

To focus all experiments in a controlled test set up, a tightening test rig has been developed. The test rig's core is a DC motor, a gearbox, a torque and angle sensor and a well defined threaded faster joint for M8 screws. The setup can be seen in figure 4. The control experiments are run on a C2000 MCU. The rig is prepared for HIL experiments.

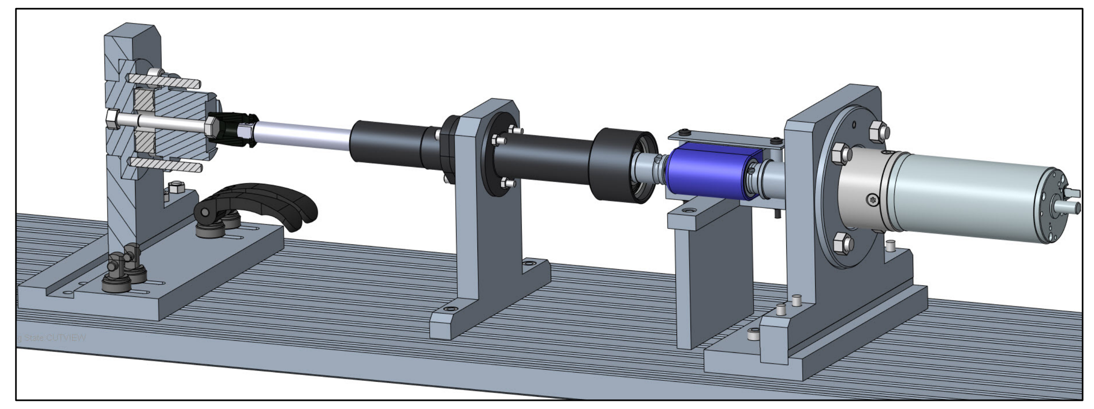

Figure 4. Model of a tightening system. Including the threaded fastener joint. Modeled in OpenModelica

Study on friction estimation with Kalman filters

The unknown friction μ_{tot} is of great interest in order to estimate the resulting clamp force F_c for a tightening.
With Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) it was shown that it is possible to estimate the friction with an error of less than 2% for continuous and highly dynamic tightenings.
The equations below are the system used for the filtering in the state space representation (1) and a discretization with a first-order approximation (2).

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \\ \dot{\mu}_{tot} \end{bmatrix} = \begin{bmatrix} \omega \\ \frac{1}{J_{tot}}\left[T - F_c\left(\frac{p}{2\pi} + \mu_{tot}\left(\frac{d_2}{2\cos\alpha} + \frac{D_{km}}{2}\right)\right)\right] \\ \omega_1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \theta(k+1) \\ \omega(k+1) \\ \mu_{tot}(k+1) \end{bmatrix} = \begin{bmatrix} \omega(k)T_s + \theta(k) \\ \frac{1}{J_{tot}}\left[T(k) - F_c(k)\left(\mu_{tot}(k)\left(\frac{d_2}{2\cos\alpha} + \frac{D_{km}}{2}\right)\right)\right]T_s + \omega(k) \\ \omega_1(k)T_s + \mu_{tot}(k) \end{bmatrix} \quad (2)$$

Publications

[1] Toh, G. , J. Park, and J. Gwon. "Determination of Clamping Force Using Bolt Vibration Responses during the Tightening Process." Applied Sciences (Switzerland) 9, no. 24. Accessed November 1, 2020

[2] E. Persson and A. Roloff, "Ultrasonic tightening control of a screw joint: A comparison of the clamp force accuracy from different tightening methods," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 230, no. 15, pp. 2595-2602, 2016.*

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