# Investigation of energy dissipation based on shock and friction to suppress critical self-excited vibrations in drilling systems

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*Summary*. In this article, a passive damper based on energy dissipation through shocks and dry friction (shock-friction damper) is investigated with regard to its effectiveness for damping self-excited torsional vibrations similar to those occurring in deep drilling. A minimal model based on a modally reduced complex finite element model of a drill string and a lumped mass representing the inertia of the forcedly connected damper is introduced for an effective and precise investigation of the dynamic motion and damping effect. Particular focus is on the energy flow within the dynamic system and on the change of the dissipation process in the friction contact. The resulting damping effect is compared with the self-excitation due to the bit-rock interaction in the drilling system. Parameters of the considered mode as well as parameters of the damper are examined regarding the damping effect. The shock-friction damper is compared to conventional friction dampers.

## Introduction

In downhole drilling systems, various types of vibration occur that can reduce drilling performance and result in premature failure of components [1]. Especially in hard and dense formations, high-frequency torsional oscillations (HFTO) occur in the range of 50 to 500 Hz. These oscillations are self-excited torsional vibrations of higher-order modes that can lead to critical torsional loads. Downhole measurement data show that the self-excitation can be described by a torque characteristic at the bit that decreases with the rotary speed. In [2], an analytical criterion based on a modal transformation is introduced to determine modes that are prone to self-excitation by linearizing the torque characteristic at the mean rotary speed of the drillstring. Increasing the damping of a system is a well-known approach to reduce self-excited vibration amplitudes. Tondl investigated the effect of tuned mass dampers and dry friction [3] on self-excited vibrations. Different types of friction contacts and friction dampers for various fields of engineering were investigated and classified [4]. For example, a friction damper is analyzed in [5] designed for railway wheels consisting of an inertia mass and a friction contact. In drilling systems, the effectiveness of inertia-based dampers is limited due to the small design space in the bottom-hole assembly (BHA) that is naturally limited by the drilled borehole size [6]. This reality necessitates investigation and optimization of the nonlinear forces characteristics between the inertia-mass to dampen the structure effectively. Similar efforts and analysis for nonlinear attachments show a significant effect on the energy output of a dynamic system [7].

## Modeling of a passive shock-friction damper

To investigate drillstring vibrations, a finite element model of an entire drillstring using the angular deviations $\boldsymbol{x}$ from the operating point (constant angular speed and twist) with $\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{f}$ is used. Herein, $\boldsymbol{M}, \boldsymbol{C}$ and $\boldsymbol{K}$ are the mass, damping and stiffness matrices and $\boldsymbol{f}$ an external force vector. The critical torsional modes are determined by a modal analysis and stability considerations. Following the modal transformation, the physical degrees of freedom $\boldsymbol{x}$ are expressed by $\boldsymbol{x} = \boldsymbol{\Phi}\boldsymbol{q}$ with the mass-normalized modal matrix $\boldsymbol{\Phi}$ and the modal degrees of freedom $\boldsymbol{q}$.
To perform an efficient and accurate investigation of the damping effect and dynamic behavior of the nonlinear shock-friction damper regarding critical self-excited drill string vibrations, the complex drilling system is reduced. Downhole measurement data show that mostly one critical mode dominates the dynamic motion of the entire drillstring when HFTO occurs. Resulting in a modal single-degree-of-freedom system $\ddot{q} + 2D_i\omega_{0,i}\dot{q} + \omega_{0,i}^2 q = \sum_{j=1}^{n} \varphi_{i,j} M_j$ where $\omega_{0,i}$ and $D_i$ are the natural frequency and modal damping of the *i*-th mode ($D_i < 0$ for the self-excited HFTO-mode), $M_j$ is an external torque that acts at the *j*-th node and $\varphi_{i,j}$ is the mass-normalized modal amplitude of the i-th mode at the j-th node. This minimal model can be extended to any damping force characteristic to determine its influence on the critical mode. The equation of motion

$$\begin{pmatrix} 1 & 0 \\ 0 & J \end{pmatrix}\begin{pmatrix} \ddot{q} \\ \ddot{x} \end{pmatrix} + \begin{pmatrix} 2D_i\omega_i & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} \dot{q} \\ \dot{x} \end{pmatrix} + \begin{pmatrix} \omega_i^2 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} q \\ x \end{pmatrix} = \begin{pmatrix} -\varphi_{i,j} M(\varphi_{i,j}\dot{q} - \dot{x}) \\ M(\varphi_{i,j}\dot{q} - \dot{x}) \end{pmatrix} \tag{1}$$

describes a critical mode connected by a torque to an inertia mass.
The torque between the inertia mass and the structure (Equation 2) consists of a friction contact with a normal force $F_N$, a coefficient of friction $\mu$, a friction radius $r$ and an elastic backlash with a stiffness $c$ and a width $S$.

$$M(\varphi_{i,j}\dot{q} - \dot{x}) = \begin{cases} F_\mathrm{N}\mu r \,\mathrm{sgn}(\varphi_{i,j}\dot{q} - \dot{x}), & |\varphi_{i,j} q - x| < S \\ F_\mathrm{N}\mu r \,\mathrm{sgn}(\varphi_{i,j}\dot{q} - \dot{x}) + c(|\varphi_{i,j} q - x| - S)\,\mathrm{sgn}(\varphi_{i,j} q - x), & |\varphi_{i,j} q - x| \geq S \end{cases} \tag{2}$$

The relative angular speed $v_\mathrm{rel} = \varphi_{i,j}\dot{q} - \dot{x}$ and the relative angular displacement $x_\mathrm{rel} = \varphi_{i,j} q - x$ between the damper and the structure are composed of the modal and physical degree of freedom.

## Investigation of vibration response and energy flow

To investigate the influence of the nonlinear shock-friction damper on the structure and the energy flow within the system time domain, simulations are used. Figure 2 (left) shows the motion of the structure and the damper. For small amplitudes, sticking occurs in the friction contact. No relative movement between the structure and the damper takes place. Due to the self-excitation ($D_i < 0$), energy periodically flows into the system (Figure 2, right), resulting in an increase of the amplitude in the sticking phase. At a certain amplitude, the inertial torque of the damper is greater than the friction torque $J\ddot{x} > F_N \mu r$, resulting in sliding regimes and energy dissipation in the friction contact. When the dissipated energy in the friction contact is not sufficient to stabilize the system, the amplitude increases further, resulting in an increased relative displacement and thus in shocks between the damper and the structure.

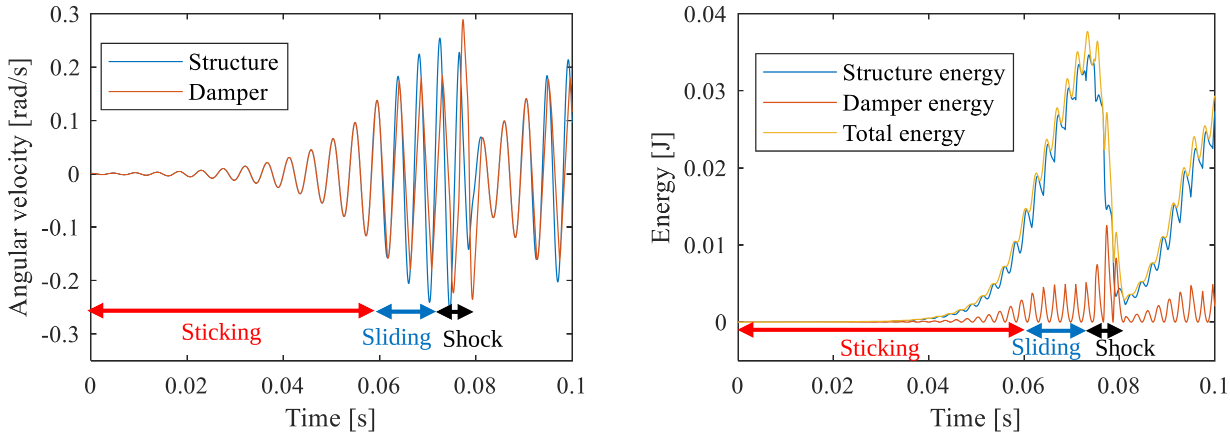


Figure 2: (left) Time response of the damper and the structure, (right) Energy flow within the system

These shocks, which do not occur in a conventional friction damper, lead to an energy transfer between the damper and the structure. Figure 2 (right) shows that while a shock occurs the energy is dissipated in the self-excited structure while the total energy remains almost constant and the energy of the damper increases. This leads to two positive effects on the stability and energy output of the system. The energy transfer reduces the energy of the structure, resulting in a reduced amplitude and thus lower energy input due to self-excitation. Secondly, the energy transfer to the damper increases the relative speed between the damper and the structure, dissipating the energy in the friction contact. Analyses with several modes show similar effects regarding the energy distribution, leading to an improved effectiveness in adjusted parameter ranges.

## Parameter influences

Analyzing various parameters show that an increase of the inertia of the damper or the mass normalized modal amplitude at the position of the friction contact results in an increased damping. This is similar to the conventional friction damper without backlash, for which an analytical solution $D_{\max} = \frac{2}{\pi^2}\varphi_{i,j}^2 J$ is found by harmonic linearization [6]. In contrast to the conventional friction damper, the provided damping depends on the backlash width, the friction torque and the natural frequency. A reference for the influence of these parameters is given by the amplitude at which relative displacement occurs $\hat{q} = \frac{F_N \mu r}{\varphi_{i,j} J \omega_{0,j}^2}$. If this amplitude is significantly smaller compared to the backlash width, the damper acts like a conventional friction damper. If the amplitude is much higher, the damping effect is reduced due to limited movement.

## Conclusions

This paper examines a combined friction and shock damper for its suitability to reduce self-excited torsional vibrations in downhole drilling systems. The combination of friction and backlash results in passive shocks, causing energy transfer between the self-excited structure and the damper that positively influences the energy output. Compared to a conventional friction damper without backlash, an increase in the damping effect is achieved by adjusting the normal force and backlash width with regard to the vibration frequency.

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