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Experimental investigation of the effect of in-plane vibrations on friction for different materials

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ABSTRACT

The friction between different materials in sliding plane at a frequency of 0–500 Hz has been studied. It was found that the friction is greatly affected by the external in-plane vibrations, with the maximal friction reduction occurred at higher ratio of vibrating velocity and sliding velocity being about 100%. The experimental friction coefficient tends to a higher value at lower sliding velocity ratio compared with the theoretical prediction, which can not only be attributed to the magnitude and direction change of friction in the sliding direction, but also the stick-slip motion and normal vibration. The results provide an insight into the friction research under in-plane vibrations and have guiding significance in the development of friction reduction technology by vibrating drill-string.

1. Introduction

Many studies on the influence of vibration on the friction force have been carried out over the past several decades. These studies suggest that the friction force can be reduced by the vibration excited both in the normal [1–10] and tangential [11–21] direction to the contact plane. The phenomenon of friction force reduction under vibrations is utilized in many technological areas by human for years. The most prominent low frequency (<1000 Hz [22,23]) applications are vibration compactors and plates. High frequency vibrations are used to reduce friction in metal working, wire drawing, cutting, and also in nano-tribological devices such as atomic force microscope [24]. In recent years, vibration even has been used in petroleum drilling to reduce the friction between drill-string and borehole wall, and this idea was first proposed by Roper in 1983 [25], but until recently several friction reduction technologies based on this principle and matching drilling tools have been developed successively, and the modes of vibration include axial vibration (longitudinal vibration) [26], torsional vibration(transverse vibration) [27] and lateral vibration(normal vibration) [28], as shown in Fig. 1. The drill string under build section lies on the borehole wall in the action of dead load and does not rotate in the process of directional drilling. The huge friction force between the drill-string and borehole wall makes the drill-string cannot slide down towards the direction of borehole extension. At the moment, any form of vibrations between drill-string and borehole wall can reduce the friction. Transverse vibration is applied by a top drive rotating the drill-string clockwise and anticlockwise alternately around the *z*-axis at the wellhead. Longitudinal vibration is applied by an exciter connected in the drill-string generating axial vibration along the axis of drill-string through a disc valve structure. Normal vibration is applied by another exciter connected in the drill-string generating normal vibration perpendicular to borehole wall through a high-speed spinning eccentric block. The exciters for generating longitudinal and normal vibrations are driven by drilling fluids.

For all these applications of vibration it is important to know how the friction forces depend on the vibration forms, frequency and amplitude. Meanwhile, vibrations can be used to explore the mechanisms of friction [29], and research results also can be used for guiding the application of vibrations in engineering areas. There have been lots of studies of the influence of vibrations on friction, of which most studies were carried out within ultrasonic vibration range. Littmann et al. [30–32] published a series of studies on the influence of in-plane ultrasonic vibrations both in the sliding direction and normal to the sliding direction on friction force. At relatively large sliding velocities, the experimental results were in good agreement with the theoretical models. Kumar [33] found that the friction force at large normal forces was larger than predicted theoretically. They proposed that this is caused by an increased mass transfer at high loads. Valentin [34] studied the influence of sliding velocity, actuation velocity and amplitude of vibration on friction coefficient, and introduced the notion of intrinsic friction slip length. With the applications of vibration

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Nomenclature

L	length of specimen in sliding direction [mm]
W	length of specimen perpendicular to sliding direction [mm]
H	length of specimen perpendicular to contact surface [mm]
E	Young 's modulus of specimen [GPa]
ρ	density of specimen [g/cm^3]
F_d	driving force in sliding direction [N]
F_f	friction force in relative velocity direction [N]
$F_{f,x}$	friction force in sliding direction [N]
$F_{i,x}$	inertia force in sliding direction [N]
F_c	Coulomb friction force [N]
N	normal load between specimens [N]
μ_f	friction coefficient under vibration in sliding direction [dimensionless]
$\vec{V}_s$	sliding velocity along in sliding direction [m/s]
$\vec{V}_v$	vibrating velocity [m/s]
V_a	amplitude of vibrating velocity [m/s]
$\vec{V}_r$	relative velocity [m/s]
$\vec{e}_x$	unit vector in sliding direction(x-direction) [dimensionless]
$\vec{e}_t$	unit vector in vibration direction of bottom specimen [dimensionless]
m	mass of specimen [kg/m^3]
a	acceleration of specimen [m/s^2]
θ	angle between sliding direction and vibration direction [deg]
μ_0	sliding friction coefficient without vibration [N]
N	normal load between specimens [N]
K	tangential stiffness of contact surfaces [N/m]
i	parameter which determines the shape of strain-stress curve [dimensionless]
z	offset displacement of asperities [m]
z_{ss}	deflection displacement magnitude of asperities [m]
U_0	displacement amplitude of vibration [m]
U	displacement of vibration [m]
ω	circular frequency [rad/s]
f	frequency of vibration [Hz]
t	time [s]
k, a, b, c, d	dimensionless constant [dimensionless]
$P(t)$	position of top point of asperity at time t [m]
$T(t)$	position of bottom point of asperity at time t [m]
$\overline{T(t)P(t+\Delta t)}$	deflection displacement of top point and bottom point of asperity [m]

Indices

1,2	upper specimen and bottom specimen
x, y, z	longitudinal (sliding), transverse and normal direction

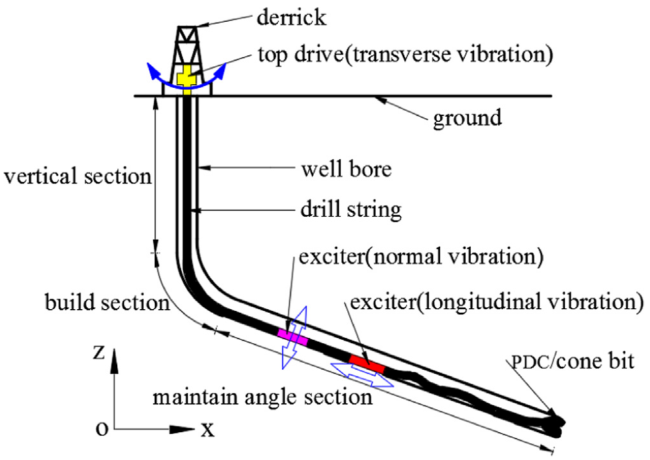

Fig. 1. Schematic of friction reduction technology by vibrating drill-string.

became more widespread, low-frequency vibration and its effect on friction have attracted the attention of scholars. Chowdhury et al. [35–39] published a series of studies on the effects of directions, amplitude, frequency of low frequency vibrations, different materials, and humidity on friction coefficient.

The first theoretical model describing the influence of tangential vibration on the friction force was proposed by Mitskevich [40]. Based on this model and rigid body Coulomb friction law, successive researchers developed interpretation models, which were used to verify experimental results. According to these studies the decreases in the friction force occur as a consequence of cyclical, instantaneous changes in the vector of the friction force, in the case of longitudinal tangential vibrations, taking place in any period of these vibrations provided that the amplitude of actuation velocity is higher than the constant sliding velocity [28–31,41,42]. The decrease in the friction occur as a consequence of changes in direction of the vector of the friction force around the sliding direction separating it into two components in the case of transverse vibrations: one parallel and the other transverse to the direction of sliding, and as a consequence only a partial interaction can take place in the direction of the motion [28,31,42]. The calculation results of the friction force for these models show significant discrepancies in comparison with the results obtained in empirical research [30–33]. A much better consistency of the calculation results as compared with the experimental results given in the above quoted articles by Littmann [30–31] and Storck [32] was obtained by Gutowski [43–45] and Tsai [46] for the model developed by Dahl [47,48] which takes into account contact deformability in the tangential direction, or with the use of the elasto-plasticity friction model proposed by Canudas et al. [49] and Dupont [50,51], which are a development of Dahl's model.

From the above analysis, experimental results cannot give consistent rules when the materials, vibration parameters, surface parameters of specimens, normal load or environment conditions change. The level of friction reduction in sliding motion under the influence of forced vibrations may vary considerably. Compared with experimental investigations, theory analysis and models are weaker and simpler. In the present study, the friction force between surfaces of different materials (steel, sandstone and shale) and a steel sample in sliding plane at different tangential vibrations has been studied. We measured the sliding friction under low-frequency longitudinal and transverse tangential vibrations and analyzed its relationship with vibration parameters and sliding velocities through the means of dimensional analysis.