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MODELING OF FRICTIONAL STICK SLIP EFFECT LEADING TO DISC BRAKE NOISE VIBRATION AND HARSHNESS

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Abstract: *Paper describes mechanism of vibration of disc brake components which can lead into noise effects known as brake Noise Vibrations and Harshness (NVH). Self-excited vibrations due to stick-slip effect and stability conditions are defined using 1 degree of freedom mechanical system. Nonlinear behavior of friction force with negative slope is considered. Response is obtained by numerical solution of ordinary differential equation. Conditions for self-exciting vibrations exhibition has been defined and discussed.*

Keywords: Stick-slip, NVH, Self-excited vibrations, Brake squeal, Dynamical instability.

1. Introduction

The unwanted side effect of the braking operation is its occasional squeal and other unwanted harshness effects. In the literature and in many studies we can find different classifications of brake noise, such as judder, hum, groan, squeal, squeak, wire-brush, chatter and moan, among others (Suchal, 2013). NVH is a problem that has been challenging engineers in industry for decades. It is commonly agreed that it occurs due to a friction induced oscillation. There are several mechanisms which can lead into NVH. Most discussed are stick and slip, sprag and slip effects (Guran, 2001), non-conservative follower force (Krillov, 2013) and mode coupling (Úradníček et al., 2016). Numerous works have analyzed the phenomenon of brake squeal, ranging from basic studies on mechanisms up to the development of suitable measurement techniques (Kinkaid et al., 2003). Nowadays, there is a strong research focus on numerical simulation (Dihua et al., 1998). Some years ago stability studies in the form of eigenvalue analysis of the linearized system became the state of the art. This kind of linear stability analysis is now used broadly in industry to analyze stability borders and to suggest measures against squeal. Nowadays, producers of braking components especially braking pads are strongly bounded by legislation to follow trends of sustainable reduction of environmental burdening and recyclability of materials (Peciar et al., 2016) which makes the process of developing the silent brake system even more challenging.

2. Modeling of Stick-slip effect

Stick-slip can be described as surfaces alternating between sticking to each other and sliding over each other, with a corresponding change in the force of friction. Typically, the static friction coefficient between two surfaces is larger than the kinetic friction coefficient. If an applied force is large enough to overcome the static friction, then the reduction of the friction to the kinetic friction can cause a sudden jump in the velocity of the movement. This effect can be demonstrated on simplified representation of the brake pad/disc frictional pair represented by 1 degree of freedom (DOF) mechanical model (Fig. 1a), where only pad elasticity in one direction is considered.

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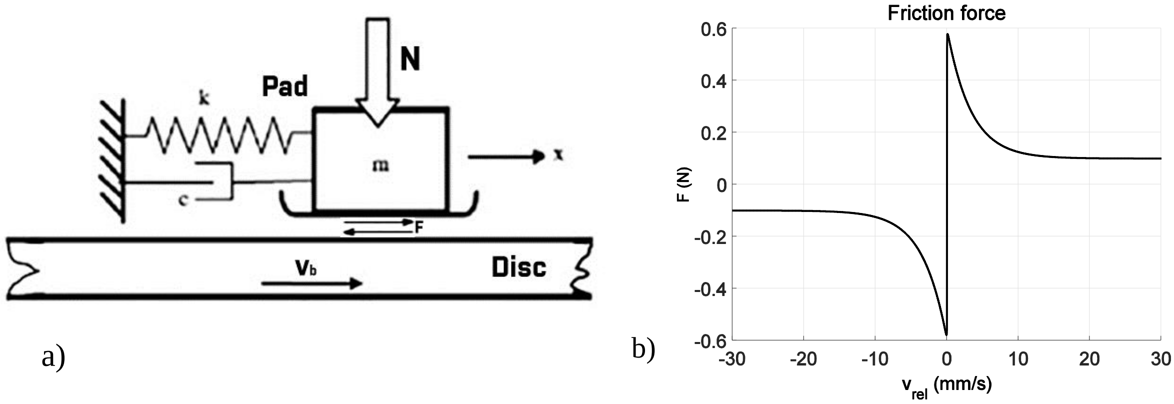

Fig. 1: a) Single DOF mechanical model of disc brake; b) Friction force function.

Governing differential equation for the model is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F\,(t, v_{rel}), \qquad (1)$$

and negative slope friction force is derived from Armstrong (1995).

$$\mathrm{F}(\mathrm{t}, \mathrm{v}_{\mathrm{rel}}) = \mathrm{N}\left[\mu_{\mathrm{c}} + (\mu_{\mathrm{brk}}\text{-}\mu_{\mathrm{c}})\mathrm{e}^{-\mathrm{c}_{\mathrm{v}}|\mathrm{v}_{\mathrm{rel}}|}\frac{2}{\pi}\mathrm{atan}(\mathrm{s}\,\mathrm{v}_{\mathrm{rel}})\right]. \qquad (2)$$

Where m – friction material mass , x - displacement, c – damping coefficient, k –stiffness, relative velocity $v_{rel} = (v_b - \dot{x}), v_b$ - disc velocity, N - normal force, μ_s - Coulomb friction coefficient, μ_{brk} - breakaway friction coefficient (static friction coefficient), μ_c - kinetic friction coefficient, s – sharpness coefficient, time derivatives $\dot{x}$ and $\ddot{x}$ represents velocity and acceleration of friction material in x direction. Function $2/\pi$ atan(-) in (2) is used to represent friction force transition along zero relative velocity. The frictional force function is shown in Fig. 1b.

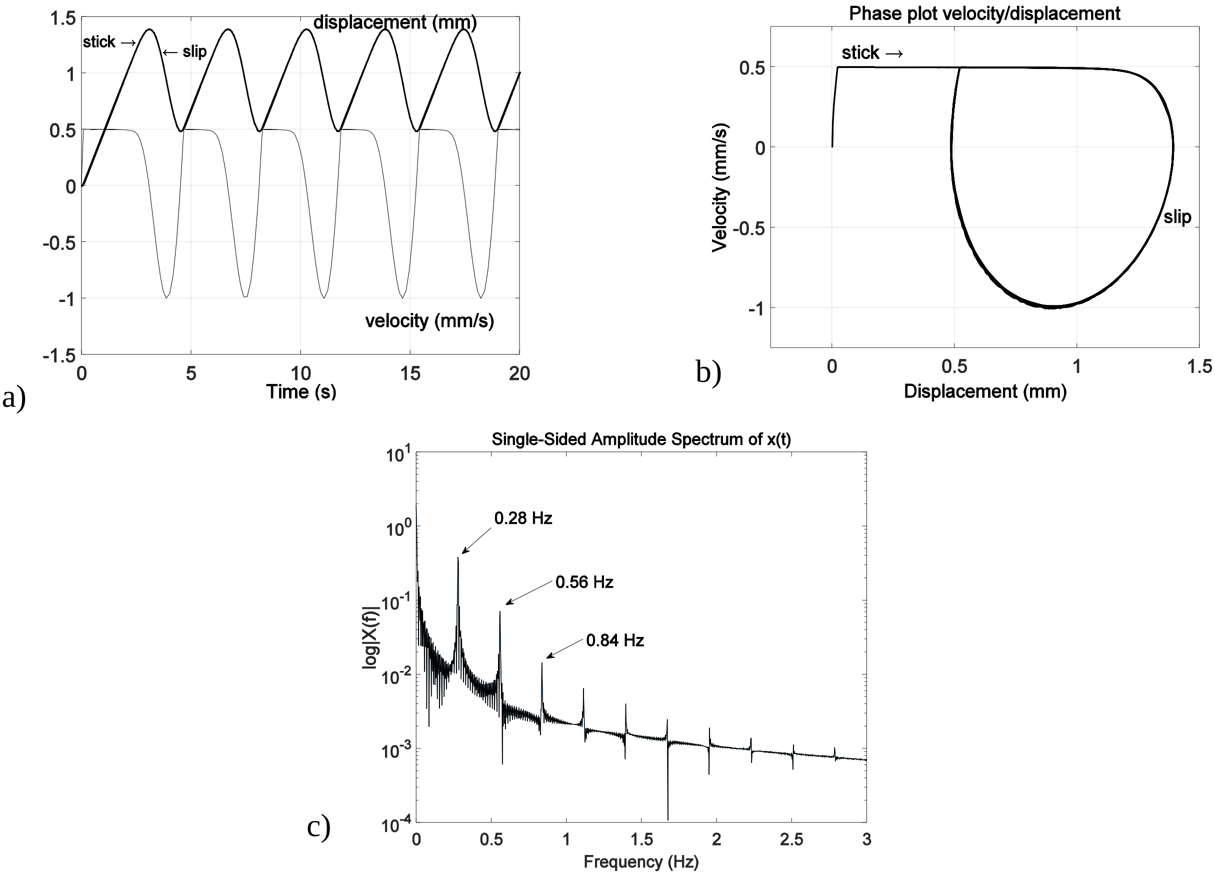

Fig. 2: a) displacement, velocity of mass; b) phase plot of displacement/velocity of mass; c) amplitude spectrum of displacement, for parameters: m = 1 kg; v_b = 0.5 mm/s; k = 5 N/mm; $\mu_{brk} = 0.6$; μ_c = 0.1; c = 0.2 N/mm.s-1; N = 10 N; s = 500 and initial conditions x = 0, dx/dt = 0.

Substituting (2), into (1)

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = N\left[\mu_c + (\mu_{brk} - \mu_c)e^{-c_v|(v_b-\dot{x})|}\frac{2}{\pi}atan(s(v_b - \dot{x}))\right]. \quad (3)$$

The equation (3) is nonlinear differential equation due to the nonlinear friction force changing its orientation and value with respect to relative velocity. Negative gradient of friction force is in contradiction with damping of the system which, under specific conditions, can destabilize system in the meaning that response amplitude is increasing with the time (Úradníček et al., 2017).

The response of the nonlinear dynamical system corresponding to the initial condition was calculated numerically using Runge-Kutta integration method included in MATLAB software through ODE45 function. For all following calculations, constant disc speed $v_b(t)$ and zero initial conditions $x(0) = \dot{x}(0) = 0$ have been considered.

In the first calculation, the negative slope friction force (2) and low disc velocity $v_b = 0.5\ \mathrm{mm/s}$ has been considered. Under these conditions system generates self-excited vibrations with polyharmonic response (Fig. 2a) due to strong nonlinearity of the friction force. System is dynamically stable with stick-slip limit cycles (Fig. 2b). Response is the combination of two motions. The first is stick motion in which the mass has the same velocity as the disc and second is the slip motion which occurs when the forces acting on the mass are greater than the friction force, which results in mass sliding over the disc. Amplitude spectrum of the displacement response is depicted in Fig. 2c. Response consists of fundamental frequency 0.28 Hz and higher harmonics which are integer multiples of fundamental frequency. Fundamental frequency value is given by friction force. In general, it depends on the difference between the static and the kinetic friction force (the bigger is the friction force around zero relative velocity the longest stick mode is lasting). System under given conditions produces stable self-excited polyharmonic vibrations.

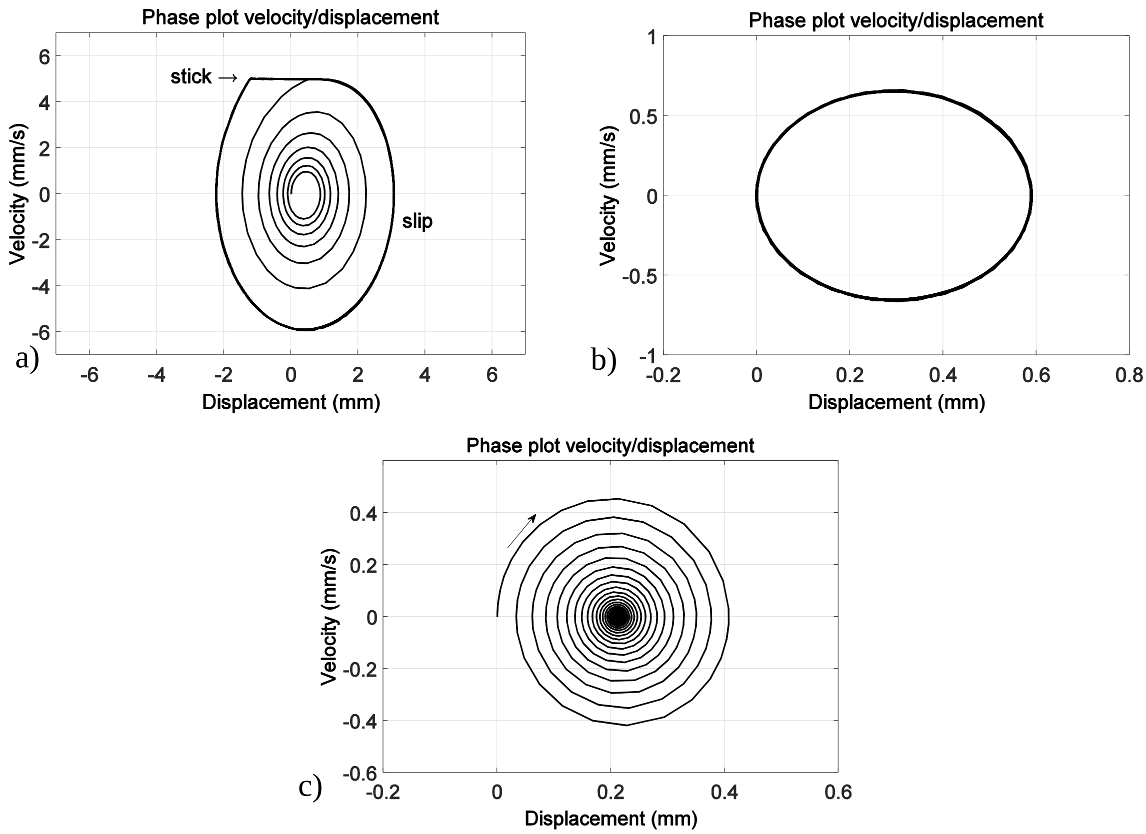

Fig. 3: Phase plot of displacement/velocity of the mass for: a) $v_b = 5\ mm/s$; b) $v_b = 6.99\ mm/s$; c) $v_b = 10\ mm/s$.

Increasing the disc velocity v_b, the sticking phase is shortening (Fig. 3a). At the critical disc speed value, the stick phase do not occur anymore and system is stable oscillating along equilibrium position (Fig. 3b). When the critical base speed is exceeded, system doesn't produce self-excited vibrations anymore and is oscillating about equilibrium position with decreasing amplitude Fig. 3c.

3. Conclusions

Stick-slip frictional effect have been described through single degree of freedom mechanical system. Frictional force has been modeled as the function with negative slope with respect to relative velocity. Nonlinear behavior has been demonstrated using numerical time integration of ordinary differential equation.

From the numerical analyses of simplified mechanical brake model, it can be seen, that stick-slip effect is source of stable self-excited vibrations. When stick-slip effect disappears due to critical velocity of the disc system is in purely sliding vibrations state. When critical velocity of the disc is exceeded, system stable oscillates about equilibrium position with decreasing amplitude.

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