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Investigation of mechanical properties of water-based friction modifier for railway applications

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Abstract

This Note outlines the investigation of the water-based friction modifier used in railway technology. This investigation involves measurements made using a novel measuring stand, a new modelling of the modifier and the identification of its parameters using measured results. The proposed model of the modifier is composed of a dry friction slider, a dash-pot and a spring. The investigation contributes to a deeper understanding of the modifier's performance. ***To cite this article: J. Piotrowski, C. R. Mecanique 332 (2004).***

Résumé

Recherches des propriétés mécaniques du modificateur frottement dans une forme de l'émulsion d'eau applique dans les chemins de fer. Cette Note présente l'étude expérimentale des propriétés mécaniques du modificateur de frottement sous forme d'émulsion d'eau, utilisé dans les chemins de fer. Le travail présente les mesures sur un banc d'essai moderne, la modélisation et l'identification des paramètres du modèle mathématique sur base des recherches expérimentales. Les éléments du modificateur sont les suivants : un coulisseau du frottement à sec, un ressort et un amortisseur visqueux. Dans la description du modèle ont été appliqués les éléments d'analyse mécanique rugueuse. Les résultats de l'étude permettent une meilleure compréhension des principes du travail du modificateur. ***Pour citer cet article : J. Piotrowski, C. R. Mecanique 332 (2004).***

Keywords: Friction; Water-based friction modifier; Railways

Mots-clés : Frottement ; Modificateur de frottement sous forme d'émulsion d'eau ; Chemins de fer

1. Introduction

Friction modifiers are chemical agents used in railway technology in order to increase, decrease or stabilise friction between wheels and rails. The effects, depending on the modifier used, are reduced wear, increased adhesion or reduced corrugations and noise [1,2].

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The modifiers have a form of a dry, solid stick or a water-based solution. The latter are electro-statically and mechanically bonded to the surface. In contrast with liquid lubricants, they are environmentally friendly because, due to the strong bonding to the surfaces, they do not leak and finally penetrate the surrounding soil.

The objective of the present work is to investigate the mechanical properties of water-based modifiers, in order to improve the understanding of their performance. To this end a measuring stand in the form of a technical pendulum has been used, which allows measurements of the quantities necessary for a determination of the friction characteristics.

The introductory measurements were made on a friction pair of clean steel and steel lubricated with oil. The results of these measurements constitute a reference for the investigation of friction modifiers.

On the basis of measured results a model of the modifier has been proposed in the form of a system composed of a dry friction slider, a spring and a dash-pot. The modifier model is a part of the model of the technical pendulum.

The measured friction characteristics of the modifier were used to identify parameters of the model and of the modifier. To this end, the model of the pendulum and of the modifier has been described with non-linear differential equations. The description involves some notion of non-smooth mechanics. The identification was made by recurrent solving of differential equations to fit measured and calculated friction characteristics.

The results of investigation show that mechanical properties of the modifier are non-linear and depend on at least 3 parameters. The investigation of mechanical properties of modifiers contributes to a better understanding of their performance and may lead to an improvement of application procedures.

2. The measuring stand

The measuring stand consists of an instrumented, fixed-pivot technical pendulum. The technical pendulum was introduced in [3]. It hangs on a pivot through the hub fixed to the rod as shown in Fig. 1. It is called a fixed-pivot

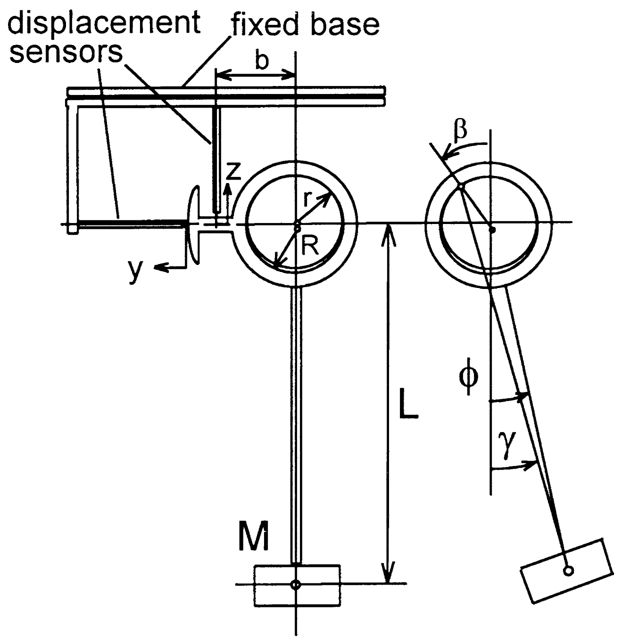

Fig. 1. Instrumented technical pendulum.

Fig. 1. Pendule technique avec l'instrumentation.

technical pendulum. The other kind of technical pendulum is one that is hung on the hub through the pivot fixed to the rod. It is called a fixed-hub technical pendulum.

The pivot (pin) diameter is smaller than the diameter of the hub hole. This allows rolling and sliding (stick/slip) of the hub and this very feature has been exploited for measurements of friction characteristics. To exert the required contact pressure on surfaces by the load Mg the hub hole has two half-toruses with properly chosen radii contacting with the pivot, machined at both ends of the hub.

The pendulum has been equiped with 2 displacement sensors measuring the linear displacements y and z of the hub. Once displacements y and z are recorded digitally, the sway angle ϕ and the contact angle β may be calculated using the formulae:

$$\phi = \frac{z}{b}, \qquad \beta = \arcsin\left(\frac{y}{R-r}\right)$$

The following equation describes the constraint when rolling takes place in the joint:

$$\beta = \frac{R}{R-r}\phi$$

The slip distance s is defined by the formula

$$s = (R-r)\beta - R\phi$$

The velocity of sliding is calculated by numerical differentiation of the slip distance

$$\dot{s} = (R-r)\dot{\beta} - R\dot{\phi}$$

The resultant force acting on the mass M is co-linear with a line inclined by the angle γ relative to the vertical direction, passing through the point of contact of the hub and pivot and the centre of mass of the pendulum, see Fig. 1:

$$\tan\gamma = \frac{R\sin\beta + L\sin\phi}{R\cos\beta + L\cos\phi}$$

The tangential (friction) and normal forces in contact of the pivot and the hub are:

$$T = \frac{Mg}{\cos\gamma}\sin(\beta-\gamma), \qquad N = \frac{Mg}{\cos\gamma}\cos(\beta-\gamma)$$

The normalised tangential force is

$$\frac{T}{N} = \tan(\beta-\gamma)$$

The above expressions have been used to calculate the friction characteristics.

3. Measurements of friction characteristics for clean and lubricated steel

The friction characteristics are described by relationship of the normalised friction force on slip velocity and the friction force on the slip distance.

The results for the clean surfaces obtained by measurements for the hub of 0.030 [m] hole diameter and the pivot of 0.027 [m] diameter are plotted in Figs. 2 and 3.

The result shown in Fig. 2 resembles the dependence of friction force on sliding velocity, as described by the Coulomb law of dry friction. This is strongly supported by the rectangular form of loops shown in Fig. 3, with discontinuities occurring when there is a change in the direction of the slip velocity.

The results of measurements for the steel pivot of 0.029 [m] diameter lubricated with oil are shown in Figs. 4 and 5. There is a striking difference between results for clean and lubricated surfaces. For some range of normalised

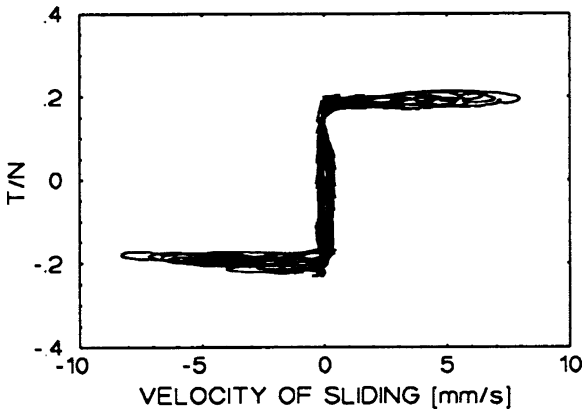

Fig. 2. Normalised friction force versus velocity of sliding for clean steel.

Fig. 2. Force du frottement normalisé pour l'acier net en fonction de la vitesse du glissement.

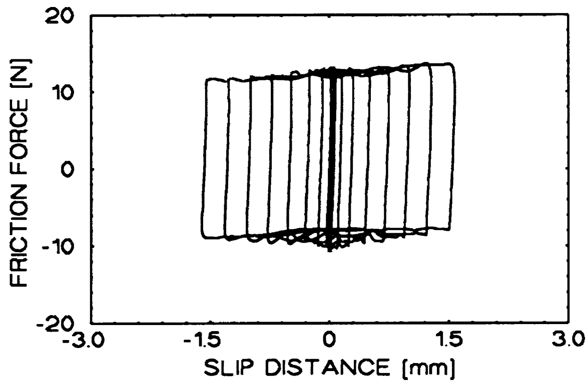

Fig. 3. The loops of friction force versus slip distance for clean steel.

Fig. 3. Cycles de la force de frottement pour l'acier net en fonction du déplacement de glissement.

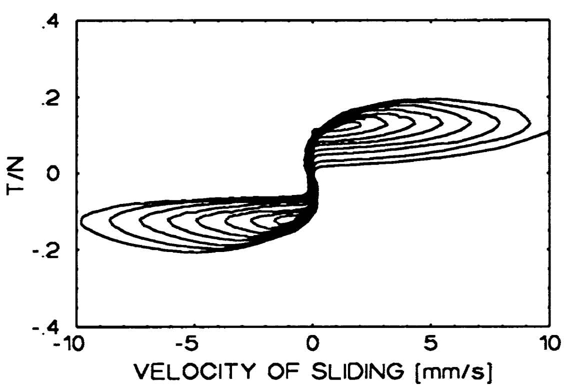

Fig. 4. Normalised friction force versus velocity of sliding for lubricated steel.

Fig. 4. Force de frottement normalise pour l'acier avec graissage à l'huile en fonction de la vitesse du glissement.

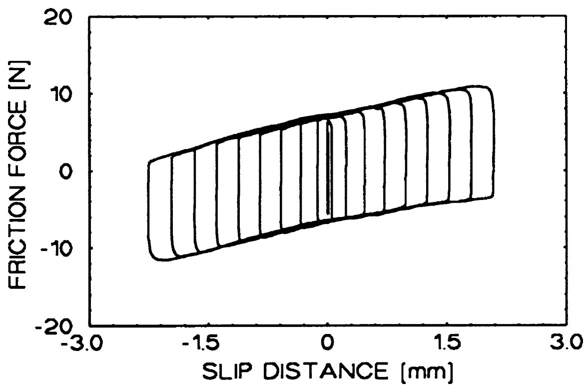

Fig. 5. Friction force versus slip distance for lubricated steel.

Fig. 5. Cycles de la force de frottement pour l'acier avec graissage à l'huile en fonction du déplacement du glissement.

tangential force T/N the surfaces stick together, but when it comes to sliding the relation between the normalised friction force and slip velocity has the form of the set of loops, which indicate that some viscous effect suddenly arises.

The loops in Fig. 5 indicate that dry friction still influences the phenomenon, but the Coulomb law of dry friction is no longer applicable.

The results of measurements for clean and lubricated steel surfaces constitute a reference for interpreting the friction characteristics obtained after the application of the modifier on contacting surfaces.

4. Measurements of friction characteristics in presence of the modifier

The measurements were made using the pivot of 0.029 [m] diameter after application of water-based modifier on its surface. After drying, the modifier leaves a grey coating bonded to the surface. To prepare for measurements the

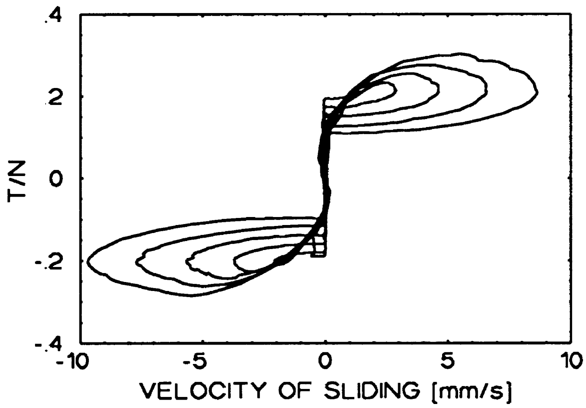

Fig. 6. Normalised friction force versus velocity of sliding in the presence of modifier.

Fig. 6. Force de frottement normalise pendant le présence du modificateur en fonction de la vitesse du glissement.

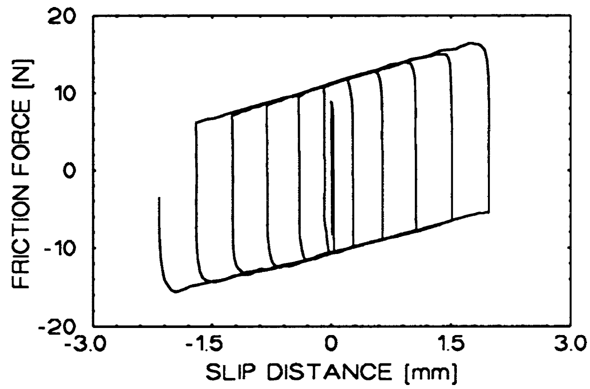

Fig. 7. The loops of friction force versus slip distance in the presence of modifier.

Fig. 7. Cycles de la force de frottement normalise pendant le présence du modificateur en fonction du déplacement du glissement.

pendulum was repeatedly swayed in order to put the surfaces in a state such that rolling/sliding paths are shining. In this state the modifier is still active, though it is not visible on the surface with the naked eye. This is the state in which the modifier resides and acts for some time interval on the surfaces of the rails or wheels.

The measured friction characteristics are presented in Figs. 6 and 7. The plots are similar to those obtained for lubricated steel. This means that the modifier used here modifies the friction properties of surfaces in a similar manner as oil but the friction is higher. Again, sticking influences the phenomenon and only when it comes to sliding does the viscous effect arise.

5. Model of the modifier

The proposed model of the modifier consists of the spring with stiffness k_2, dash-pot and the dry friction slider. It is presented in Fig. 8 as a part of the model of the technical pendulum.

The co-ordinate Y describes the linear, lateral displacement of the pendulum's centre of mass M. The stiffness parameters k and k_1 describe restoring properties of the pendulum. They may be determined analytically [4] or experimentally [3]. The inertial parameters of the pendulum are determined by simple measurements described in [3].

The characteristic of the friction slider is described by the following non-smooth relation [4,5]:

$$\Omega\colon\quad F \in [-F_0, F_0], \quad v_s \in -\mathbf{K}(F, \Omega)$$

The cone $\mathbf{K}$ is described by

$$v_s \in \begin{cases} \{0\} & \text{if } |F| < F_0 \\ R^+ & \text{if } F = +F_0 \\ R^- & \text{if } F = -F_0 \end{cases}$$

where F is the friction force of the slider, F_0 the break force and v_s the slip velocity.

The equations of motion of the model of the pendulum and the modifier take on the following form:

$$M\ddot{Y} + kY + k_2(X - Z) = F$$
$$\dot{X} = \dot{Y} - \frac{k_2}{c}(X - Z)$$

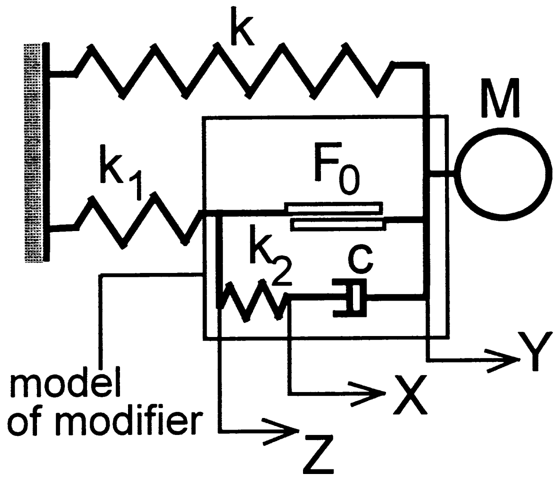

Fig. 8. Model of the modifier as a part of the pendulum model.

Fig. 8. Modèle du modificateur comme la partie du modèle du pendule.

$$\dot{Z} = -\frac{1}{k_1 + k_2}(\dot{F} - k_2\dot{X})$$

$$\dot{F} = \begin{cases} \{-k_1\dot{Y} - k_2(\dot{Z} - \dot{X})\} & \text{if } |F| < F_0 \\ -\{-[-k_1\dot{Y} - k_2(\dot{Z} - \dot{X})]\}^+ & \text{if } F = +F_0 \\ \{[-k_1\dot{Y} - k_2(\dot{Z} - \dot{X})]\}^+ & \text{if } F = -F_0 \end{cases}$$

where

$$\{u\}^+ = \begin{cases} u & \text{if } u \geqslant 0 \\ 0 & \text{if } u < 0 \end{cases}$$

The friction force is

$$T = F + k_2(Z - X)$$

The slip distance s and slip velocity v_s are:

$$s = Z - Y, \qquad v_s = \dot{s} = \dot{Z} - \dot{Y}$$

The details of the description of a similar system with dry friction may be found in [4].

6. Parametric identification

To identify the parameters of the model, the equations of motion have been recurrently solved numerically in order to fit calculated friction characteristics to those obtained from measurements.

After a number of runs the best fit is obtained. It gives the following parameters of the model, reduced to the pivot surface:

$$\frac{F_0}{Mg} = 0.2, \qquad \frac{k_2}{Mg} = 62.1\ [1/\text{m}], \qquad \frac{c}{Mg} = 245.3\ [\text{s/m}]$$

The calculated friction characteristics of identified modifier model are shown in Figs. 9 and 10. The calculated friction characteristics are qualitatively similar to measured ones.

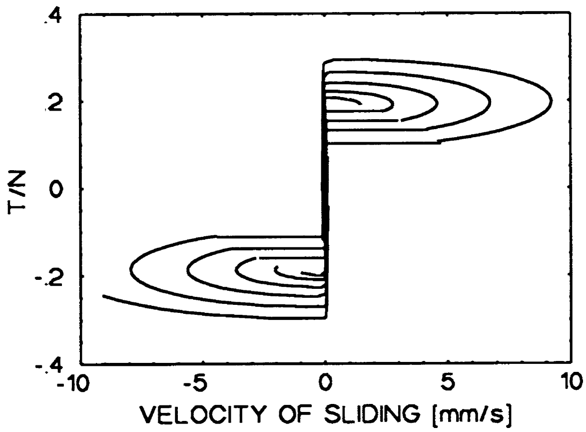

Fig. 9. Normalised friction force versus velocity of sliding for identified modifier model.

Fig. 9. Force de frottement normalisé en fonction de la vitesse du glissement pour le modèle du modificateur identifié.

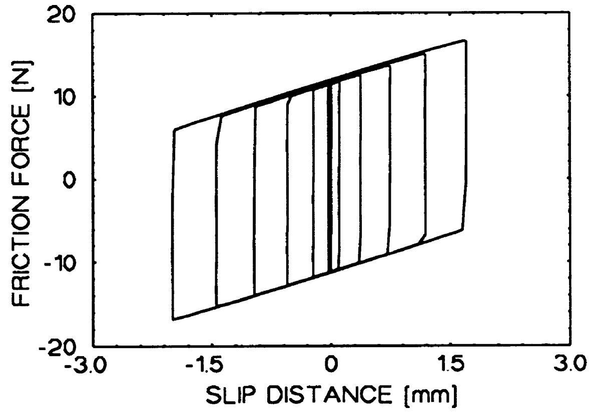

Fig. 10. The loops of friction force versus slip distance for identified modifier model.

Fig. 10. Cycles de la force de frottement normalisé en fonction du déplacement du glissement pour le modèle du modificateur identifié.

7. Conclusions

The friction properties of steel treated with the investigated water-based modifier are qualitatively similar to those of steel lubricated with oil. The friction may be higher than for clean steel as in case of the investigated modifier or lower for LCF modifier [2], which reduces the friction.

The proposed 3-parameter model composed of a spring, a dash-pot and a dry friction slider adequately describes mechanical properties of the modifier. The dry friction slider is a necessary element of the model because it controls sticking.

One can conclude from the results of the presented investigation that the description of properties of the modifier by a single number-coefficient of friction is too crude.

The instrumented technical pendulum is a simple but precise measuring apparatus for measurements of friction characteristics at low slip velocities.

Future investigation should concentrate on the influence of contact pressure on friction characteristics, higher slip velocities and on possible improvement of the modifier model by the introduction of the non-linear spring and dash-pot.

The further objective of the modifier investigation should be to include the modifier model into the description of rolling contact of wheel and rail.

Acknowledgements

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