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UNSYMMETRIC DRY FRICTION FOR MODELS OF SURFACE CLEANING

У процесі очищення поверхні відбуваються різні нелінійні ефекти. Серед різних нелінійних ефектів, що відбуваються в таких системах, важливе значення має сухе тертя. Таким чином, ряд робіт присвячено дослідженню цього ефекту. У числових запрошеннях зазвичай використовується деяке наближення перехідних областей між різними постійними значеннями сили сухого тертя. Це дозволяє наблизити нелінійні ефекти, що мають місце в таких системах. Для представлення деяких із цих ефектів запропонована модель несиметричного сухого тертя в цій роботі.

Досліджена модель має один ступінь свободи і включає конкретний тип нелінійності. Він передбачає використання величин з попереднього моменту часу та логічних операцій «і» і «або». Детально описана чисельна процедура дослідження цього явища. Представлені та проаналізовані результати розрахунків за різними параметрами досліджуваної динамічної системи. З отриманих результатів видно застосованість даної моделі для відтворення досліджуваного нелінійного явища.

Досліджено варіацію переміщення як функції часу, зміну швидкості як функції часу, варіацію прискорення як функцію часу, варіацію швидкості, помножену на прискорення як функцію часу.

Наведено варіації величин, що визначають несиметричну силу сухого тертя як функції часу, так і функції швидкості.

Досліджено уявлення у фазовій площині: швидкість як функція переміщення, прискорення як функція швидкості, швидкість, помножена на прискорення як функція переміщення.

Досліджено три ширини обох взаємно рівних перехідних областей. Детально представлені результати, що представляють динамічну поведінку аналізованої системи. Вплив ширини перехідних областей спостерігається в представлених графічних результатах.

Запропонована модель несиметричного сухого тертя застосовується як частина інших більш складних моделей, що використовуються для дослідження процесу очищення поверхні.

Ключові слова: очищення поверхні, несиметричне сухе тертя, числова модель, нелінійне явище, графічні результати.

INTRODUCTION

Surface cleaning is an important engineering problem. In the process of surface cleaning various nonlinear effects take place. Among the various nonlinear effects taking place in such systems dry friction is an important one. Thus a number of papers are devoted to the investigation of this effect. In numerical investigations usually some approximation of the transition regions between different constant values of the force of dry friction is used. This enables to approximate the nonlinear effects taking place in such systems. For representation of some of those effects the model of unsymmetric dry friction is proposed in this paper.

The investigated model has one degree of freedom and incorporates a specific type of nonlinearity. It involves the use of the quantities from the previous moment of time and logical operations "and" and "or". Numerical procedure for investigation of this phenomenon is described in detail. Results of calculations for various parameters of the investigated dynamical system are presented and analysed. From the obtained results the applicability of this model for reproduction of the investigated nonlinear phenomenon is seen.

Conventional model of dry friction with circular – linear approximation is investigated in [1]. Conventional model of dry friction with elliptic approximation is investigated in [2]. Conventional model of dry friction with trigonometric approximation is investigated in [3]. Investigations of phenomena in esentially nonlinear vibrating systems are performed in [4]. Basic engineering problems in which the force of dry friction is taken into account are presented and investigated in [5].

Important engineering problems of surface cleaning by cavitation bubble dynamics are analysed in [6]. The process of cleaning in food production industry is presented in [7]. Interactions of particles with surfaces are investigated in [8]. Forces between particles and their mutual interactions are described in [9]. Measurements of adhesion of particles are performed in [10]. Extensive experimental investigations of particles using atomic force microscopy are presented in [11].

The proposed model of unsymmetric dry friction is applicable as part of other more complicated models used for the investigations of the process of surface cleaning.

MODEL OF UNSYMMETRIC DRY FRICTION FOR SURFACE CLEANING PHENOMENA

The dynamical system is described by the following equation:

$$m\ddot{x} + c\dot{x} + H + kx = P\sin\omega t, \tag{1}$$

where x denotes the displacement of the analysed dynamical system, m is the mass of the investigated object, c is the coefficient of viscous friction, H denotes the approximate force of unsymmetric dry friction, k is the coefficient of stiffness, dot over the variable is used for indication of differentiation with respect to the time t, P is the amplitude of excitation, ω is the frequency of excitation.

The following quantity is defined as:

$$\bar{C} = \begin{cases} \dfrac{h}{\Delta}, \text{ when } |\dot{x}| < \Delta + \Delta_a, \\ -\dfrac{h}{\Delta}, \text{ when } |\dot{x}| \geq \Delta + \Delta_a \text{ and } |\dot{x}| < \Delta + 2\Delta_a, \\ 0, \text{ when } |\dot{x}| \geq \Delta + 2\Delta_a, \end{cases} \tag{2}$$

where h denotes the coefficient of dry friction, Δ is the width of the transition between the values of the force of dry friction, Δ_a is the supplementary width of the transition between the values of the force of dry friction.

The quantity C is defined as:

$$C = \begin{cases} 0, \text{ when } \left(\left(\dot{x} > 0\right) \& \left(\dot{x} < \dot{x}_p\right)\right) \vee \left(\left(\dot{x} < 0\right) \& \left(\dot{x} > \dot{x}_p\right)\right) \text{ and } |\dot{x}| \geq \Delta, \\ \bar{C}, \text{ elsewhere,} \end{cases} \tag{3}$$

where the subscript p denotes the previous value of the corresponding quantity.

Value of the unsymmetric force of dry friction is calculated as:

$$H = H_p + C\left(\dot{x} - \dot{x}_p\right). \tag{4}$$

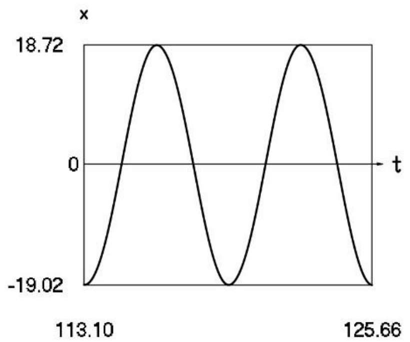
Thus the following equation is solved:

$$m\ddot{x} + \left(c + C\right)\dot{x} + kx = P\sin\omega t - H_p + C\dot{x}_p. \tag{5}$$

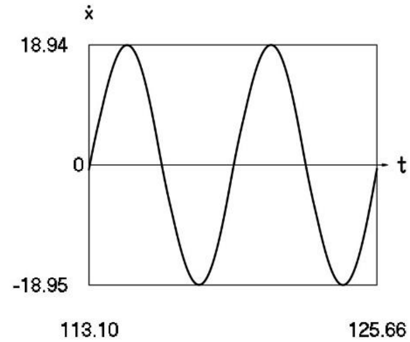
RESULTS OF INVESTIGATION OF THE PHENOMENON OF UNSYMMETRIC DRY FRICTION

The following values of the parameters of the investigated dynamical system were assumed: $\omega = 1$, $h = 1.6$, $m = 1$, $c = 0.1$, $k = 1$, $P = 4$. Calculations from zero initial conditions were performed. Two periods of steady state motions were investigated.

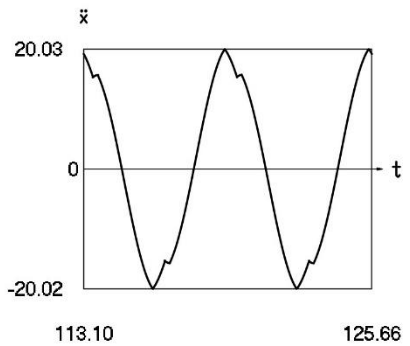
Results when $\Delta = \Delta_a = 3.2$ were obtained and are represented in Fig. 1.



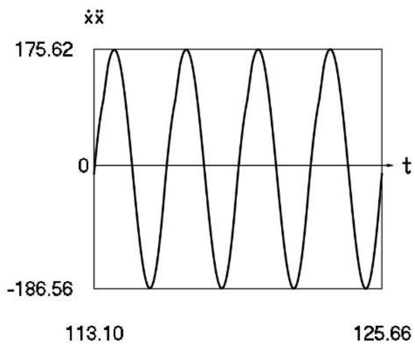
a) Variation of displacement as function of time



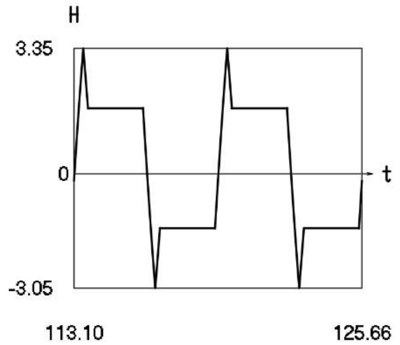
b) Variation of velocity as function of time



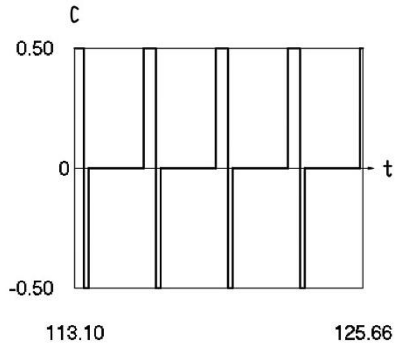
c) Variation of acceleration as function of time



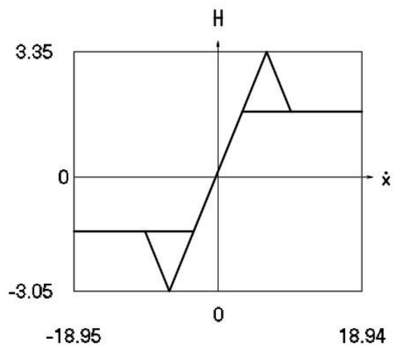
d) Variation of velocity multiplied by acceleration as function of time



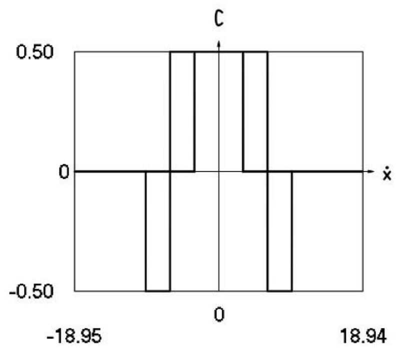
e) Variation of *H* as function of time



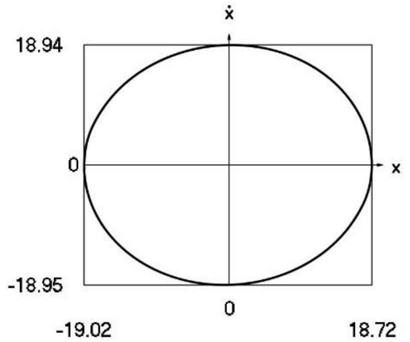
f) Variation of *C* as function of time



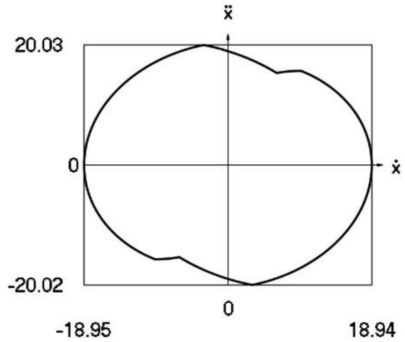
g) Variation of *H* as function of velocity



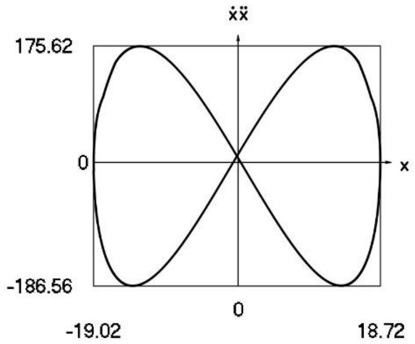
h) Variation of *C* as function of velocity



i) Representation in the phase plane: velocity as function of displacement



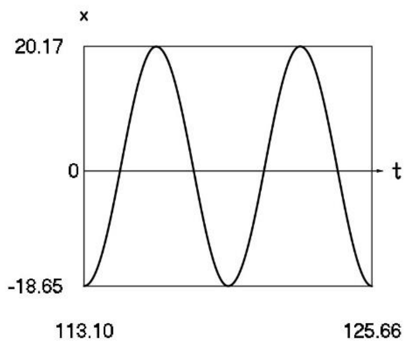
j) Representation in the phase plane: acceleration as function of velocity



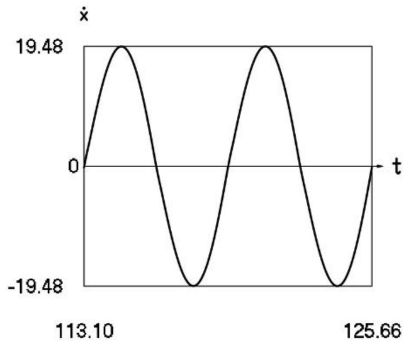
k) Representation in the phase plane: velocity multiplied by acceleration as function of displacement

Figure 1. Dynamics of the system with unsymmetric dry friction in steady state regime of motion for the case of wide transition regions

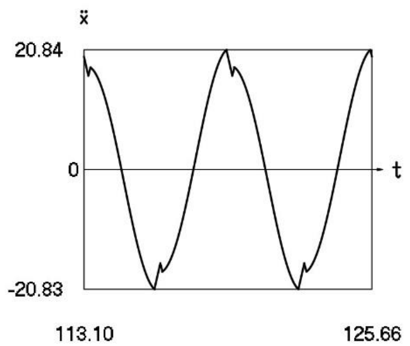
Results when $\Delta = \Delta_a = 1.6$ were obtained and are represented in Fig. 2.



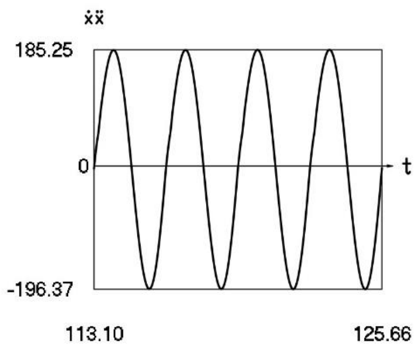
a) Variation of displacement as function of time



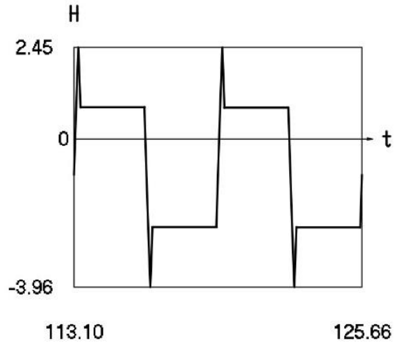
b) Variation of velocity as function of time



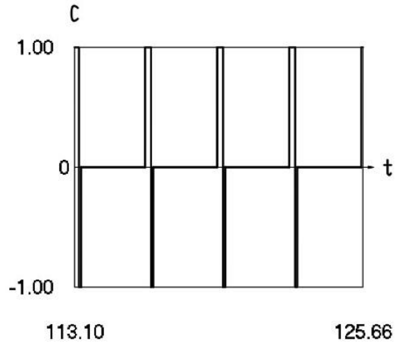
c) Variation of acceleration as function of time



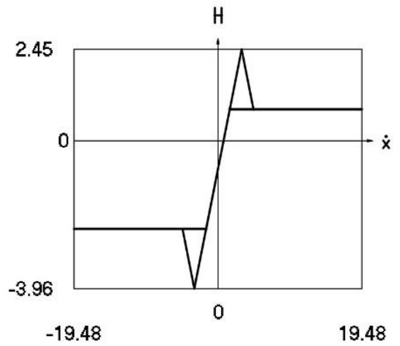
d) Variation of velocity multiplied by acceleration as function of time



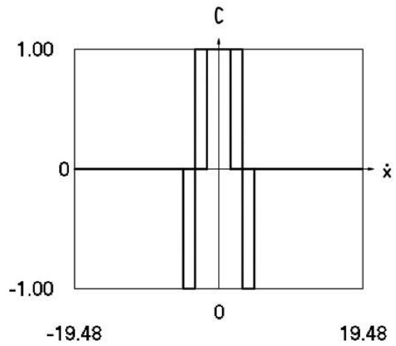
e) Variation of *H* as function of time



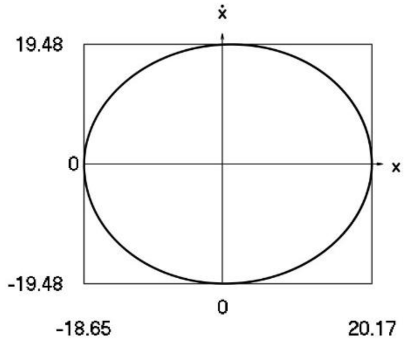
f) Variation of *C* as function of time



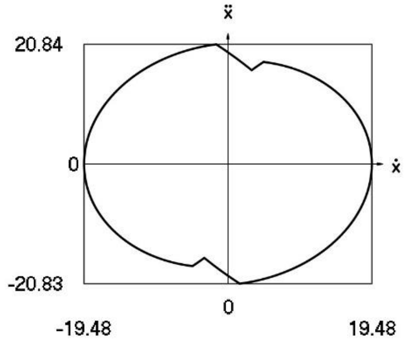
g) Variation of *H* as function of velocity



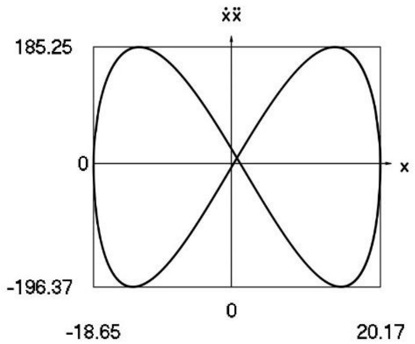
h) Variation of *C* as function of velocity



i) Representation in the phase plane: velocity as function of displacement



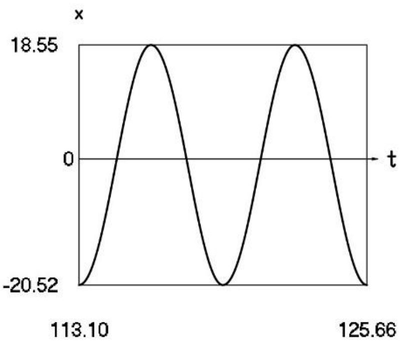
j) Representation in the phase plane: acceleration as function of velocity



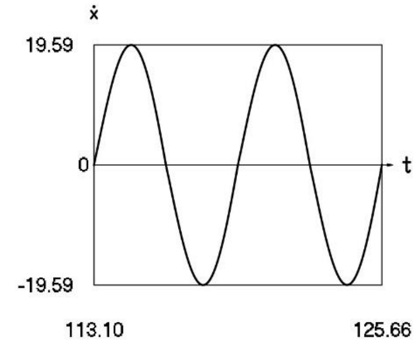
k) Representation in the phase plane: velocity multiplied by acceleration as function of displacement

Figure 2. Dynamics of the system with unsymmetric dry friction in steady state regime of motion for the case of transition regions of medium width

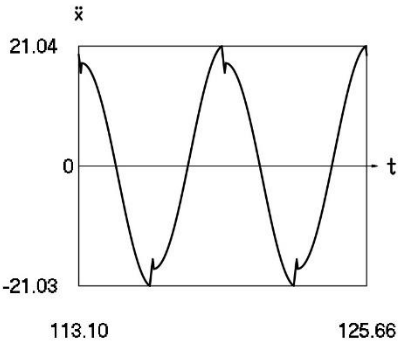
Results when $\Delta = \Delta_a = 0.8$ were obtained and are represented in Fig. 3.



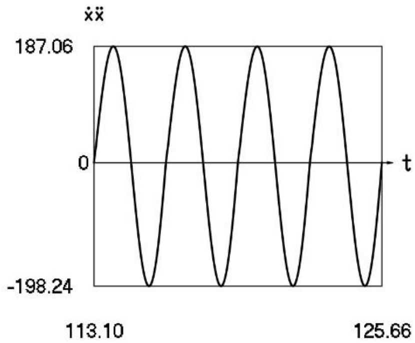
a) Variation of displacement as function of time



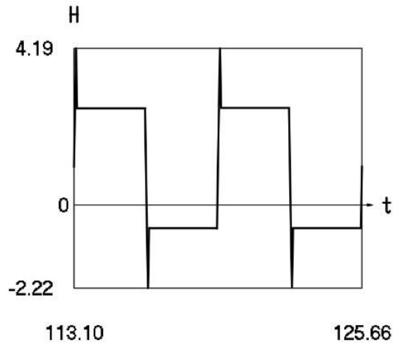
b) Variation of velocity as function of time



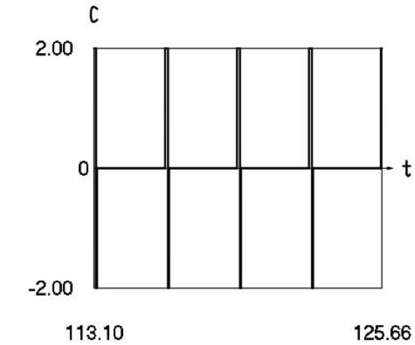
c) Variation of acceleration as function of time



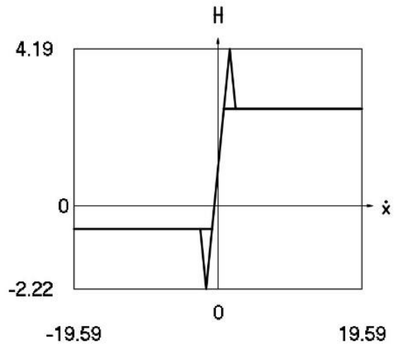
d) Variation of velocity multiplied by acceleration as function of time



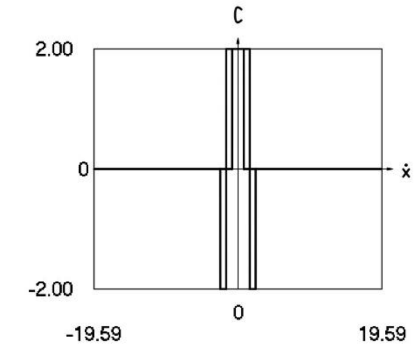
e) Variation of *H* as function of time



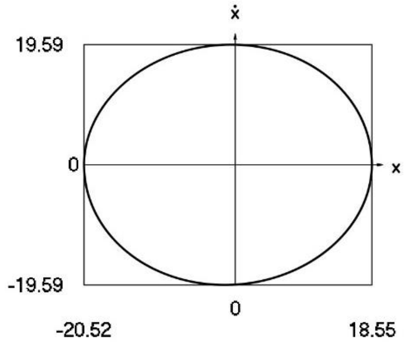
f) Variation of *C* as function of time



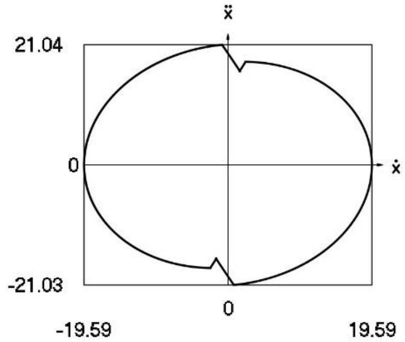
g) Variation of *H* as function of velocity



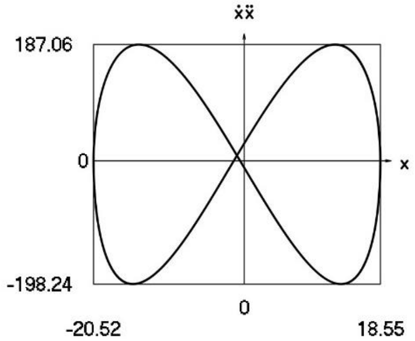
h) Variation of *C* as function of velocity



i) Representation in the phase plane: velocity as function of displacement



j) Representation in the phase plane: acceleration as function of velocity



k) Representation in the phase plane: velocity multiplied by acceleration as function of displacement

Figure 3. Dynamics of the system with unsymmetric dry friction in steady state regime of motion for the case of narrow transition regions

Three widths of both mutually equal transition regions are investigated. Results representing the dynamic behavior of the analysed system are presented in detail. The influence of the widths of the transition regions is observed in the presented graphical results.

CONCLUSIONS

Development of numerical models for surface cleaning is an important engineering problem. In the process of surface cleaning various nonlinear effects take place. For representation of some of those effects the model of unsymmetric dry friction is proposed. Numerical procedure for investigation of this phenomenon is described in detail. Results of calculations for various parameters of the investigated dynamical system are presented and analysed. From the obtained results the applicability of this model for reproduction of the investigated nonlinear phenomenon is seen.

Variation of displacement as function of time, variation of velocity as function of time, variation of acceleration as function of time, variation of velocity multiplied by acceleration as function of time are investigated. Variation of the quantities determining the unsymmetric force of dry friction as functions of time as well as functions of velocity are presented. Representations in the phase plane: velocity as function of displacement, acceleration as function of velocity, velocity multiplied by acceleration as function of displacement are investigated.

Three widths of both mutually equal transition regions are investigated. Results representing the dynamic behavior of the analysed system are presented in detail. The influence of the widths of the transition regions is observed in the presented graphical results.

The proposed model of unsymmetric dry friction is applicable as part of other more complicated models used for the investigations of the process of surface cleaning.

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K. Ragulskis, A. Bubulis, A. Pauliukas, P. Paškevičius, R. Maskeliūnas, L. Ragulskis. Unsymmetric dry friction for models of surface cleaning.

In the process of surface cleaning various nonlinear effects take place. Among the various nonlinear effects taking place in such systems dry friction is an important one. Thus a number of papers are devoted to the investigation of this effect. In numerical investigations usually some approximation of the transition regions between different constant values of the force of dry friction is used. This enables to approximate the nonlinear effects taking place in such systems. For representation of some of those effects the model of unsymmetric dry friction is proposed in this paper.

The investigated model has one degree of freedom and incorporates a specific type of nonlinearity. It involves the use of the quantities from the previous moment of time and logical operations “and” and “or”. Numerical procedure for investigation of this phenomenon is described in detail. Results of calculations for various parameters of the investigated dynamical system are presented and analysed. From the obtained results the applicability of this model for reproduction of the investigated nonlinear phenomenon is seen.

Variation of displacement as function of time, variation of velocity as function of time, variation of acceleration as function of time, variation of velocity multiplied by acceleration as function of time are investigated.

Variation of the quantities determining the unsymmetric force of dry friction as functions of time as well as functions of velocity are presented.

Representations in the phase plane: velocity as function of displacement, acceleration as function of velocity, velocity multiplied by acceleration as function of displacement are investigated.

Three widths of both mutually equal transition regions are investigated. Results representing the dynamic behavior of the analysed system are presented in detail. The influence of the widths of the transition regions is observed in the presented graphical results.

The proposed model of unsymmetric dry friction is applicable as part of other more complicated models used for the investigations of the process of surface cleaning.

KEYWORDS: SURFACE CLEANING, UNSYMMETRIC DRY FRICTION, NUMERICAL MODEL, NONLINEAR PHENOMENON, GRAPHICAL RESULTS.

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