EUROPEAN MECHANICS SOCIETY

EUROMECH
Colloquium 578

Rolling Contact Mechanics for Multibody System Dynamics

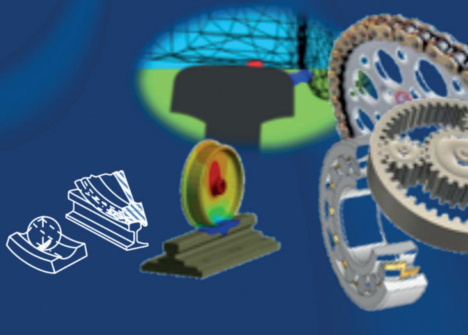
10 - 13 April 2017, Funchal, Madeira, Portugal

Book of Abstracts

PROGRAMME INCLUDED

Edited by:

Jorge A. C. Ambrósio, Werner Schiehlen and João Pombo



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EUROMECH COLLOQUIUM 578

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10 – 13 April 2017, Funchal, Madeira, Portugal

Title:

BOOK of ABSTRACTS of the EUROMECH Colloquium 578
on Rolling Contact Mechanics for Multibody System Dynamics

Editors:

Jorge A. C. Ambrósio, Werner Schiehlen and João Pombo

Institutional Support:

- *Institute of Mechanical Engineering (IDMEC), Portugal*
- *Instituto Superior Técnico, Lisboa, Portugal*
- *Direcção Regional do Turismo da Madeira*

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Welcome

On behalf of the organizers of the EUROMECH Colloquium 578 on Rolling Contact Mechanics for Multibody System Dynamics we are pleased to welcome you to Funchal for this event.

The main goal of the EUROMECH Colloquium is to bring together scientific experts in the different areas that contribute to the Rolling Contact Mechanics, evaluate the State-of-the-Art, identify the shortcomings and opportunities for research, and promote the interaction between leading scientists, young researchers and industrial experts. The Colloquium will address scientific topics that contribute to the mechanical and computational challenges to handle rolling contact mechanics in the context of multibody dynamics. The reviewing of the classic theories in elastic and plastic contact, the computational algorithms for their efficient use in the framework of multibody dynamics applications, the tribology aspects characteristic of many of the mechanical systems of interest, the consequences of wear both in the response of the system and in the use of the background contact theories are just some of the aspects of relevance that justify a close look.

We invite you to be an active participant in this Colloquium and to contribute to any topic of your scientific interest. By promoting a relaxed atmosphere for discussion and exchange of ideas we expect that new paths for research are stimulated and promoted and that new collaborations can be fostered. We hope that the EUROMECH Colloquium 578 on Rolling Contact Mechanics for Multibody System Dynamics will have an important impact on the research in all topics included in its programme.

We want to express our appreciation to all members of the Scientific Committee involved in the preparation of this Colloquium and the selection of contributors, to Mrs. Paula Jorge who managed its different aspects, and to all the contributing authors and participants who will support the forthcoming Colloquium. We hope that all of you feel rewarded for your participation and contribution, and that you may refer to it in the future as being an important event in the development of the scientific areas addressed.

Yours Sincerely,

Jorge Ambrósio • *Instituto Superior Técnico, University of Lisbon, Portugal*

Werner Schiehlen • *University of Stuttgart, Germany*

João Pombo • *Heriot-Watt University, United Kingdom*

COMITTEES

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Tel: +351 21 841 90 44

How to get to **EUROMECH COLLOQUIUM 578**

LOCAL

Hotel VIDAMAR RESORTS MADEIRA
Estrada Monumental 175-177,
9000-100 Funchal - Madeira - Portugal
Tel: (+351) 291 717 700

TAXI

There is one taxi stand at the Arrivals area of Madeira Airport, level 0.

PUBLIC TRANSPORTATION

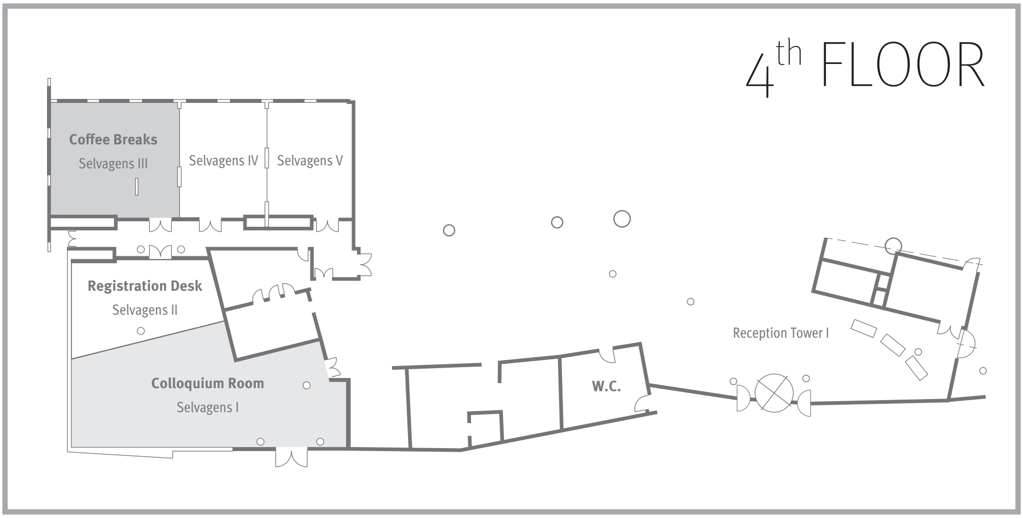
The aerobus works from 9:30 am to 0:45 am. It stops at Boa Nova, Campo da Barca, Praça da Autonomia, Marina Shopping and **Estrada Monumental**.

COLLOQUIUM ROOM

The Colloquium presentation room, Selvagens I, is located at the 4th Floor of the Hotel that is also the entrance floor.

REGISTRATION

Registration desk will be open one hour before the beginning of the colloquium: Monday, April 10, 13:00pm, in the Room ‘Selvagens II’



COFFEE-BREAKS

The coffee-breaks will take place in room 'Selvagens III', and will be open to all participants. Kindly wear your badge all time.

LUNCHES

The lunch tickets included in your badge will be honored at the restaurant of the Hotel Vida Mar 'Ocean Restaurante', 2nd Floor. Note that the restaurant tickets have different colors for the different days of the event and are only valid for the lunch of the day printed in front.

INSTRUCTIONS FOR PRESENTERS

Presentations will have 20 minutes, including discussion;
The files required for the presentation (PowerPoint or PDF) must be uploaded and tested in the computer of the room, before the beginning of the session. ***Colloquium computer runs Window 10 and have installed Office 2013 and Acrobat PDF reader.***

Tour and Colloquium Dinner Information

The Colloquium tour and Dinner will be held on April 12, bus will depart at 09:00 am from the Hotel VIDAMAR Resorts Madeira. ***Please, do not forget to bring your tour voucher.***

Wonders of the West - Porto Moniz

Leaving Funchal along the coastline, we reach Camara de Lobos (where Sir Winston Churchill spent some time painting during his stay in Madeira) then we reach Cabo Girão, which is the world's second highest sea cliff, finally reaching Ribeira Brava. Driving up the mountain, through the beautiful green valleys dotted with little white washed houses and dramatic waterfalls dropping from the heart of the mountain, all the way to Encumeada

surrounded by a Laurissilva forest. Continuing to Porto Moniz known for its natural swimming pools, originally created when the Volcanic lava first contacted with the Atlantic Ocean's cold water. Driving along the extravagant western and dramatic coast, our next stop will be at São Vicente for lunch at a 360º panoramic restaurant overlooking the ocean.

The tour will end with the Colloquium Dinner, at a typical Restaurant Adega da Quinta, a former manor house in Quinta do Estreito. A picturesque restaurant with panoramic windows overlooking the breathtaking view of the Câmara de Lobos bay and picture-perfect garden.
Bus should return the hotel around 10:00 p.m.

MOVING AROUND

Hotel VidaMar is located 10 minutes by bus, and 20 minutes walking from the Funchal City Center. The busses 01, 02 can be taken in Estrada Monumental. The distance between the Hotel's main door and the Estrada Monumental is ca 50 meters.

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PROGRAMME

PROGRAMME AT GLANCE

EUROMECH COLLOQUIUM 578
Rolling Contact Mechanics
for Multibody System Dynamics

10 – 13 April 2017
Madeira, Funchal
Portugal

	MONDAY **APR 10**	TUESDAY **APR 11**	WENDNESDAY **APR 12**	THURSDAY **APR 13**
09:00 – 10:40		**SESSION 03** 70 38 19 56 62		**SESSION 07** 69 34 67 68 9
10:40 – 11:00		*Coffee-Break*		*Coffee-Break*
11:00 – 12:40		**SESSION 04** 42 45 53 15 35 55		**SESSION 08** 24 13 5 33 61 31
13:00 – 14:00	***REGISTRATION***	*Lunch*		*Lunch*
14:00 – 14:20	**OPENING SESSION**	**SESSION 05** 63 41 17 25 57 36	***Colloquium Tour and Dinner***	**SESSION 09** 30 21 52 22
14:20 – 15:20	**SESSION 01** 47 4 18 29			
15:20 – 15:40				**CLOSING SESSION**
15:40 – 16:00	*Coffee-Break*			*Farewell Drink*
16:00 – 16:20	**SESSION 02** 1 3 40 10 2 51	*Coffee-Break*		
16:20 – 17:40		**SESSION 06** 32 12 16 44 26		
17:40 – 18:00				
18:00 – 22:00				

MONDAY, **APRIL 10**

13:00 – 14:00	*Registration*
14:00– 14:20	*Opening Session*

SESSION 01 — Session Chair: ***João Pombo***

Time	ID	Title
14:20	47	A SHORT HISTORY OF CONTACT MECHANICS, ROLLING CONTACT AND MULTIBODY ***Werner Schiehlen***
14:40	4	CURRENT UNDERSTANDING OF THE CREEP PHENOMENON ***Edwin Vollebregt***
15:00	18	ANALYTICAL MODELLING OF FRICTION ENHANCERS FOR WHEEL-RAIL CONTACT ***Katharina Babilon, Amir Moshiri-Kahak and Raphael Pfaff*** *Presenting Author:* ***Katharina Babilon***
15:20	29	TRIBOLOGY IN WHEEL-RAIL CONTACT AND CROSS CONNECTIONS TO TYRE-ROAD PHENOMENA ***Klaus Six, Alexander Meierhofer, Gerald Trummer, Bettina Suhr and Martin Rosenberger*** *Presenting Author:* ***Klaus Six***

15:40 – 16:00	*Coffee Break*

SESSION 02 — Session Chair: ***Paulo Flores***

Time	ID	Title
16:00	1	SOPHISTICATED BUT QUITE SIMPLE CONTACT CALCULATION FOR HANDLING TIRE MODELS ***Georg Rill***
16:20	3	MULTI-BODY VEHICLE SYSTEMS ROLLING ON ROAD PROFILES - VELOCITY TRANSFORMATIONS FROM WAY TO TIME ***Walter V. Wedig***
16:40	40	A VISCOELASTIC TYRE FRICTION MODEL BASED ON A PARTIAL DIFFERENTIAL-ALGEBRAIC INCLUSION ***Ryo Kikuuwe and Kahhaw Hoo*** *Presenting Author:* ***Ryo Kikuuwe***

17:00	10	USING OF PACEJKA TIRE MODEL WITHIN A POWERED TWO-WHEELERS MULTIBODY MODEL FOR EMERGENCY ***Laura Costa, Christophe Perrin and Thieery Serre*** *Presenting Author:* ***Thieery Serre***
17:20	2	IDENTIFICATION AND PREDICTION OF ROAD FEATURES AND THEIR CONTRIBUTION ON TIRE ROAD NOISE ***Johannes Masino, Benjamin Wohnhas, Michael Frey and Frank Gauterin*** *Presenting Author:* ***Michael Frey***
17:40	51	COMPLEMENTARITY PROBLEMS AND MULTIBODY DYNAMICS WITH CONTACTS, JOINTS, AND FRICTION ***Florian Potra***

TUESDAY, **APRIL 11**

SESSION 03 — Session Chair: *Stefano Bruni*

Time	ID	Title
09:00	70	ROLLING RESISTANCE MODELLING IN THE CELTIC STONE DYNAMICS ***Jan Awrejcewicz and Grzegorz Kudra*** *Presenting Author:* ***Jan Awrejcewicz***
09:20	38	CRACK GROWTH ASSESSMENT IN ROLLING/SLIDING CONTACT ***Michal Kráčalík and Werner Daves*** *Presenting Author:* ***Michal Kráčalík***
09:40	19	OCCURRENCE AND REMOVAL OF WIGGLES IN TRANSIENT ROLLING CONTACT SIMULATION ***Ivan Kosenko, Sergey Stepanov and Kirill Gerasimov*** *Presenting Author:* ***Ivan Kosenko***
10:00	56	FULL-SCALE TESTING OF LASER CLAD RAIL TRACK; PART II - RESULTS OF SUB-SURFACE MICROSTRUCTURAL, MICRO-HARDNESS AND RESIDUAL STRESS ANALYSIS ***Stephen Lewis, Dirk Engelberg, Shaun Earl, Aditya Narayanan, David Fletcher, Mahmoud Mostafavi, Matthew Peel, Martyn Pavier and Roger Lewis*** *Presenting Author:* ***Roger Lewis***
10:20	62	MODELING AND ANALYSIS OF FRICTION EFFECTS IN MULTIBODY DYNAMICS ***Filipe Marques, Paulo Flores, José Carlos Pimenta Claro and Hamid M Lankarani*** *Presenting Author:* ***Filipe Marques***

10:40 – 11:00 *Coffee Break*

SESSION 04 — Session Chair: *Werner Schiehlen*

Time	ID	Title
11:00	42	A FAST METHOD FOR DETERMINATION OF CREEP FORCES IN NON-HERTZIAN CONTACT OF WHEEL AND RAIL BASED ON A BOOK OF TABLES ***Stefano Bruni, Jerzy Piotrowski, Binbin Liu and Egidio Di Gialleonardo*** *Presenting Author:* ***Stefano Bruni***
11:20	45	FROM SEMI-HERTZIAN TO EQUIVALENT CONTACT MODELS IN A SIMULINK MULTIBODY ENVIRONMENT ***Hugues Chollet***

11:40	53	CHARACTERISTICS OF WHEEL-RAIL CONFORMAL ROLLING CONTACT ***Julio Blanco-Lorenzo, Javier Santamaria, Ernesto G. Vadillo and Nekane Correa*** *Presenting Author:* ***Julio Blanco-Lorenzo***
12:00	15	ACCURACY AND COMPUTATIONAL EFFICIENCY OF RAILWAY MULTIBODY MODELS WITH CONTACT LOOKUP TABLES ***José L. Escalona and Javier F. Aceituno*** *Presenting Author:* ***Javier F. Aceituno***
12:20	35	A CO-SIMULATION APPROACH TO THE RAIL-WHEEL CONTACT WITH FLEXIBLE RAILWAYS ***Pedro Antunes, Hugo Magalhães, Jorge Ambrosio, João Pombo and Joao Costa*** *Presenting Author:* ***Pedro Antunes, Hugo Magalhães***
12:40	55	DAMAGE MECHANISM RELATED TO PLASTICITY AROUND HETEROGENEOUS INCLUSIONS UNDER ROLLING CONTACT LOADING ***Philippe Kwassi Amuzuga and Daniel Nelias*** *Presenting Author:* ***Philippe Kwassi Amuzuga***

13:00 – 14:00	*Lunch*

SESSION 05		Session Chair: *Arend Schwab*
Time	ID	Title
14:00	63	CALCULATION OF THE DYNAMIC BEHAVIOR OF ROLLING BEARINGS WITH DETAILED CONTACT CALCULATIONS ***Timo Kiekbusch and Bernd Sauer*** *Presenting Author:* ***Timo Kiekbusch***
14:20	41	SIMPLIFICATION OF FOUR CONTACT POINT SLEWING BEARINGS FOR MULTIBODY SIMULATIONS ***Iker Heras, Josu Aguirrebeitia, Mikel Abasolo and Joseba Albizuri*** *Presenting Author:* ***Iker Heras***
14:40	17	DYNAMICAL SIMULATION OF ROLLING BEARINGS WITH ELASTIC PARTS IN CABA3D ***Dmitry Vlasenko*** *Presenting Author:* ***Dmitry Vlasenko***
15:00	25	AN ADVANCED MODELING TECHNIQUE FOR ROLLING ELEMENT BEARINGS IN ELASTOHYDRODYNAMIC LUBRICATION (EHL) ***Leoluca Scurria, Jakob Fiszer, Tommaso Tamarozzi, Pavel Jiranek and Wim Desmet*** *Presenting Author:* ***Leoluca Scurria***

15:20	57	FRICTION COEFFICIENT ROLE ON EFFICIENCY OF SPUR GEARS WITH TIP RELIEFS ***Alberto Diez-Ibarbia, Alfonso Fernandez-Del-Rincon, Ana De-Juan, Miguel Iglesias, Pablo Garcia and Fernando Viadero*** *Presenting Author:* ***Alberto Diez-Ibarbia***
15:40	36	COMBINED EFFECTS OF ELASTIC DEFORMATION AND LUBRICATION ACTION IN HUMAN KNEE JOINTS ***Paulo Flores and Filipe Marques*** *Presenting Author:* ***Paulo Flores***
16:00 – 16:20		*Coffee Break*

SESSION 06		**Session Chair:** ***Georg Rill***
Time	ID	Title
16:20	32	A LINEAR TYRE MODEL FOR BICYCLE HANDLING EVALUATION ***Arend Schwab and Jaap Meijaard*** *Presenting Author:* ***Arend Schwab***
16:40	12	ANALYSIS OF THE TYRE-ROAD INTERACTION WITH A NON-SMOOTH DELAYED CONTACT MODEL ***Sandor Beregi and Denes Takacs*** *Presenting Author:* ***Sandor Beregi***
17:00	16	EXPERIMENTAL OBSERVATION ON TYRE TREAD RUBBER NORMAL CONTACT HYSTERESIS ***Ye Zhuang, Chengwei Zhu and Yong Wang*** *Presenting Author:* ***Ye Zhuang***
17:20	44	A TIRE MODEL BASED ON GEOMETRICALLY EXACT SHELLS FOR MODAL ANALYSIS IN STEADY STATE ROLLING ***Michael Roller, Joachim Linn, Axel Gallrein and Peter Betsch*** *Presenting Author:* ***Joachim Linn***
17:40	26	INFLUENCE OF THE TIRE DAMPING TO THE TIRE-ROAD VERTICAL CONTACT DYNAMICS ***Ye Zhuang, Xueliang Gao and Yong Wang*** *Presenting Author:* ***Yong Wang***

WEDNESDAY, **APRIL 12**

09:00 – 22:00	*Colloquium Tour and Dinner*

THURSDAY, **APRIL 13**

SESSION 07		**Session Chair:** ***Jan Awrejcewicz***
Time	**ID**	**Title**
09:00	69	COATING BEHAVIOR IN HEAVILY LOADED LUBRICATED CONTACTS ***Ilya I. Kudish, Sergey S. Volkov, Andrey S. Vasiliev and Sergey M. Aizikovich*** *Presenting Author:* ***Sergey M. Aizikovich***
09:20	34	MULTIBODY MODELLING AND DYNAMIC ANALYSIS OF TAPERED ROLLER BEARINGS ***Jorge Ambrósio, Marisa Lima and Gil Santos*** *Presenting Author:* ***Jorge Ambrósio***
09:40	67	KINETIC AND CONTACTING ANALYSES OF MULTI-CYCLES PRELOADED BALL-SCREW ***Chin-Chung Wei***
10:00	68	APPLICATION OF A TRANSIENT ROLLING-CONTACT MODEL TO THE DYNAMICS OF ELASTIC BALL-PLANE/V-GROOVE CONTACT ***Farid Al-Bender***
10:20	9	INTERACTION OPTIMIZATION IN BRIDGE-TRACK-CAR SYSTEM ***Vladimir Poliakov***

10:40 – 11:00	*Coffee Break*

SESSION 08		**Session Chair:** ***Edwin Vollebregt***
Time	**ID**	**Title**
11:00	24	REVIEW OF THE DEVELOPMENT OF THE CREEP-CONTROLLED WHEELSET FOR HIGH-SPEED RAILWAY VEHICLES ***Reinhold Meisinger***
11:20	13	WEAR IN ROLLING CONTACT OF RAILWAY WHEELS WITH WATER AND ICE IN THE CONTACT ZONE ***Michael Beitelschmidt, Sten Urban and Bernhard Peters*** *Presenting Author:* ***Michael Beitelschmidt***
11:40	5	INFLUENCE OF THE ROLLING RESISTANCE ON THE PRESSURE DISTRIBUTION OF THE WHEEL RAIL CONTACT ***Florian Doerner and Christian Schindler*** *Presenting Author:* ***Florian Doerner***

12:00	33	SIMULATION OF A SHARP CURVED TRACK ON A ROLLER RIG ***Jan Kalivoda***
12:20	61	ON DEVELOPING A TRAM NEW WHEEL PROFILE USING MULTIBODY SIMULATION TOOLS ***Tomasz Staskiewicz, Bartosz Firlik, Wojciech Jaskowski and Leszek Wittenbeck*** *Presenting Author:* ***Tomasz Staskiewicz***
12:40	31	MODELLING OF SPATIAL MECHANICAL JOINTS WITH REALISTIC PROPERTIES: A FINITE ELEMENT ANALYSIS ***Fernando Isaac, Filipe Marques, Nuno Dourado and Paulo Flores*** *Presenting Author:* ***Fernando Isaac***
13:00 – 14:00		*Lunch*

SESSION 09		**Session Chair:** ***Jorge Ambrósio***
Time	**ID**	**Title**
14:00	30	INHERENT DYNAMIC BALANCING OF LINKAGES WITH ROLLING JOINTS ***Volkert van der Wijk***
14:20	21	OCCURRENCE AND REMOVAL OF WIGGLES IN TRANSIENT ROLLING CONTACT SIMULATION ***C.D. Van der Wekken, E.A.H. Vollebregt and C. Vuik*** *Presenting Author:* ***C.D. Van der Wekken***
14:40	52	IMPLEMENTATION OF THE INTERACTION BETWEEN THE BILLET AND THE ROLL IN A MESHLESS BASED HOT ROLLING SIMULATION ***Umut Hanoglu and Bozidar Sarler*** *Presenting Author:* ***Umut Hanoglu***
15:00	22	DRY FRICTION DISTRIBUTED OVER A CONTACT PATCH BETWEEN A RIGID BODY AND A VISCO-ELASTIC PLANE ***Alexandra Zobova***
15:20		*CLOSING SESSION*
		FAREWELL DRINK

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ABSTRACTS

Abstract ID-1

SOPHISTICATED BUT QUITE SIMPLE CONTACT CALCULATION FOR HANDLING TIRE MODELS

Georg Rill

OTH Regensburg, Germany

georg.rill@oth-regensburg.de

Keywords: contact point calculation, effective road plane, tire model, vehicle model, simulation results

Summary: Handling tire models like Pacejka [1] or TMeasy [2] consider the contact patch as one coherent plane. As a consequence, the irregularities of a rough road profile must be approximated by an appropriate local road plane that serves as an efficitive road plane in order to calculate the geometric contact point and the corresponding contact velocities. The Pacejka/SWIFT tire model employs a road enveloping model that generate the effective height and slope by two rigid elliptical cams that represent the front and rear edges of the tire in the contact zone. TMeasy just uses four representative road points for that purpose. In addition, TMeasy shifts the geometric contact point to a static contact point that describes the point where the resulting normal force is applied. A further shift to a dynamic contact point takes the compliance of the tire in lateral direction into account. In doing so, a rather sophisticated but still simple contact calculation is possible. Simulations obtained with a simple tire test rig and fully nonlinear three-dimensional models of a motor-scooter and a passenger car will demonstrate the potential of this contact approach.

References:

[1] Pajejka, H.: Tire and vehicle dynamics. Elsevier, 2005.

[2] Rill, G.: TMeasy – The handling tire model for all driving situations. In M.A. Savi, editor, Proc. of the XV Int. Symp. on Dynamic Problems of Mechanics (DINAME 2013), Buzios, RJ, Brazil, February 17-22, 2013.

Abstract ID-2

IDENTIFICATION AND PREDICTION OF ROAD FEATURES AND THEIR CONTRIBUTION ON TIRE ROAD NOISE

Johannes Masino, Benjamin Wohnhas, Michael Frey, Frank Gauterin

Karlsruhe Institute of Technology, Germany
johannes.masino@kit.edu, benjamin.wohnhas@googlemail.com, michael.frey@kit.edu, frank.gauterin@kit.edu

Keywords: Road condition, tire road noise, prediction of road features, road feature classification

Summary: The type and condition of road surfaces have not only various influences on the vehicle itself and the passengers, but also affect people living close to road infrastructure and pedestrians. A big contributor to traffic noise is the tire road noise, not only above 40km/h, but in all driving conditions. Many studies show the effect of traffic noise on the living quality, the impact on health and found relationships between the level of transportation noise and speech interference, sleep disturbances, and general annoyance.
Other literature studies the relationship between mean roughness and tire road noise or found an increase of up to ± 5dB(A) depending on the texture of the road surface. However, less focus was set on the investigation of the influence of road features, such as level crossings, roadway damages, road condition, on the tire road noise. With our paper we close this gap in the literature.
Firstly, we identify relevant road features based on civil engineering literature and interviews with experts, which can mainly be found on city roads. Secondly, we perform experimental measurements based on international standards, such as the Controlled-Pass-By method (ISO 13325:2003), to characterize the sound pressure level of these road features and the contribution to road noise in reference to a road with low level tire road noise. To investigate the effects of various parameters, we perform the measurements with different experimental setups, e.g. varied velocities and vehicles.
The results of our experiment confirm our hypothesis and show a significant noise contribution from road features, such as potholes, level crossings, etc. Furthermore, we present a method how to comprehensively predict and identify road features with vehicle sensors to monitor city roads. With this output, one can prioritize road segments with high level of noise and repair them specifically and efficiently.
Overall, we not only investigate the influence of road features on road noise but also a method how to identify them. Therefore, our paper is a contribution to increase the living quality efficiently.

Abstract ID-3

MULTI-BODY VEHICLE SYSTEMS ROLLING ON ROAD PROFILES - VELOCITY TRANSFORMATIONS FROM WAY TO TIME DOMAIN

Walter V. Wedig

KIT Karlsruher Institut für Technologie, Germany
wwedig@t-online.de

Keywords: Stochastic FFT Analysis, Variance Velocity Diagrams, Mean Velocity Jumps, Bifurcations in Probability, Nonlinear Wave Road Effects

Summary: For the stochastic FFT analysis [1] of measured road surfaces, Kolmogorov's theorem of symmetry and consistency is applied to scale the power spectrum distributions obtained by averaging the piecewise Fourier series expansions of the road data. The paper proposes the same technique to derive velocity transformations necessary when the vehicle is rolling with various speeds on road surfaces which are e.g. optically scanned with slow motion. In correspondence to harmonic wave roads, frequency distributions of road excitations depend on the velocity of stationary measurement meanwhile variance and mean of the road process remain invariant with respect to velocity changes of the vehicle.

Applications of first order road profiles to multi-body system dynamics are discussed for half-car models with n wheels and m degrees of freedom. Stationary car vibrations are investigated by means of covariance equations [2] where the classical algebraic part is extended by exponential matrix functions of the system matrix multiplied by the time differences of all ground contacts in order to include ground correlation effects. A caravan trailer of seven degrees of freedom and three wheels e.g. leads to 153 co-variances showing increasing sub-resonances in the variance-velocity diagram induced by the time delays in the three base excitations through the wheels.

The road-vehicle models become highly nonlinear when the velocity of the vehicle is fluctuating because of the up and down of the road surface and the strong coupling of the along and across car dynamics. New effects derived in this paper are probability bifurcations of stationary vehicle velocities. The unimodal velocity density bifurcates into a bimodal probability distribution with two peaks when the driving force approaches the critical range where the vertical car vibrations become resonant. In the special case of harmonic wave roads, the paper derives corresponding effects of deterministic velocity jumps of vehicles that coincide exactly with the well-known effect well-known in rotor dynamics already detected by A. Sommerfeld [3] in 1902.

References:

[1] *Wedig,WV. Jump Phenomena in Road-Vehicle Dynamics, Int. J. of Dynamics and Control, ISSN 2195-268X, Springer: Berlin. 2015.*

[2] *Wedig, VW. New resonances and velocity jumps in nonlinear road-vehicle dynamics. In: Procedia IUTAM, Volume 19, IUTAM Symposium Analytical Methods in Nonlinear Dynamics, edited by Peter Hagedorn and Eoin Clerkin, Elsevier B.V. pp. 209-218, 2016.*

[3] *Sommerfeld, A. Beiträge zum dynamischen Ausbau der Festigkeitslehre, In: Physikalische Zeitschrift, 3. No.13, p.266 & 286, 1902*

Abstract ID-4

CURRENT UNDERSTANDING OF THE CREEP PHENOMENON

Edwin Vollebregt

VORtech CMCC, Netherlands
edwin.vollebregt@vortech.nl

Keywords: rolling contact, creepage, creep force, friction, wheel-rail

Summary: The cornerstone of wheel-rail rolling contact theory is the creep phenomenon. This was described in a qualitative way by Reynolds (1874) and then modelled quantitatively by Carter (1926) and Fromm (1927). In 1958 Johnson extended the initial 2D theory to 3D, including lateral creepage and spin. After that Kalker developed the linear theory (1967), simplified theory (1973) and full (variational) theory (1979) and the corresponding FASTSIM (1982) and CONTACT algorithms (1982-1990).

Recent developments mainly focus on the deviations of these initial theories from experimental creep force measurements. For small creepages the creep force increases less rapidly than predicted by theory, and for large creepages the creep force decreases instead of staying constant at the Coulomb maximum. These effects were described by Bucher (2002) and Ertz (2004), implemented by Polach in his fast algorithm (2005), incorporated into FASTSIM by Spiryagin, Polach and Cole (2013) and in CONTACT by Vollebregt (2014). Related work is done at the Virtual Vehicle research center by Tomberger (2011) and Meierhofer et.al. (2014).

Experience shows that these theories work, but the creep phenomenon itself remains kind of mysterious. Why is this creeping at any rate possible? How does the relationship between creepage and creep force come about? And where does friction fit in?

In this paper we'll present our current understanding of the creep phenomenon. First of all, we distinguish two different forms, due to traction and due to material or geometric dissimilarity. Then we'll advocate that creepage is actually the by-product of a more fundamental mechanism, the elastic deformation of objects under force. We equate friction in the contact interface to the amount of deformation of the bodies involved. In rolling this deformation "leaks away" and produces creepage as a result. This explains, among others, why the creep force depends on the relative velocity difference. A schematic is then presented that describes rolling contact using non-linear spring and damping elements. We'll show how this relates to the common formulas, and how this predicts a new "rocking phenomenon" that has so far not been observed.

Abstract ID-5

INFLUENCE OF THE ROLLING RESISTANCE ON THE PRESSURE DISTRIBUTION OF THE WHEEL RAIL CONTACT

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Keywords: finite-element-analysis, rolling resistance, wheel-rail contact

Summary: It has been proven by physical experiments that the anelastic material behavior of the wheel and rail steel is the main cause of the rolling resistance. Its value depends on the load, the speed and the wheel radius and can reach up to a maximum of 0.0015. In Point Mechanics the rolling resistance is modelled by the forward movement of the area center of the pressure distribution. This movement is caused by non-symmetry owing to the anelastic material behavior and is about 0.7 mm for high rolling resistance values. The point of maximum pressure moves even more due to the non-symmetry.
The research work shows that anelastic material data for situations like the wheel-rail-contact is not available in literature and cannot be obtained from experiments. Therefore, the linear viscoelastic constants of the wheel and rail steel are adapted to fit the rolling resistance values in finite element simulations. Based on these results it has to be assumed that the rolling resistance leads to an increase of approximately 10% in the maximum pressure value and an approximate decrease of 10% in the value of the contact area for high rolling resistance.

Abstract ID-9

INTERACTION OPTIMIZATION IN BRIDGE-TRACK-CAR SYSTEM

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Keywords: high-speed railway, bridge dynamics, safety of motion, track, wearing, comfort

Summary: The paper will describe the optimization facility of interaction within the bridge-track-car system that concerns high-speed railway traffic on the bridges zones. The complete model taking into account vertical oscillation of the car body, bogies, wheels, rails, and superstructure of the bridge. There are several criteria that allow estimating various parameters of dynamic interaction and reaching the optimal dynamic parameters dealing with wheel-rail contact safety, comfort of passengers, and ballast wearing.

Abstract ID-10

USING OF PACEJKA TIRE MODEL WITHIN A POWERED TWO-WHEELERS MULTIBODY MODEL FOR EMERGENCY SITUATIONS ANALYSIS

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Keywords: Motorcycle dynamics, Pacejka tire model, Emergency manoeuvres

Summary: This paper deals with a numerical modelling of the Powered Two-Wheelers (PTW) dynamic in order to simulate its behaviour during emergency situations. Firstly, a multibody model of a Honda VFR has been developed. It consists of six bodies and eleven degrees of freedom and takes into account the specificities to simulate hard braking, avoidance and slalom manoeuvres. The different bodies are the rear and front wheels, the fork unsprung masses, the fork sprung masses and handlebar, the main frame with the driver body and the swinging arm. The main frame is free (six degrees of freedom), each wheel had one degree of freedom in rotation, the handlebar had one degree of freedom in rotation like the swinging arm and the fork had one degree of freedom in translation. The inputs of the model are the traction or braking force and the torque applied by the driver on the handlebar.

In order to ensure the stability of the vehicle, special attention is focused on the modelling of tires and suspensions. The model is developed with a classic telescopic fork and swinging arm for suspensions. Concerning tires, to ensure road/tire contact, the Magic Formula tire model of Pacejka adapted to motorcycle is implemented. Its particularity is the lateral force (F_yo) which consists of lateral force and camber thrust. The second term is the equation for camber angle. As with the Magic Formula equation used for automobiles, the tire model's lateral force F_yo is determined by the ''Magic Formula coefficients'' B_y, C_y, D_y, E_y, B_y, C_y, E_y and S_hy and by variables indicating the tire's condition : vertical load, tire slip angle and camber angle.

In parallel, a motorcycle Honda VFR was instrumented to conduct a series of track tests in order to validate the model. Around forty emergency manoeuvres have been realised (slaloms, avoidances, hard braking) and simulated to compare the data from the experimentation and numerical simulation.

Abstract ID-12

ANALYSIS OF THE TYRE-ROAD INTERACTION WITH A NON-SMOOTH DELAYED CONTACT MODEL

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Keywords: tyre-road contact, dynamic tyre deformation, non-smooth delayed tyre model, lateral vibrations, wheel shimmy

Summary: The vibration of an elastic tyre running on a rigid road surface is one of the oldest and most challenging problems in vehicle dynamics. Therefore, several tyre models have been developed to capture the deformed shape of the contact region and calculate the resulting tyre forces. However, the most commonly used quasi steady-state tyre models tend to be inaccurate in the low or medium speed range. One solution to overcome this issue is to introduce time relaxation parameters addressed to certain dynamic features of the tyre. Nevertheless, this can result some loss of the physical insight. Alternatively, more complex, continuum-based tyre models can be used which are capable to describe the travelling waves in the rolling tyre-ground contact. Unfortunately these lead to partial differential equations, which can be solved only numerically, e.g. using finite element algorithms.

The stretched string tyre model can be a good compromise in this respect since for pure rolling the deformation is described by a single PDE for which the travelling wave solution can be composed analytically. However, this travelling wave solution cannot capture the sliding effect in the contact region. In our study we introduce a numerical method in which the travelling wave solution related to rolling and the partial side-slip of the contact patch are taken into account simultaneously. A case-selective algorithm is used which determines the sticking and sliding regions that can occur while the tyre makes lateral vibrations.

The above described non-smooth delayed tyre model is implemented in the numerical simulation of a towed wheel. It is shown that this model enables to identify the so-called hysteresis effect regarding stability. Namely, if the rectilinear motion becomes unstable by increasing the towing speed, the shimmy motion disappears only for smaller speeds than it is suggested by the linear stability boundary. Thus, our method is capable to provide qualitatively very accurate results using a low number of tyre parameters, whereas the computation time still remains manageable. Therefore, the non-smooth delayed tyre model can be suitable to be developed further for real-time simulation environments.

Abstract ID-13

WEAR IN ROLLING CONTACT OF RAILWAY WHEELS WITH WATER AND ICE IN THE CONTACT ZONE

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Keywords: Rolling Contact, Wear, Rail Wheel System, Winter Conditions, Water Intermediate Layer, Ice Phase Transition, Ice Modifications, Discrete Element Model

Summary: Observations of railway operators show a remarkably increased wear rate of railway wheels under extreme winter conditions, especially at locomotive wheels. Examinations of worn wheels show abrasion and not rolling contact fatigue as the main cause of material removal. The presence of a water and ice layer in the contact zone may influence the contact fundamentally and may play an important role in the not yet fully understood wear mechanism. Pressures in the rail wheel contact reach values up to 1000 MPa in a contact time below 500 µs. In this temperature and pressure regime, if prevailing in the contact zone, at least six different modifications of ice exist besides the liquid water phase. Even at temperatures above 0° C an ice modification may exist. Therefore, highly dynamic phase change processes in the water/ice layer can be observed. Therefore, the objective of the current proposal is to describe numerically the water/ice to steel interaction by a discrete approach for both ice and water with appropriate material properties. The phase change path in the pressure-temperature field of a representative ice and water particle is examined by solving the differential equation system for the change of temperature and phase fractions with respect to time subject to the pressure time history of a roll-over period. It shows that during the contact time, several phase changes occur and ice modifications with a density of more than 1300 kg/m³ exist. These processes may take place in cavities and asperities of the steel surface and possibly lead to additional stress causing wear in the wheel's material.

Abstract ID-15

ACCURACY AND COMPUTATIONAL EFFICIENCY OF RAILWAY MULTIBODY MODELS WITH CONTACT LOOKUP TABLES

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Keywords: Multibody railway dynamics, Contact lookup tables, Symbolic computation

Summary: This paper shows a computationally real-time capable formulation of the equations of motion of railway vehicles. The main features of the approach described in this paper are:
The equations of motion are obtained using a systematic procedure based on multibody dynamics.
The terms of the equations of motion are obtained using symbolic computations when possible.
Coordinates used to describe the kinematics of the bodies are referred to a track frame that follows the bodies movement. In addition, moving frames to describe the bodies relative motion with respect to track are defined.
The equations of motion are obtained using a velocity transformation of the Newton-Euler equations of the vehicle bodies, which are assumed to be rigid.
Relative motion between group of bodies is described by adopting relative coordinates which avoid the use of constraints.
Wheel-rail tread contacts and flange contacts are treated with pre-calculated lookup tables which can take into account the track irregularities.
The comparative study presented in this paper when applying the formulation proposed to a railroad vehicle shows that it could simulate the motion of a vehicle in real time.

Abstract ID-16

EXPERIMENTAL OBSERVATION ON TYRE TREAD RUBBER NORMAL CONTACT HYSTERESIS

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Keywords: tyre-road viscoelastic contact, compliant contact model, rubber impact experiment

Summary: The contact interface in multibody mechanical systems is very important, since it would largely influence the system performance. To simulate and evaluate such interface for better system design, a lot of contact models have already been proposed under hertz theory and later augmented with the damping (viscoelasticity) or energy dissipation to express the nonlinear elastic and viscoelastic properties in compliant contact. While, there is not much contact experiment results shown in the literatures. In this paper a novel impact drop test rig is developed, which simulate the tyre-road vertical contact by the impact between a falling steel sphere and the fixed tread rubber specimen. To precisely capture the contact process in the short interval, the indentation depth, impact acceleration and contact force during the contact are measured simultaneously by the linear encoder, accelerometer and force transducer respectively. Several tyre tread rubber specimens with different viscoelastic property are tested with the rig. Some interesting phenomena could be observed, 1). The depth-dependent-hysteresis in the force-indentation plot is significant in all the test results. The difference between the contact force in the compressing (loading) and in the rebound (unloading) phase is obvious. While, the contact adhesion force is not significant in the test. There is no obvious minus force in the hysteresis figure; 2). The contact force hysteresis loop of different specimen could be observed and correlated well with the rebound height. The lower the rebound height the larger is the hysteresis loop area; 3). The asymmetry of the energy dissipation in loading and unloading phase within each hysteresis loop is quite clear. The analysis of the test data is followed. And to better interpret the experiment data, the compliant models available are selected to fit the test data. Then a modified model is proposed to express the asymmetrical energy dissipation in the hysteresis loop curves.

Abstract ID-17

DYNAMICAL SIMULATION OF ROLLING BEARINGS WITH ELASTIC PARTS IN CABA3D

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Keywords: Multibody dynamics with rolling elements, Roller bearing dynamics, Elastic rolling contact, Elastic multibody dynamics

Summary: Nowadays CABA3D (Computer Aided Bearing Analyzer 3D) developed by Schaeffler Technologies is one of the most powerful industrial software for the simulation of dynamic processes in rolling bearings. CABA3D has, in contrast to conventional multi-body software, a hydrodynamic friction and contact model specially designed for rolling bearings. The tool provides information about kinematics, load distribution and friction forces of bearing elements (rings, cages, rolling elements, etc.), helping engineers to understand phenomena inside rolling bearings.
The simulation results in reference FEA software show that elasticity of bearing elements can significantly influence on the dynamics, kinematics, load distribution and friction forces acting in bearings.
The paper is concerned the dynamical simulations of bearings with elastic parts in CABA3D. Since the deformations of the elastic parts are small, the model reduction techniques can be used for the reduction of computational cost to acceptable levels.
The newest version of contact model in CABA3D calculates the contact forces between elastic and rigid bearing elements. It is shown that distributed coupling methods can be used for the definition of contacting faces in elastic bodies. The “slicing” contact model in CABA3D was sufficiently adapted for elastic bodies.
Simulation results show that CABA3D provides very detailed and precise information regarding contacts and dynamics of rigid and elastic bearing elements.

Abstract ID-18

ANALYTICAL MODELLING OF FRICTION ENHANCERS FOR WHEEL-RAIL CONTACT

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Keywords: wheel-rail contact, adhesion enhancer, analytical modelling

Summary: Modelling of the wheel-rail contact is a topic in railway research almost since beginning of operation. Initially, the focus was mainly on effects in the running dynamics of vehicles. Analytical modelling approaches, such as Carter, de Pater and Johnson or Haines and Ollerton dominated the research of the first decades. In contrast to these, Kalker devised the well-known CONTACT and later FASTSIM algorithm, which were developed with computational efficiency in mind. Especially FASTSIM is well used to day. More recent approaches, thanks to the advent of accessible computer power, used a finite element analysis of the wheel-rail contact area.
Most solutions to the wheel-rail contact problem assume the homogeneity of wheel and rail materials, which is not the case, because third bodies, for example sand- particles, are in the wheel-rail contact. Consequently, this paper develops a contact model for non-homogeneous contact areas. Since sanding or other frictions enhancers are mostly applied in cases of braking or accelerating, the assumption of negligible slip, present in most existing theories, is dropped.
For this purpose, a contact patch according to Hertzian theory is assumed and split into rectangular discrete elements. These columns are deformed from the point of entering the rail towards the exit of the wheel-rail-contact due to the applied brake or traction torque. The contact of each column can transfer a limited force, resulting from the deformation which may lead to slip occurring in the contact patch.
This limited force is defined by either the friction force, originating from the pressure in the wheel-rail-contact or the transferable force via a third body, e.g. a sand grain.
The resulting adhesion area is in accordance with published results for the homogeneous case, while the introduction of friction enhancer increases this adhesion area, which explains the effect of friction enhancers to reduce wheel slip. The simulations further show that there are differences in effectiveness of friction enhancers depending on the present torque.
With the result of the simulation the efficiency of the sanding system can be improved for example according to the amount of friction enhancer or the duration of sanding.

Abstract ID-19

CONTACT TRACKING ALGORITHMS IN CASE OF THE OMNI-DIRECTIONAL WHEEL ROLLING ON THE HORIZONTAL SURFACE

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Keywords: omni wheel, contact tracking, unilateral constraint, contact detection, model of friction, roller inclination

Summary: Vehicles with flexible ability to maneuver in any direction desired just almost resting at initial position are usually equipped by the so-called omni-directional wheels. Omni-wheel is defined as one having rollers along its rim. Formalisms previously developed for the multibody dynamics description are applied to develop the omni-wheel dynamical model. This model being class component in frame of an object-oriented modeling environment is possible to be embedded into the model of the whole rolling vehicle of any type. Two possibilities for the roller relative orientation are usually being implemented in the engineering solutions for the omni-wheels: (a) case of the roller axis belonging to the wheel plane; (b) case of the roller axis being angled with respect to the plane mentioned. Case (a) turns out to be the simplest one and contact tracking algorithm for the floor - roller contacting provides the fastest dynamical model. Case (b) evidently being more flexible consumes more time for computations. At the same time its implementation remains much more efficient in compare with an approach based on the general formulae of contact computations. These algorithms are possible to be combined with the simplest and fastest point-contact model which runs regularly in the process of motion simulation. Moreover algorithms outlined above demonstrate their reliability and impact-free manner of rollers switching while the rolling process. Implementation of these algorithms is described, and computational experiments demonstrating procedures of the model numerical verification are presented.

Abstract ID-21

OCCURRENCE AND REMOVAL OF WIGGLES IN TRANSIENT ROLLING CONTACT SIMULATION

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Keywords: rolling contact, wheel-rail, transient, multi-body dynamics, traction, instabilities

Summary: A detailed model for wheel-rail contact analysis is provided by Kalkers variational theory. This theory is provided by the CONTACT software.
Recent developments by Vollebregt aim at integrating CONTACT into transient vehicle models like SIMPACK Rail. This application gives rise to the need of using a given timestep independent of the rolling velocity and gridsize. Unexpectedly, this causes a wiggle-like phenomenon to arise in the tangential traction profile. Unlike the situation in computational fluid dynamics, these wiggles appear when the timestep becomes small compared to the gridsize. This phenomenon is grid-dependent and in contrast with the Carter-Fromm solution for 2D steady state rolling and therefore clearly nonphysical.
In the article an explanation for the occurrence of these wiggles is given. A method is presented that focuses on scaling of the timestep used for the influence coefficient matrices. This method stops the occurrence of wiggles. Furthermore, certain time-stepping appears to give rise to smoothing of peaks in the traction profile. The cause for this smoothing is explained and a solution for this problem is given. These two refinements result in an improved algorithm that allows for small timesteps to be chosen in CONTACT, producing results consistent with results using larger timestep sizes.

Abstract ID-22

DRY FRICTION DISTRIBUTED OVER A CONTACT PATCH BETWEEN A RIGID BODY AND A VISCO-ELASTIC PLANE

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Keywords: dry friction, wheel dynamics, realization of non-holonomic constraints, distributed friction, visco-elastic contact

Summary: We consider the dynamics of an absolutely rigid body moving on a rough horizontal plane. We assume that the plane deforms during the motion and the normal reaction in each infinitesimal area is proportional to the deformation and its velocity (Kelvin-Voigt model). On a rigid body, moving along the plane, the dry friction distributed over the contact patch acts. To find the resulting friction force and torque, we integrate the infinitesimal Coulomb dry friction forces over the contact patch (like for Contensou friction). The main difference from the Contensou friction is that the contact patch, as well as the normal plane's reactions, depends on position, orientation, the velocity of the center of mass and angular velocity of the body. The particular cases are considered in details: the dynamics of a homogeneous sphere and the dynamics of the wheel modeled by a thin paraboloid. For each stage of motion, the analytical approximations for friction force and torque are proposed. They allow to solve the dynamical equations analytically and give the domains of applicability for such approximations. The precision of the approximations is discussed. Particularly, we interest if the non-holonomic constraint of motion without sliding can be realized by means of distributed dry friction. The results can be applied in dynamics of such types of multibody systems, as wheeled robots and roller bearing systems. The work is supported by Russian Foundation for Basic Research (project 16-01-00338).

Abstract ID-24

REVIEW OF THE DEVELOPMENT OF THE CREEP-CONTROLLED WHEELSET FOR HIGH-SPEED RAILWAY VEHICLES

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Keywords: Controlled wheelset, High speed bogie, Creep coupling

Summary: During the time of the first MAGLEV trains in the industry (MBB, now AIRBUS Group) a new high speed railway bogie with creep-controlled wheelsets was developed and tested on the Munich roller test rig for speeds up to 500 km/h.
To demonstrate the typical behavior of this system a simplified single creep-controlled wheelset is suspended with springs on a frame which is fixed to the inertial system and moves with constant speed in a circular curve. The right wheel and the left wheel are connected by an electromagnetic creep-coupling, which is controlled with the relative rotation speed between the two axles as measurement. Though all investigations are made with cone-shaped wheels on cylindrical rails this model contains most of the properties of profiled wheels and rails. The creep forces at the wheel-rail contact point are derived with KALKERs linear theory. Gyroscopic effects and some small terms will be omitted in the mathematical model used for the controller design with root locus analysis and for simulation. Sensor and coupling dynamics are neglected. The time histories of lateral and rotational movements are simulated. The advantage of the creep-controlled wheelset is discussed by comparison the results with the behavior of the special cases solid-axle wheelset and the loose wheelset. The solid-axle wheelset has a good curving capability but an unstable hunting dynamics for the simulated speed of 270 km/h (the according critical speed is 191 km/h). The loose wheelset has a stable hunting dynamics but the curving capability is unstable. The creep-controlled wheelset however has a stable hunting dynamics and a good curving capability with small lateral displacements.
Finally a video from the real MBB bogie with creep-controlled wheelsets on the roller test rig is presented. There the lateral and rotational movements of the bogie are free (no linkage with the carbody). At first results with the solid-axle wheelset from 60 km/h till the critical speed of 113 km/h are shown. Then the results with excellent damping of the creep-controlled wheelset are presented in steps from 113 km/h to 200 km/h, to 400 km/h and to 500 km/h (maximum roller test rig speed).

Abstract ID-25

AN ADVANCED MODELING TECHNIQUE FOR ROLLING ELEMENT BEARINGS IN ELASTOHYDRODYNAMIC LUBRICATION (EHL) FIELD

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Keywords: Bearing, Elastohydrodynamic Lubrication, EHL, Modeling Technique, 5-dof, Multibody, Analytical method

Summary: The large use of rolling element bearings in power transmissions, together with the constantly growing request for computationally efficient and accurate predictions of their system-level NVH performances, is pushing the development of novel numerically efficient modeling techniques. FE-based approaches turn out to be too time consuming for system-level machine analysis. For this purpose the attention is often focused on analytical models that are able to grasp the essential effects characterizing the solution while guaranteeing fast and reliable results.
The conducted research presented in this paper takes a step forwards by proposing a bearing modeling strategy that is able to simulate the bearing behavior while accounting for the most relevant phenomena such as EHL, centrifugal loads, roller crowning and roller-raceway misalignment.
The strategy has been developed for angular contact ball bearings and roller bearings but it can be easily extended to other cases (e.g. deep groove and thrust ball bearings, tapered and barrel roller bearings).
The proposed modeling techniques consider 5-dof (degrees of freedom) inner ring displacement with respect to the outer ring together with their relative rotational speed. The output is thus given by the 5-dof reaction forces and moments acting on the bearing's shaft due to the displacement vector assigned as input.
The strategy consists of three steps. Starting from the input vector, the first step is to compute the relative displacement of the rings for each rolling element location. Then the EHL contact model is introduced to compute the rolling element equilibrium by imposing force equilibrium. Once the equilibrium of each rolling element is computed, a kinematics-based transformation matrix is applied to each contact force giving the equivalent forces and moments with respect to the bearing axis.
Finally, each rolling element contribution with respect to the bearing axis is summed defining the output vector.
The proposed techniques turned out to be fast and accurate enough for a large number of applications where FEM's accuracy is not required while the most relevant phenomena must be accounted for. Furthermore, the internal bearing behavior calculated during the solution process can be output for further post-processing.

Abstract ID-26

INFLUENCE OF THE TIRE DAMPING TO THE TIRE-ROAD VERTICAL CONTACT DYNAMICS

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Keywords: tire damping, tire-road contact, vertical dynamics

Summary: Tire-road interface is typical multibody systems with unilateral contact. In such contact interface, vertical and tangential dynamics are two main focus. In vertical dynamics, the mostly utilized models are the 2 DOF quarter car models, which connect the unsprung and the sprung mass with spring and damper. In such kind of models, the damping of the tire is normally not considered for simplicity. In this paper, the damping of the tire is considered. The influence of it to the vertical dynamics is evaluated as follows. Firstly, a linear damping of the tire is added into the 2 DOF quarter car suspension. The effect of the tire damping to the suspension transmissibility is analyzed from the frequency responses of the sprung mass acceleration and the tire dynamics load due to road frequency sweep input, which indicates that the influence of the damping is significant, especially around the second order resonance frequency of the 2 DOF model. Secondly, the nonlinear damping and stiffness of the tire is added to the 2 DOF quarter car model. In such case, the tire is interpret with the tread damping, stiffness and carcass stiffness. In this way, the tire as a whole could derive a vertical contact constitutive model. The parameters in the model are determined partly from the tread rubber material dynamic test and partly from the experiment with the newly developed quarter car suspension test rig. Simulation with the nonlinear 2 DOF model in time domain is carried out to evaluate the effect of the tire damping to the vertical dynamics. Finally, a JKR type tire-road contact model is proposed by considering the nonlinear damping of the tire. In this model, the relationship between vertical load and contact patch area is established. Discussion of the tire-road vertical dynamic contact mechanism is provided through the simulation with the model.

Abstract ID-29

TRIBOLOGY IN WHEEL-RAIL CONTACT AND CROSS CONNECTIONS TO TYRE-ROAD PHENOMENA

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Keywords: Wheel-Rail Contact, Friction, Rolling Contact, Tribology, Tyre-Road Contact

Summary: Tribological phenomena in the contact between wheels and rails have a high influence on vehicle-track interaction, i.e. vehicle dynamics, traction and braking dynamics, wheel-rail wear and damage, etc. For more than ten years, Virtual Vehicle Research Center is doing research in the field of wheel-rail tribology in collaboration with scientific and industrial partners. There, several creep force models have been developed considering these tribological phenomena. These models are able to account for the influence of third body layers, liquids, temperatures arising from the dissipated energy in the contact, surface-roughness, etc. More recently, the influence of low amounts of water in combination with wear debris/iron oxides on the frictional behaviour of the wheel-rail contact has been investigated and implemented in the model library. Furthermore, the interaction between the mentioned tribological phenomena and wheel-rail wear and damage has been investigated and modelled.

The developed creep force models allow the prediction of, e.g., falling friction phenomena at high creepages and the influence of the vehicle speed on the traction characteristic as well as the impact of all these phenomena on wheel-rail wear and damage, which has also been investigated and modelled. All models have been parameterised and validated by scaled, full-scale and on-track testing.

This contribution will give an overview about the research on wheel-rail tribology carried out at Virtual Vehicle Research Center. In addition, ideas and initial results will be presented showing how the approaches, which were originally developed for the wheel-rail contact, might be transferred to the modelling of tyre-road contacts. In this context, particle based modelling of granular materials – Discrete Element Method (DEM) – can play a key role to get a better understanding of the ongoing physical effects in the contact zone, especially when focusing on the behaviour of tyres on gravel or packed snow.

Abstract ID-30

INHERENT DYNAMIC BALANCING OF LINKAGES WITH ROLLING JOINTS

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Keywords: Inherent dynamic balance, Rolling joints, linkages

Summary: Dynamic balance is an important characteristic of linkages in applications where high-speed motions with few base vibrations are required, for instance for pick and place tasks with short cycle times and high precision in the semi-conductor industry. For high precision also rolling joints are advantageous as compared to revolute pairs since they do not have clearance.

Dynamic balance of a certain linkage is obtained by a specific design of the mass distributions of each of the links and, if necessary, by additional elements. In general a chosen linkage can be dynamically balanced by adding countermasses and counterinertias. This however has shown to result in balance solutions with such an increase of mass, inertia, and complexity, that they are hardly applicable in practice. With the relatively new approach of inherent dynamic balancing, balanced mechanisms can be synthesized from principal vector linkage architectures, which are fundamental linkages with solely the kinematic conditions for balance. With this approach it was shown possible to synthesize a wide variety of new advantageously balanced linkage designs that are applicable.

This work will show for the first time how the inherent dynamic balance approach can be extended to linkages with rolling joints. The challenge with respect to revolute pairs is that the contact point between two links of a rolling joint is not a stationary point in one of the links. Common balance methods therefore are not easily applicable but with the inherent dynamic balance approach this is well possible.

As example an inherently balanced 2-degree-of-freedom pantograph linkage with rolling contacts in each of the four joints is shown and investigated. Four configurations of the balanced linkage are possible depending on the relative positions of the rolling members, all having equal gear-ratios. In general the center of mass is a stationary point in an additional link moving similarly, but for specific conditions this link has length zero for which the center of mass is in a stationary point in one of the pantograph links. A dynamic simulation of the linkage was made for validation and extension to advanced inherently balanced linkages with solely rolling joints is discussed.

Abstract ID-31

MODELLING OF SPATIAL MECHANICAL JOINTS WITH REALISTIC PROPERTIES: A FINITE ELEMENT ANALYSIS

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Keywords: Non-Ideal Spatial Mechanical Joints, 3D Finite Element Analysis, Rolling, Radial Clearance, Plastic Behavior, Normal Contact Forces, Stress and Strain Fields

Summary: In this work a pioneer approach is presented to deal with non-ideal operative aspects of a journal-bearing spatial revolute joint by means of a three-dimensional finite element analysis (3D-FEA) in a realistic way. The developed model incorporates the inertia of the joint members and the corresponding material elastic properties. The fact that real members present dimensional and geometrical deviations resulting from the assembly process and operative conditions lead to frequent modifications on the design conditions that are worthwhile analyzing. Thus, a meticulous study was performed on the interaction of both members under rolling, taking into account the existence of a radial clearance. It is known that rolling between two cylindrical shape contacting surfaces is a phenomenon that must be carefully addressed as it implicates the consideration of a different constitutive law associated with the material behavior as the parts assume a plastic behavior (i.e., penetration).
A predefined angular velocity was firstly imposed to the bearing axis and simultaneously a vertical displacement was prescribed to the journal until it reaches a given maximum penetration depth. The issued results allowed to perceive that when a point on the surface of the journal has just made contact with the bearing, the outer cylindrical surface of the journal moves slower than the point on the surface of the bearing. The consequence is a relative slip between the two surfaces. Also, as a region on the journal adheres to the bearing wall it moves faster. After a certain distance, the referred region (i.e., the one belonging to the journal) sticks to it, acquiring the same angular velocity.
Coulomb friction is assumed between the two surfaces as friction plays a vital role in this process. The post-processing of data provides the evaluation of the normal contact forces and both radial and tangential stress and strain fields in the regions of the joint that are most pronouncedly loaded.

Abstract ID-32

A LINEAR TYRE MODEL FOR BICYCLE HANDLING EVALUATION

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Keywords: bicycle, dynamics, handling, tyre model

Summary: The Carvallo-Whipple bicycle model [1] has been very successful in the study of dynamics and control of bicycles. However, a recent study on system identification of the bicycle-rider control system [2] revealed a possible defect in the model. In trying to identify the plant, in this case the bicycle, some of the coefficients in the linearized dynamics equations of motion associated with the steering dynamics showed a significant offset compared with the Carvallo-Whipple model entries. One of the suspects is the finite tyre stiffness, which is not present in the Carvallo-Whipple model. Here we investigate the effect of finite tyre stiffness on the dynamics and handling of a bicycle by extending the Carvallo-Whipple model with finite stiffness tyres.
For most circumstances during normal riding of a bicycle, a linear tyre model suffices. The proposed tyre model is based on a taut string model for the belt combined with a bristle model for the tread. Based on a few parameters for the stiffness of the bristles and the string, a normal pressure distribution for stationary rolling and constant normal deflection, and hence the normal force, as well as an effective rolling radius, can be derived. Owing to the finite contact length, an infinite-order model for the force and moment response of longitudinal slip, sideslip and spin results. For a finite frequency range of interest, this model may be approximated by a first-order or a second-order relaxation length model.

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Abstract ID-33

SIMULATION OF A SHARP CURVED TRACK ON A ROLLER RIG

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Keywords: railway vehicle, roller rig, curving

Summary: Roller rigs have been built world-wide to research into the dynamics of railway vehicles. These rigs have been proved as useful devices especially for basic research, for validation of new theories and verification results of computer simulations, for development of innovative designs and the optimization of vehicle components.

At the CTU in Prague the first scaled roller rig was built and put into the operation in 1988. Since that time it has been continuously developed. The last major improvement came in 2015 when a new test bogie with actively steered wheelsets was developed and put on the rig.

Unlike a majority of roller rig designs the CTU roller rig was from the early beginning designed to perform not only experiments in the straight track, but also curved track simulations. However it's capability to simulate negotiation of a very sharp curve is limited. In curves of small radii wheelset have a large yaw angle with respect to the rail. Consequently wheelsts wheels move off the top of rollers and as a results of this de-crowning movement a component of the normal force in the horizontal plane occur and significantly influence results of roller rig experiments. The paper evaluates the effects of de-crowning movement on differences between track and roller rig run.

Currently a new roller rig is being developed at the CTU. Its design allows to continuously keep wheelset wheels at the top of the rollers and thus minimize de-crowning effects.

Abstract ID-34

MULTIBODY MODELLING AND DYNAMIC ANALYSIS OF TAPERED ROLLER BEARINGS

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Keywords: Roller Bearing, Multibody Dynamics, Railway Dynamics, Hertz Contact, Elastohydrodynamic Lubrication

Summary: The understanding of the dynamic performance of roller bearings, used in railway vehicles for instance, is fundamental to support the evaluation of the bearings performance via monitoring systems. The vibration output of the axleboxes is the measurable outcome of the bearing dynamic response, under operating conditions, that is characterized in this work. The main goal of this work is to develop a dynamic analysis tool, referred to as BearDyn, in MATLAB®, able to handle models representative of actual railway axle bearings, by using a multibody formulation to describe the mechanical elements of the bearing and their interactions. Realistic bearing geometric data is obtained by precise measurements of tapered bearings. The interactions between the elements are described by continuous contact force models based on the Hertz elastic contact theory and modified according to experimental evidence. Tribological lubrication models are applied to describe the tangential forces in the presence of lubricant. Finally, the BearDyn is demonstrated in the framework of realistic train operations that include the bearing loading due to the wheel-rail contact and the supporting mechanisms and structures of the vehicle primary suspension. The bearing dynamic response is obtained in terms of forces, kinematic quantities and different interaction measures, in the time domain, being the dynamic response in the frequency domain, obtained by using Fast Fourier Transforms, which is ultimately used for direct correlation with the outcome of the monitoring stations.

Abstract ID-35

A CO-SIMULATION APPROACH TO THE RAIL-WHEEL CONTACT WITH FLEXIBLE RAILWAYS

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Keywords: Rail-wheel Contact, Railway Vehicle Models, Flexible Railway Track, Multibody Dynamics, Finite Element Method

Summary: The standard approach to the railway vehicle dynamics includes running the vehicle multibody models in rigid railway tracks. The rail-wheel contact, independently of the rolling contact model used, is either handled online or via lookup tables. This traditional approach disregards the coupling effects between the railway vehicle dynamics and the railway track geometry and flexibility. In this work the assumption of rigidity of the railway track is released and a finite element model of the complete track, i.e., rails, pads, sleepers, ballast and infrastructure, is used to represent the track geometry and flexibility. A rail-wheel contact model that evaluates the contact conditions and forces is used online. The dynamics of the railway vehicle is described using a multibody methodology while the track structure is described using a finite element approach. Due to the fact that not only the multibody and the finite element dynamic analysis use different integration algorithms but also because the vehicle and track models are simulated in different codes a co-simulation procedure is proposed and demonstrated to address the coupled dynamics of the system. The methodology proposed in this work is finally demonstrated in an application in which a light railway vehicle operates in a reduced gauge track with geometric and structural irregularities acquired experimentally.

Abstract ID-36

COMBINED EFFECTS OF ELASTIC DEFORMATION AND LUBRICATION ACTION IN HUMAN KNEE JOINTS

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Keywords: Human articulations, Knee joint, Elastic contact, Lubrication effect

Summary: The main purpose of this work is to present a general and comprehensive methodology to deal with the combined effects of elastic deformation and lubrication action in artificial human knee joints of plateau type. This particular type of human joint is composed by a femur element, a tibia element and a fluid lubricant. The femur component is considered to be rigid with a spherical geometry. In turn, the tibia component is constituted by two adjacent regions, namely a rigid zone and an elastic layer. In the present study, the relative motion caused by external loads deforms the elastic layer only. In fact, the external loads are absorbed by the fluid lubricant that acts as a damper and by the elastic layer that acts as a spring element. Thus, in order to account for both elastic and lubrication actions, the Winkler elastic foundation model is combined with the lubrication effect due to the relative motion between the femur and tibia surfaces. It should be highlighted that the pressure distribution associated with the elastic foundation approach ensures a paraboloidal rather ellipsoidal as in the case of the Hertzian contact theory. In turn, the fluid pressure due to the lubricant action is proportional to the lubricant viscosity, the relative velocity of the surfaces and is inversely proportional to the third power of the film thickness. Preliminary results obtained from the analytical approach considered in this work are compared with some experimental data in terms of fluid film thickness variation with time. In general, it can be stated that the analytical outcomes are corroborated with the published experimental data, which allows for the comparison and validation of the presented methodology. Finally, it must be mentioned that the incorporation of the proposed methodology in a general multibody dynamics code will be object of future developments.

Abstract ID-38

CRACK GROWTH ASSESSMENT IN ROLLING/SLIDING CONTACT

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Keywords: Cracks, Crack Driving Force, Contact Loading, Plasticity

Summary: The paper describes some main aspects of a tool for crack growth assessment in rolling/sliding contact situations, which is in development. Rolling and/or sliding contact encloses many engineering applications as gears, bears, brakes, screw joints, wheel/rail contact etc. The repetitive contact loading may cause cracks in or near the contact surfaces. A crack growth assessment tool will be an essential capability in multi body simulations of such engineering applications. An accurate and verified crack growth prediction tool allows calculating the remaining life time or time to maintenance of the component. Basis for such tool are parametric studies of various crack geometries and loading conditions. In these studies crack driving forces are computed and both main parameters and some of their mutual relations are determined. A main task of the work at hand is to find and show relations between crack geometries, contact loading conditions, crack tip plasticity and crack loading mode. The derived dependencies will be reported and their influence on the crack growth rates and directions will be shown and discussed.

Abstract ID-40

A VISCOELASTIC TYRE FRICTION MODEL BASED ON A PARTIAL DIFFERENTIAL-ALGEBRAIC INCLUSION

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Keywords: Differential-Algebraic Inclusion, Tyre, Friction, Set-valuedness, Magic Formula

Summary: This paper presents an elastic rolling friction model for the modelling of tyre-road interaction. The model is an extension of the differential-algebraic friction model proposed by Kikuuwe et al. (IEEE Trans. Rob., 2006), which combines the Coulomb-like (set-valued) friction model and the linear spring-dashpot model in a computationally convenient manner. The proposed model can be seen as a distributed version of Kikuuwe et al.'s model, in the sense that the tangential viscoelastic displacement and the Coulomb-like friction force are distributed along the contact patch. The proposed rolling friction model captures partial slip and partial stiction within a contact patch, the tangential viscoelastic deformation of the surface, and rate-dependent friction laws.

Some of the previous physics-based tyre models have been built based on the LuGre friction model. One known flaw of LuGre model is that it does not produce the exact stiction. In addition, previous LuGre-based tyre models produce non-realistic elastic displacement in the tail end of the contact patch. The proposed tyre model overcomes these shortcomings with the use of the set-valued friction law and the tangential traction being location-wise proportional to the vertical pressure.

In the proposed model, the distributed tangential displacement in the contact patch is propagated along the contact patch due to the rolling motion, and it causes distributed tangential viscoelastic force. Meanwhile, the relative velocity between the surface material and the road produces the Coulomb-like distributed friction force, which is set-valued when the relative velocity is zero and can be rate-dependent. These distributed viscoelastic and friction forces exactly balance to each other, constituting a partial differential-algebraic inclusion along the time and the space. A numerical integration algorithm for this partial differential algebraic inclusion is derived through the implicit Euler discretization, which contributes to the elimination of the set-valuedness from the algorithm. The outputs of the model (the longitudinal force, the lateral force, and the self-aligning torque) are obtained through a simple numerical integration of the distributed force along the contact patch.

This paper also presents some results of parameter fitting of the proposed model to the empirical data reproduced by Pacejka's magic formula.

Abstract ID-41

SIMPLIFICATION OF FOUR CONTACT POINT SLEWING BEARINGS FOR MULTIBODY SIMULATIONS

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Keywords: Slewing bearing, Four contact point bearing, Stiffness, Finite Element Method

Summary: Slewing bearings are rolling bearings commonly used for orientation purposes in many applications, like wind turbines, solar trackers or tower cranes. These machines constitute complex multibody systems, and the behaviour or their components must be somehow characterized for numerical simulations. For this purpose, Finite Element Method is a very useful tool. Nevertheless, a Finite Element model for the simulation of a machine composed by several components, including rolling bearings, will be computationally unapproachable if they are not simplified by some means. A typical way to simplify the modelling of rolling bearings is to substitute them by a point-mass located in its centre of mass and the corresponding stiffness matrix. The values for the stiffness are usually given by manufacturers, but no calculation methodology can be found in literature. In this manuscript, a detailed Finite Element model to compute the values for the axial, radial and tilting stiffness is presented. The convergence of this type of models is usually hard due to contact nonlinearities; in this sense, a new solution is proposed, which ensures the convergence of the model for any load case. The results are compared with those obtained from an analytical model that only considers the stiffness of the ball-raceway contact, neglecting the effect of the elastic behaviour of the rings. The results reveal that the stiffness of the rings is as relevant as the ball raceway contact, thus not considering them leads to inaccurate results. The main goal of this work is to establish the basis for further research, where the developed Finite Element model will be used to obtain an analytical expression for the direct calculation of the stiffness. With this aim, a design of experiments is proposed considering the main parameters, i.e. the mean diameter, ball diameter and ball preload.

Abstract ID-42

A FAST METHOD FOR DETERMINATION OF CREEP FORCES IN NON-HERTZIAN CONTACT OF WHEEL AND RAIL BASED ON A BOOK OF TABLES

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Keywords: wheel-rail contact, non-Hertzian contact, book of tables, multibody dynamics

Summary: A new regularisation of non-elliptical wheel-rail contact patches is proposed, which enables building the look-up table called the Kalker book of tables for non-Hertzian contact (KBTNH). The non-elliptical contact patch, which can be obtained using any approximate non-Hertzian method for solving the normal contact problem in the wheel-rail interface, is regularised by a simple double-elliptical contact region (SDEC). A moderate volume Kalker book of tables for SDEC region has been computed in co-simulation of Matlab and software CONTACT. The book of tables provides the creep forces and the moment for any prescribed combinations of the creepages in the contact patch by means of linear interpolation. The creep forces and moment obtained from KBTNH have been compared to those obtained directly by program CONTACT and FASTSIM algorithm. The comparison shows that the KBTNH is in good agreement with CONTACT for a wide range of creepage condition and shapes of the contact patch, whereas the use of FASTSIM on the elliptical patch and SDEC region may lead to significant deviations from the reference CONTACT solutions. In the example of application, the KBTNH has been applied for curving simulations. The results obtained show significant differences from those obtained using an elliptical regularisation of the contact patch because the elliptical regularisation neglects the contribution of spin creepage to the longitudinal creep force. The fast calculation speed and high accuracy of determining creep forces for non-Hertzian wheel-rail contact make the proposed method a suitable tool for the wheel-rail contact calculation in multibody dynamics system simulation.

Abstract ID-44

A TIRE MODEL BASED ON GEOMETRICALLY EXACT SHELLS FOR MODAL ANALYSIS IN STEADY STATE ROLLING

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Keywords: tire model, geometrically exact shells, modal analysis

Summary: Acting as an interface between tire and road, the tire model plays a fundamental role in the simulation of road vehicles. In the past, forward dynamic simulations with multi body car models were performed using simplified tire models with only a few degrees of freedom. In contrast to that, in NVH analysis of the same kind of car models linearization of detailed 3D finite element tire models around a steady state solution in rolling contact were used. Recently this approach could be improved substantially by utilizing geometrically nonlinear shell-like tire models for both types of applications [1].
In our recent work [2] we presented a tire model based on geometrically exact shells augmented by variety of features, which are indispensable for realistic modelling of car tires. In particular, we demonstrated the capabilities of our model with respect to its usage in transient forward dynamic multibody simulations of a car. In this contribution we complement our previous work by exploring the properties of our shell based finite element tire model, applying the approach of [3] for a steady state analysis of a 3D FEM tire in rolling contact. To introduce the approach and validate our method we show the well-known split of the modes in a simplified example of a rotating cylinder. Additionally, we investigate similar effects in the example of a rolling tire in perfect contact with a flat road.

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Abstract ID-45

FROM SEMI-HERTZIAN TO EQUIVALENT CONTACT MODELS IN A SIMULINK MULTIBODY ENVIRONMENT

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Keywords: semi-Hertzian contact, equivalent, Simulink

Summary: In previous presentations, the author has proposed STRIPES a semi-Hertzian solution in order to improve the contact pressure and related shear stresses description in the railway contact. A simplified approach of plastic deformation has even been taken into account.
However it is sometimes usefull to accelerate the simulation using the same data, but with simplified models. This has been done in an option reducing the model to multi-Hertzian ellipses. Even in this case, plasticity can be partly simulated.
This paper will describe an even more simplified model : an equivalent contact model, based on a semi-Hertzian representation of the contact area. The advantage is in the management of "contact jumps" between non adjacent contact areas.
The equivalent parameters are identified from the forces calculated with the semi-Hertzian model in nominal conditions, then stored in tables, and used in the Simulink model of a railway vehicle. Taking avantage of this graphic environment, the arrangement of the blocks will be described in details. The limits of such model will be emphasised.

Abstract ID-47

A SHORT HISTORY OF CONTACT MECHANICS, ROLLING CONTACT AND MULTIBODY SYSTEM DYNAMICS

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Keywords: History of Contact Mechanics, Rolling Contact, Multibody System Dynamics

Summary: Contact mechanics is a branch of solid mechanics where two or more bodies are involved. The classical contact problem solved by Hertz (1882) is based on spherical bodies surfaces, linear-elastic material, constant static loading in normal direction and smooth surfaces. The rigorous results are often used as benchmarks. Details can be found in the monographs of Johnson (2003) and Popov (2015).
Rolling contact plays a unique, central and dominant role for human mobility. The two contacting bodies involved are the wheel and the guideway. And these two components are not found in our natural environment, they were invented by humans. Most of the other kinds of transportation like flying, swimming or diving have been inspired by birds and fishes. This is the reason why the wheel was invented very recently, namely 3.500 years before Christ. For comparison, the life on our planet started 4 billion years ago. A first rail tracks were laid 1767 in UK for horse drawn vehicles and since 1825 for railways. The first asphalt roads were built around 1850 in France, and in 1885 the first car powered by a gasoline engine was successfully completed by Benz in Germany. This means that by the end of the 19th century the basic components for the mechanization of transport were invented. The rolling contact, Carter (1926) and Kalker (1967) or Pacejka (1975), respectively, considered linear or nonlinear material, cylindrical wheel disks and horizontal guideways, rough surface with friction, static loading and steady-state rotating wheels. For details see Popp and Schiehlen (2010).
Multibody System Dynamics provides an engineering software tools for design, simulation and testing of complex dynamical systems, too, in particular for vehicle systems. Two more recent review papers by Schiehlen (1997) and Shabana (1997) deal with multibody dynamics. The contact between the bodies by joints is in multibody system codes as a standard implemented but the wheel-guideway forces of the rolling contact have to be added to complete the vehicle system. The challenges combining rolling contact with multibody system dynamics will be discussed during the Colloquium.

Abstract ID-51

COMPLEMENTARITY PROBLEMS AND MULTIBODY DYNAMICS WITH CONTACTS, JOINTS, AND FRICTION

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Keywords: Multibody Dynamics, Complementarity Problems, Coulomb Friction

Summary: We present a convergence analysis in a measure differential inclusion sense of a class of time-stepping schemes for multibody dynamics with contacts, joints, and friction. This class of methods solves one linear complementarity problem per step and contains th semi-implicit Euler method, as well as some trapezoidal-like methods for which second-order convergence was recently proved. By using the concept of a reduced friction cone, the analysis includes a convergence result for the case that includes joints. An unexpected intermediary result is that we are able to define a discrete velocity function of bounded variation, although the natural discrete velocity function produced by our algorithm may have unbounded variation.

Abstract ID-52

IMPLEMENTATION OF THE INTERACTION BETWEEN THE BILLET AND THE ROLL IN A MESHLESS BASED HOT ROLLING SIMULATION

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Keywords: Hot rolling, Meshless methods, Radial basis functions, Plastic deformation, Slice model

Summary: The goal of this work is to simulate effects of various rolling parameters in a rolling simulation system where the solution is achieved by a meshless method. This rolling simulation has been previously developed based on Local Radial Basis Function Collocation Method (LRBFCM). Physical modelling of rolling requires a complex 3D geometry however in this work computational domains of the simulation are based on vertically aligned slices towards the rolling direction. Each slice position is defined as a function of time. Strong form equations for both thermal and mechanical models are solved by LRBFCM for each slice. Collocation nodes are uniformly distributed over the physical domain and solution is obtained by interpolation of unknowns over overlapping local influence domains based on 5 or 7 nodes. Definition of the initial slice in terms of size, temperature filed and velocity as well as material properties and groove geometries are the input parameters of the simulation. Adjusting all these input parameters is a significant task in industry in order to understand and create more efficient rolling designs. The simulation presented here is sensitive to each rolling parameter and multiple simulations may be run to determine the effects of each parameter. For each slice calculation, boundary conditions are updated explicitly depending on the previous slice properties. Groove surface line is also redrawn for each slice position with the help of discrete roll surface points. During the contact of a slice with a roll, Robin type boundary condition with a high number of heat transfer coefficient is considered for the thermal solution and the traction with friction boundary condition is considered for the mechanical solution for the boundary nodes. If the friction force exceeds the traction then the condition is transformed into sticking boundary condition. If there is no contact, only regular cooling is applied without any deformation. The simulation results may be seen in terms of temperature, displacement, strain and stress for each slice position and roll separating force, roll torque and roll speed for each rolling stand. A user-friendly computer application for industrial use is created by using C# and .NET frameworks.

Abstract ID-53

CHARACTERISTICS OF WHEEL-RAIL CONFORMAL ROLLING CONTACT

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Keywords: Wheel-rail contact, Conformal contact, FE modelling

Summary: Wheel-rail rolling contact is the most characteristic aspect of rail vehicle dynamics. Most wheel-rail rolling contact theories used nowadays rely on the assumption of non-conformity in the contact. However, not very rarely situations arise in the railway context in which the validity of this assumption becomes questionable. These include the contact between the wheel flange root and the rail gauge corner during sharp curves negotiation, and the contact with heavily worn wheel and rail profiles. In these cases, the contact patch becomes curved in the lateral direction, and there is a non-negligible lateral contact angle variation within it.

In this work a detailed investigation of wheel-rail conformal rolling contact has been conducted. For this purpose, both Finite Element models and an extension of Kalker's exact rolling contact theory which takes into account the effects of conformity have been used. Situations with varying degrees of conformity have been considered, and the effects brought about by conformity both in the normal and in the tangential parts of the contact problem have been analyzed. It is found that already with quite modest levels of conformity, with total contact angle variations of just around 20º in the lateral direction, the effects of conformity begin to be appreciable, particularly in the tangential part of the contact problem.

While the FE modelling approach offers more versatility, the conformal exact rolling contact theory approach is better suited for the solution of contact problems, as it can produce precise results with much lower computational costs, and with nearly no practical limitations to take care of (basically, the need for linearity in the geometry and in the material behaviour, which in the wheel-rail case are many times complied with). As part of the development of the extension of the exact rolling contact theory for conformal contact, a simple approximation of the influence coefficients for conformal geometries is proposed, based on the influence coefficients for the half-space, which is seen to be satisfactory for moderate levels of conformity (with total lateral contact angle variations of up to about 45º).

Abstract ID-55

DAMAGE MECHANISM RELATED TO PLASTICITY AROUND HETEROGENEOUS INCLUSIONS UNDER ROLLING CONTACT LOADING

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Keywords: Contact, Plasticity, Heterogeneity

Summary: The lifetime of contacting mechanical parts is strongly affected by the presence of heterogeneities in their materials, such as reinforcements (fibers, particles), precipitates, porosities, or cracks. Hard heterogeneities having complex forms can create local overstress that initiating fatigue cracks near the contact surface. The presence of heterogeneities influences the physical and mechanical properties of the material at microscopic and macroscopic scales. A quantitative analysis of the over-stresses generated by heterogeneities is necessary to the comprehension of the damage mechanisms.
The study aims to precisely determine the pressure field distribution on the effective contact area and to predict the profile and the evolution of the stress/strain fields at each loading cycle on a representative elementary volume that takes into account the gradient of hardness, the presence of carbides and the existence of an initial compressive stress from thermochemical origin. Moreover, it provides relationship between the microscopic physical mechanisms of deformation under cyclic loadings and the macroscopic response of concerned structures. The present study is applied to rolling bearings which are the critical elements of the aero-engine's mainshaft.
In the scheme of all analyses conducted in the present work, it can be argued that, although the heterogeneities (such as carbides or nitrides) are responsible for the high resistance of the studied materials, some of them (those whose length exceeds tens of micrometer or those which form stringers in a particular direction) become, over fatigue cycles, the main sources of damage, from their local scale up to the macroscopic failure of the structure.

Abstract ID-56

FULL-SCALE TESTING OF LASER CLAD RAIL TRACK; PART II - RESULTS OF SUB-SURFACE MICROSTRUCTURAL, MICRO-HARDNESS AND RESIDUAL STRESS ANALYSIS

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Keywords: Wheel Rail Contact, Laser Cladding, Wear, RCF, Microstructure, HAZ

Summary: Laser cladding of railway track has been shown to be an effective technology for the mitigation of excessive wear and rolling contact fatigue. Small and large scale tests on laser clad rail have shown that by creating a thin layer of premium material on the tribo-active surface of the railhead wear is not only vastly reduced by a factor of between 78- 89% but also that the onset of rolling contact fatigue is vastly delayed. The ratcheting mechanism by which rolling contact fatigue is initiated is almost eliminated in comparison to standard rail material as evidenced in small-scale tests. Cladding also reduces the tendency for material flow which is a primary cause of failure of insulated track joints shown at both the small and full-scales. Cladding also seems to maintain the rails resistance to bend fatigue. This paper aims to investigate these tribologicicaly enhancing properties of laser clad layers by investigating their mechanical properties and microstructure. Full-scale tangent track and insulated joint specimens were sectioned, polished and etched and then the microstructure of the clad, heat effected zone and parent rail materials inspected using optical microscopy, SEM, micro hardness testing and a variety of other techniques. This will lead to an increased understanding of how these materials perform so well under the conditions of the wheel/rail contact.

Abstract ID-57

FRICTION COEFFICIENT ROLE ON EFFICIENCY OF SPUR GEARS WITH TIP RELIEFS

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Keywords: Friction coefficient, Load sharing, Tip relief, Efficiency

Summary: The effect of the friction coefficient on the efficiency of spur gear transmissions with tip reliefs was analysed in this proposal. In order to perform this assessment, the efficiency values using a friction coefficient constant along the meshing cycle was compared with those obtained including an enhanced friction coefficient formulation, which is based on elastohydrodynamic lubrication fundamentals. In addition to analysing the influence of the choice of the friction coefficient on efficiency, the profile modifications impact on the coefficient of friction as well as on the efficiency was assessed. Three different scenarios of tip relief were set out; when the tip relief was included only in the pinion, only in the driven wheel and in both gears at the same time.

Abstract ID-61

ON DEVELOPING A TRAM NEW WHEEL PROFILE USING MULTIBODY SIMULATION TOOLS

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Keywords: wheel/rail interface, wheel profile, light rail vehicle, multibody simulation

Summary: A lot of effort was put by researchers around the world to design cheaper, more durable and safer railway wheel profiles. The advantages of which can be drawn by numerous rolling stock operators and infrastructure managers. Therefore, tram systems are far more desolated than interoperable railway grid. The railway experience cannot be applied entirely to light rail systems due to many differences, such as: wheel diameter, axle load, track curvature, rail and rail crossings types. Hence they require an individual focus. Authors dealt with a very small slice of a whole vehicle, but nevertheless very important regarding vehicle dynamics – the wheel profile interacting with rail.

The optimization process was preceded by wide investigation into wheel/rail interface engaging thermovision imaging, wheel profiles geometry measurements, track irregularities measurements, numerous simulations of the interface and whole vehicle on tracks (multibody dynamics), which supported the choice of optimization criteria, which were: wear index, Y/Q derailment coefficient and contact area. The decision making process was based on evolutionary algorithm which was combined with a multibody simulation software. Tens of thousands of potential wheel profiles were examined, but only a few of them were picked for further evaluation using finite elements method software and during supervised exploitation. It was found out that there is always a trade-off between some optimization criteria, hence the tram one best wheel profile which is the safest (regarding derailment risk), the most durable and the most track-friendly does not exist. The resultant profiles were also confronted with chosen existing ones, used throughout Europe.

All the presented work is realized within the framework of a research project „Identification and modeling of nonlinear phenomena at the wheel/rail contact area for the development of a new tramway wheel profile” (LIDER/20/521/L-4/12/NCBR/2013), that has been started with a financial support from the Polish National Centre for Research and Development.

Abstract ID-62

MODELING AND ANALYSIS OF FRICTION EFFECTS IN MULTIBODY DYNAMICS

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Keywords: friction modeling, contact forces, multibody dynamics

Summary: It is known that friction effects occur in multibody systems and in most of the cases the function and the operating conditions of mechanical systems is based on the them. Furthermore, as result of friction phenomena, the state of a system can change rapidly, resulting in discontinuities in the system variables. Other effects associated with friction in mechanical systems are the vibration and noise propagation to the system components, nonlinear systems' behavior and wear at the contact zone. Overall, the knowledge of the friction regimen as well as the friction forces developed in contacting parts with relative motion is crucial for the dynamic analysis of mechanical systems and has consequences in the design process. Thus, this work deals with the modeling and analysis of friction effects in multibody systems with the purpose to better understand and to obtain accurate responses in terms of multibody dynamics. In this process, pure dry sliding friction, stick-slip effect, viscous friction, Stribeck effect, frictional lag are some of the main phenomena associated with friction that are object of deep analysis and discussed here. In a general and simpler manner, the friction models can be divided into two main groups, namely the static friction models and the dynamic friction models. The static models describe the steady-state behavior of the relation friction force/relative velocity, while in the dynamic models allow for the capturing of more properties by using extra state variables. In a simpler manner, the static and dynamic friction models differ mostly on the modeled friction effects, implementation complexity and computational efficiency. Therefore, this research aims at analyzing in detail the role of friction modeling in the dynamic response of multibody system, as well as discuss the importance of friction models selection to describe accurately the friction related phenomena. Several demonstrative examples of application that include friction in ideal mechanical joints and systems involving contact-impact events will be considered to evidence the main assumptions and procedures adopted in this work. The engineering analysis and design implications of this work can thus be perceived.

Abstract ID-63

CALCULATION OF THE DYNAMIC BEHAVIOR OF ROLLING BEARINGS WITH DETAILED CONTACT CALCULATIONS

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Keywords: rolling bearing, multi body simualtion, rolling contact, cylindrical roller bearing, contact solvers

Summary: Rolling bearing are among the most used machine elements. The bearing life time is usually calculated based on ISO 16281. However, this calculation only applies for failures due to subsurface fatigue. Many other bearing failures have different causes (e.g. slip, cage fractures). Many of these failures are influced or caused by the dynamic behaviour of the bearings' inner components. The dynamic of rolling bearings is difficult to predict as it depends on the behaviour of the different contacts in the bearing. The submission at hand introduces self-developed dynamic models of rolling bearings including detailed contact and friction calculations based on a universal modelling strategy.
The focus is on the contact calculation in the roller-raceway and the roller end-rip contact. Different contact models are used for the determination of the contact pressure distribution for each contact. These models allow an one- or two-dimensional discretisation of the contact area of each contact as the basis for the friction calculation. Therefore, different approaches for contact solvers are included in the models to overcome the target conflict of calculation accuracy and speed. As the dynamic inside the bearing is highly non-linear, very small calculation time steps need to be used. Also the number of contacts in a bearing is huge (roller-raceway, roller-rip, roller-cage, cage-ring for each rolling element), which results in higher calculation times and there is also a strong interaction between the different contacts. The models presented are able to simulate reasonable time periods with very detailed contacts to investigate the bearing behaviour and the contacts themselves. This includes the calculation of slip, film thickness, lubricant shear stress etc. for different – even transient – operating conditions.
Besides the modelling strategy, some calculation results for combined loaded cylindrical roller bearings are shown and compared with measured results from a special bearing friction torque test bench. Also the cage and roller speeds are measured and used to validate the model results.

Abstract ID-67

KINETIC AND CONTACTING ANALYSES OF MULTI-CYCLES PRELOADED BALL-SCREW

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Keywords: Preload, Multi-cycle, Kinetic, Contact, Friction

Summary: Preloaded ball-screw is wildly used as accuracy translation device in many industrial applications. Contacting mechanism of the multi-cycles ball-screw is very important for ball-screw designer in realizing ball's contacting and performance motioning in a ball-screw. The aim of the study is in establishing a detail kinetic and contacting analyses model on the design of two and four cycles in a double nut ball-screw. Contacting forces, friction and kinetic motion at contact areas between ball and raceway are discussed with these two models with different operating conditions. Results shows theoretical model is well conformation with experimental results of surface strain on nut. Four cycle model has more accuracy than two cycle model, and these two models all can used in realizing contact and kinetic behaviors on double-nut multi-cycle ball-screw. Effect of preload decay is revealed in the study for contact forces and transmission torque. Preload decay cannot affect transmission torque, but is very important for contact forces of each ball cycle. Proper applied preload can reduce the difference among contact forces at each ball cycle, and keep high transmission performance.

Abstract ID-68

APPLICATION OF A TRANSIENT ROLLING-CONTACT MODEL TO THE DYNAMICS OF ELASTIC BALL-PLANE/V-GROOVE CONTACT

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Keywords: contact mechanics, Hertzian contact, longitudinal creepage, lateral creepage, spin, tractive rolling dynamics

Summary: In this paper, the simulation of transient rolling friction is reported. The interplay between friction and the other system dynamics is investigated. Firstly, a brief introduction is given to rolling friction model, which enables one to simulate the transient traction stresses in the contact of a rolling body upon a counter surface. Thereafter, that model is used in the dynamic simulation of systems comprising rolling elements. The basic characteristics of such systems, such as the traction forces in the contact and the resulting complex stiffness are examined. It turns out that systems comprising rolling elements can manifest complex dynamics that depends on the amplitude and frequency of excitation.

For the case of a ball rolling on a massless plate, an increasing complex stiffness as a function of excitation frequency is observed, up to a certain break frequency. For higher frequencies, the amplitude of the complex stiffness becomes constant. The influence of plate inertia, was also investigated in the time and the frequency domains.

Finally, owing to its relevance in industrial applications, a system of a ball rolling between two V-grooved tracks is investigated, where a combination of kinematic creepage and dynamic creepage occurs. The study of these dynamic effects in frictional contacts, can significantly help improve the position accuracy of systems comprising these elements. Furthermore, a profound knowledge of the frictional dissipation in the rolling contacts, such as given in this paper, permits a better estimation of lifetime and performance degradation due to fatigue and wear.

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Abstract ID-69

COATING BEHAVIOR IN HEAVILY LOADED LUBRICATED CONTACTS

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Keywords: functionally graded elastic materials, heavily loaded lubricated contacts, method of mathched asymptotic expansions

Summary: EHL problems for line and point heavily loaded contacts of solids made of functionally graded isotropic elastic materials are considered. Coating functionally graded properties are arbitrary. The lubrication regime is isothermal while the lubricants are incompressible with Newtonian rheology. The problems are analyzed by the earlier developed methods of matched asymptotic expansions, semi-analytical and numerical methods. The EHL problems for functionally graded materials are split into a sequence of problems for dry and lubricated contacts. The problems for dry contacts of functionally graded materials are solved by a semi-analytical method while the lubrication problems in the inlet and exit zones of lubricated contacts are reduced to solution of asymptotic EHL equations obtained in the case line contacts of homogeneous materials. These equations are solved numerically. Solutions for functionally graded and homogeneous materials are compared and analyzed. Some conclusions with respect to lubrication film thickness and friction force in coated contacts are made. The results of the analysis can be used for optimization of coating and lubricant properties in heavily loaded EHL contacts.

Abstract ID-70

ROLLING RESISTANCE MODELLING IN THE CELTIC STONE DYNAMICS

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Keywords: rolling resistance, Celtic stone, contact forces

Summary: Aim of the present work is to exhibit a certain approach in constructing reduced models of resulting contact forces occurring on a contact area between an ellipsoidal body and planar surface, with emphasis put on rolling resistance model. Modelling concerns a certain class of problems, where one can assume fully developed sliding on a contact area resulting in relative motion in vicinity of the contact being planar motion of rigid bodies. Resultant friction action is reduced to the friction force and moment acting at the center of finite contact area. Their models are based on the integral expressions under assumption of classical Coulomb's friction law valid at each point of the contact zone. In order to obtain higher simulation speed, special class of approximations is used, being some kind of generalization of Padé expansion. Friction forces are coupled with rolling resistance via contact pressure distribution in one mathematical model. It is assumed simplified model of pressure distribution, that is Hertzian model, which is then modified (distorted) in a special way in order to take into account the rolling resistance. The model is tested numerically and experimentally by the use a special rigid body, that is a Celtic stone, also known a wobblestone or rattleback. Dynamics of the celt is investigated with a special attention paid to the role played by the rolling resistance.

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