Finite Element Analysis on Squeal-Noise in Railway Applications

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In this paper, we present the results of an experimental investigation on squeal noise emitted by a disc brake for railway applications. The measurement, that show in an evident manner the onset of instability forms during the braking phase were made on a test-rig in real scale on which we measured by means of a sound intensity probe the noise emitted by the disc brake. By using a Fast Fourier Transform (FFT) we identified the strongest detected frequencies. The aim of this paper is to analyse such phenomena by conducting a Finite Element Analysis (FEA) of the 3D CAD model of the disk modelled in Ansys Workbench FEM software, in order to, better understand the path that leads a stable system to unstable behaviour. The system analysed is composed of a steel disk and four pads made of an array of cylinders made of frictional material. Such pad system has been designed in order to simplify the simulation, assuming that it acts on the disk surface just in some points. The numerical results agree with the experimental ones.

Keywords: *Dry friction, geometrical instability, squeal, modal analysis, finite element method.*

1. INTRODUCTION

Brakes are one of the most important components in terms of safety and performance in vehicles, and due to increasing requirements related to stability and comfor–tability, have become more complex [1-3]. Noise and vibrations are more and more important for the automo–tive industry, especially for vehicle manufacturers and component suppliers, and is generally regulated by noise pollution legislation, while the interior noise and sense of vibrations are much strictly evaluated by customers themselves [4,5]. The increasing problem of noise generation during braking assumes an economic and technical importance in the transport industry [6,7]. The generation of noise and its supp–ression have become important considerations to be assessed during the design phase and execution of the brake systems. In fact, as noted by Abendroth and Wernitz [11,12], many pads manufacturers spend up to 50% of their budget in engineering activities on noise and vibration problems [13-16]. Much progress has been made and many solutions have been suggested, for example by reducing the causes, adding constrained layer (shims) or by moving damping modal coupling elements that constitute the brake assembly [17-21]. Not all of these solutions contribute to the improvement of the vehicle braking qualities [22-24]. Due to these undesirable consequences, friction materials used in automotive braking systems must have wear resistance and high mechanical strength, low thermal conductivity, lubrication components with a role of increasing seizure resistance [25-27]. An interaction between a brake disc and friction material of automotive brake is charac–terised by a number of dry contact phenomena. These phenomena are influenced by brake operation condi–tions (applied pressure, speed, and brake interface temperature) and material characteristics of a friction couple. The coefficient of friction should be relatively high and keep a stable level irrespective of temperature change, humidity, age, degree of wear and corrosion, presence of dirt and water spraying from the road [28,29]. The complex dynamic behaviour of such mechanical systems can be studied within the multibody framework [30-35]. Multibody systems are mechanical systems composed of continuum bodies and kinematic joints which can be rigid and/or deformable. Several examples of mechanical systems that can be modelled using the multibody approach can be found in different engineering applications [36-46]. Examples of the use of multibody modelling can be the study of robotic systems that are based on systems present in nature [47], and studies on the measurements and mitigation of vibrations in structures for comfort improving [48,49]. Therefore, advanced analysis approaches and computa–tional procedures are necessary for performing reliable dynamic simulations [50-58]. Control strategies for rigid-flexible multibody systems also are particularly challenging and require computational approaches capable of handling nonlinear behaviour of a general multibody systems [59-66]. In the last decades, a considerable amount of scientific literature has been produced on the possibility to eliminate noise [67]. Brake noise can be categorised according to the frequ–encies range in which the phenomenon occurs. We talk about low-frequency noise for frequencies between 100 and 300 Hz, while for frequencies above 2000 Hz but below the first in plane mode of the disc we talk about low-frequency squeal while high-frequency squeal is the

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noise produced by self-induced vibration [68-70]. There are two theories that try to describe squeal phenomenon. One theory ascribes the increase of vibration amplitudes to the stick-slip mechanism. The other assigns it to geometrical instability of the brake assembly. In spite, both approaches agree that squeal phenomenon depends above all on a variation of the friction force. In this paper, we chose to keep constant the friction coefficient μ, since it is possible to obtain variables friction forces due to the presence of variables closing forces. This is the assumption underlying the studies carried out by Spurr [71], Earles and Soar [72,73]. In this paper, we show that if two modes are geometrically coupled, for increasing values of friction coefficient, frequencies tend to coincide[74-75]. Once the two modes couple, they become unstable. The paper is organised as fol–lows. In section 2 we describe the mathematical model used for understanding the pathway that leads to unstable behaviour. In section 3 we focus the attention on the finite element analysis conducted on the meshed 3D geometry of the disk-pads created with SolidWorks 3D software and simulated in Ansys Workbench FEM Software, while section 4, we report an experimental activity conducted on disk brake for recording sound pressure levels during braking. The final section presents the conclusions.

2. MATHEMATICAL MODEL

The system analysed in this paper consists of a SEE (mod. 10-9007302) steel disk mechanically coupled to a system of four pads used in railway applications. Each pad has six pairs of cylinders, made of friction material, connected by a cantilever. The mechanical behaviour of such cantilevers is shown in Fig. 1.

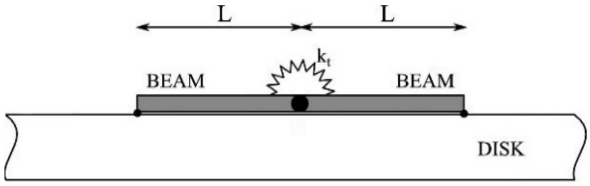


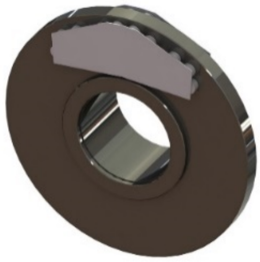
Figura 1. Mechanical scheme for cantilevers

In this way, the disk is always in contact with the 48 cylinders. In Fig. 2(a) and 2(b) are indicated respectively the disk and one of the four sub-systems composing the pads. The disk has a diameter of 640 mm, a thickness of 45 mm and geometrical characteristic indicated in the same figure. The twelve cylinders, which form the pad, have a diameter of 35 mm and a height of 20 mm. In Fig. 3 is reported the assembly model developed in Dassault Systèmes SolidWorks 3D software.

(a) Disk

(b) Pad

Figure 2. Physical system



a) CAD assembly model

(b) CAD pad model

Figure 3. CAD assembly

Given the geometry and the materials used for the pad, for the numerical analysis, we considered the four sub-systems rigid except cantilevers and disk modelled as flexible bodies. In Fig. 4, we have reported the meshed assembly realised for the subsequent FEM ana–lysis carried out. In such figure, it is possible to dis–tinguish the parts considered flexible (meshed parts) from the ones considered rigid (no-meshed parts). From the use of Lagrange equation reported:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial q}\right)^T - \left(\frac{\partial T}{\partial q}\right)^T + \left(\frac{\partial V}{\partial q}\right)^T = Q^T \tag{1}$$

we developed the differential equations of motion of the system as follows:

$$M\ddot{q} + Kq = Q_{pad} + Q_v \tag{2}$$

with ***M*** and ***K*** mass and stiffness matrix of the disk-pad system, respectively; $\boldsymbol{Q_{pad}}$ is the force field between disk and pads and $\boldsymbol{Q_v}$ is the quadratic velocity vector resulting from the differentiation of the kinetic energy with respect to time and with respect to the body coordinates. This quadratic velocity vector contains the gyroscopic and Coriolis force components.

$$Q_v\left(q,\dot{q}\right) = G\left(\mathrm{O}\right)\dot{q} \tag{3}$$

$\boldsymbol{Q_{pad}}$ can be seen as a force field proportional to the friction coefficient present between disc and pad.

$$M\ddot{q} + G(\Omega)\dot{q} + Kq = Q_{pad}(q;\mu) \simeq -\mu K_p q \tag{4}$$

Thus, (2) can be rewritten as:

$$M\ddot{q} + G(\Omega)\dot{q} + (K + \mu K_p)q = 0 \tag{5}$$

The eigenvalue problem of (5) allows us to predict instability forms of the system. The modal parameters of the disk-pad system have been calculated by using ANSYS FEM software.

3. NUMERICAL SIMULATION

Several simulations were conducted under ANSYS Workbench, for fixed values of closing force and angular velocity of the disk. The friction coefficient μ is considered constant for each simulation and caused to vary from the value 0 to 1 in order to study the influence of dry friction on the occurrence of forms of instability. For simplicity, a Coulomb law characteristic is applied. The upper limit of the frequency range to be studied is fixed at 8000 Hz. To define the contact behaviour between the cylinders and disc, frictional contact has been selected leaving liberty to separate in their normal direction while in the tangential direction, sliding occurs only when the shear stress exceeds the value multi–plying the normal stress by the constant friction coef–ficient μ. For ensuring contact compatibility at the in–terface preventing penetration of the contacting point, Augmented Lagrange formulation has been used providing the normal force $F_n = k_n x_n + \lambda$ with λ contact pressure, whenever a contacting point penetrates normally target face. In Fig. 5 are indicated the real and imaginary part of the eigenvalues which are relative to unstable modes. Besides the first form of instability that is recorded for values greater than zero of the coef–ficient of friction, the first unstable mode is recorded around 7500 Hz for values of μ > 0,18 as shown in the top left diagram of Fig. 5. Five modes tend to become unstable. In Fig. 6 are indicated the natural frequencies versus nodal diameters for the disk-brake analysed. By the figure it can be observed that the pad force field generates modes which become unstable to increase of μ only for ND = 0.

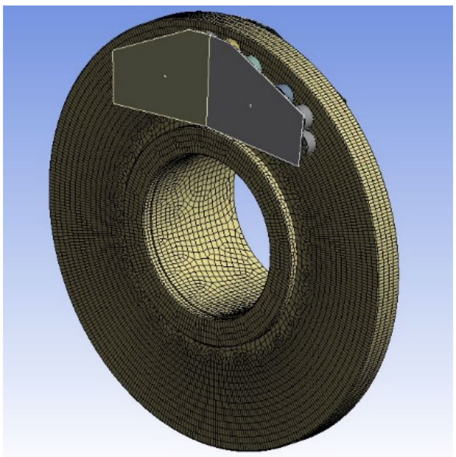


Figure 4. Mesh of brake assembly

4. EXPERIMENTAL INVESTIGATION

To verify the results obtained from the finite element analysis, we confronted the numerical results with the sound pressure levels recorded during an experimental investigation conducted on a test-bench during braking, from 70 km=h to zero. The experimental apparatus is normally used for braking tests for railway systems. In our case, the benchmark consists of a 640 mm diameter and 45 mm in thickness disk and four sub-systems pads. Pressurized air pushes a piston connected through a mechanical linkage to the brake shoes in order to rub on the disk, using the resulting friction force to slow the wheel.

In 4 seconds the calliper closing force reaches its maximum value (1000 daN) and then keeps constant. Two microphones were placed one meter close to the disk: one in front of the pads and the other on the opposite side along the disk diameter, as illustrated in Fig. 7. In Fig.8, the sound pressure frequency spectrum recorded during braking is reported. Some peak frequencies increase as caliper closing force grows up, as it can be seen. This can be due to stress-stiffening phenomenon. Furthermore, it can be noted that: 1) less than 4000 Hz frequency peaks appear as soon as braking starts; 2) 6000 Hz frequency peak damps in 6 seconds; 3) 7500 and 9300 Hz frequency peaks appear after first 6 seconds.

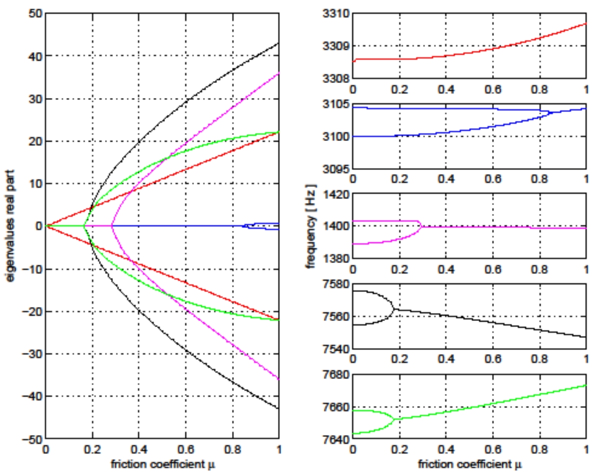


Figure 5. Eigenvalues versus friction coefficient

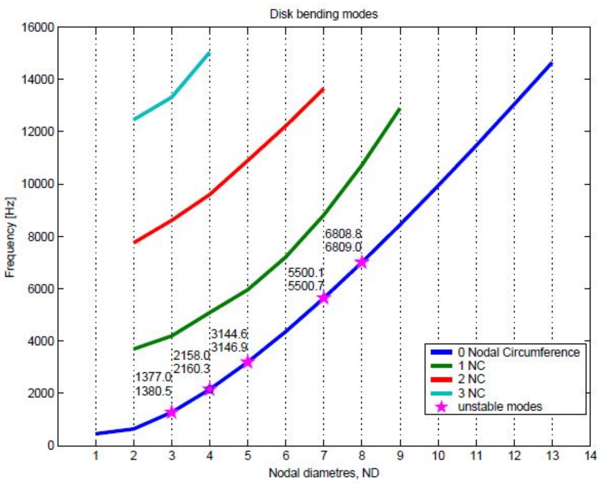


Figure 6. Eigenvalues versus nodal diametres

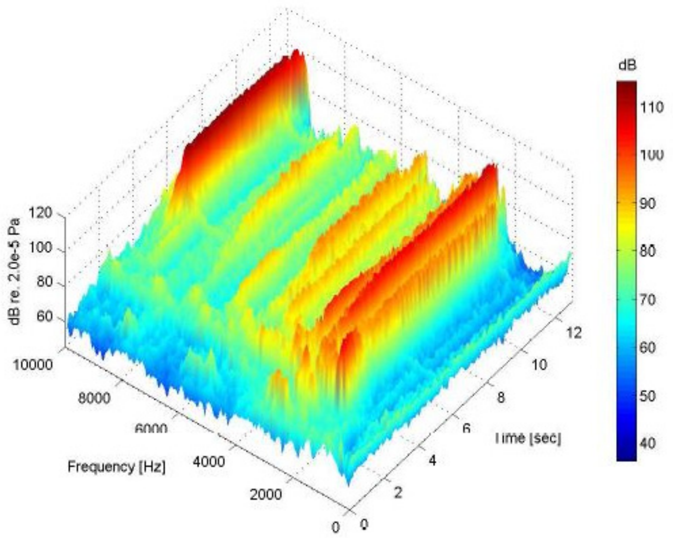
Figure 7. Disk brake bench

The results of the numerical simulations fairly match experimental data. In particular, the adopted model can predict geometric instability incoming at frequencies close to 1300, 2100, 3100, 5500 and 6800 Hz,

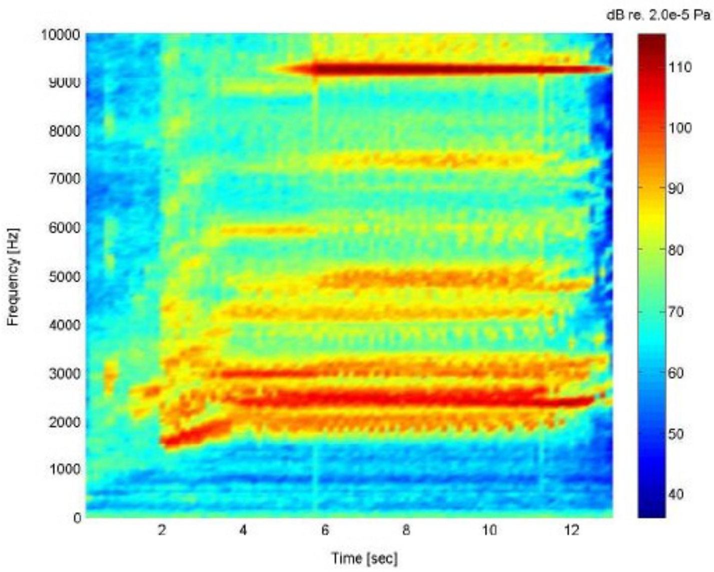
especially in first braking moments. Contrariwise, the model does not predict one important peak close to 9300 Hz. Considering that the first transversal pad-subsystem beam resonance frequency is close to that value, one can deduce that such value is due to a form of dynamic instability such as stick-slip nor to geometric instability. For this reason, the adopted model is not able to predict it. This work confirmed squeal to be a very complicated phenomenon in which dynamic and geometric instability take place simultaneously.

5. CONCLUSIONS

A theoretical study followed by an experimental activity is presented in this paper. Furthermore, we presented a mathematical model to describe the dynamic behaviour of a disk brake system for railways applications. In this system, the pad is composed of arrays of pad sub-system elements composed of cylinders mounted at the end of elastic beams. The pad model proposed was realised in order to facilitate variable force fields between disc and pad systems in order to analyse the influence of a variable friction force on the dynamic behaviour of the whole system.



(a) Sound pressure waterfall



(b) Sound pressure color map

Figure 8: Measurements of the experimental apparatus

The numerical analysis and the subsequent experi–mental investigation allows to make the following consideration: 1) five modes became instable to increase of the friction coefficient μ; 2) the instable modes are (0,3), (0,4), (0,5), (0,7) and (0,8); 3) the instability rela–tive to the (0,5) mode occurs for value of the parameter $\mu > 0,5$ and hence it isn't significative for this problem; 4) The experimental data are in a good agreement with the theoretical results; 5) Every instability form pre–dicted by the model occurs in the experimental analysis; 6) Nevertheless in the experimental results appears a frequency component of about 9300 Hz which is not predicted by the theoretical model. This component could be generated by stick-slip phenomenon. In fact, the pad sub-system beam has a transversal natural frequency close to the foregoing frequency. This work is the first step of a wide research project on the self-excited vibrations induced by dry friction.

REFERENCES

[1] Jeong E, Oh C. Evaluating the effectiveness of active vehicle safety systems. Accident Analysis and Prevention, Vol. 100, pp. 85-96, 2017.

[2] Diels C. and Thompson S.: Information expectations in highly and fully automated vehicles, Advances in Intelligent Systems and Computing, Vol. 597, pp. 742-748, 2018.

[3] Zhang P., Ding X., Zhang Y., Yuan Q. and Sun M.: Research on design and application of vehicle simulation driving test platform for university lab. Lecture Notes in Electrical Engineering, Vol. 456, pp. 647-654, 2018.

[4] Oettle, N. and Sims-Williams, D.: Automotive aeroacoustics: An overview, in: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 231, No. 9, pp. 1177-1189, 2017.

[5] Huang, H. B., Li, R. X., Yang, M. L., Lim, T. C. and Ding, W. P.: Evaluation of vehicle interior sound quality using a continuous restricted Boltzmann machine-based DBN, Mechanical Systems and Signal Processing, Vol. 84, pp. 245-267, 2017.

[6] Choudhary, A. K., Mense, Y., Singh, S. and Shridhare, M.: Investigation and reduction of brake squeal and groan noise, SAE Technical Papers, Vol. 2015-September(September), doi:10.4271/2015-01-2687, 2015.

[7] Lü, H. and Yu, D.: Stability analysis and improve–ment of automotive disc brake based on interval analysis, Qiche Gongcheng/Automotive Enginee–ring, Vol. 38, No. 3, pp. 317-322, 2016.

[8] Zhang, L., Wu, J. and Meng, D.: Transient analysis of a flexible pin-on-disk system and its application to the research into time-varying squeal, Journal of Vibration and Acoustics, Transactions of the ASME*,* Vol. 140, No. 1, doi:10.1115/1.4037468. 2018.

[9] Du, Y. and Wang, Y.: Squeal analysis of a modal-parameter-based rotating disc brake model, International Journal of Mechanical Scien–ces, Vol.131-132, pp. 1049-1060, doi:10.1016/ j.ijmecsci.2017.07.033, 2017.

[10] Zhang, J., Y. H Li, J. Fang, and W. Z Zhao.: Research on squeal noise of tread brake system in rail freight vehicle, in: *Proceedings of the 2nd International Conference on Design, Materials, and Manufacturing, ICDMM 2017*, 23-25.06.2017, Beijing, China, Vol. 220, No. 1.

[11] Abendroth, H. and Wernitz, B.: The Integrated Test Concept: Dyno - Vehicle, Performance - Noise, SAE Technical Paper 2000-01-2774, 2000, https://doi.org/10.4271/2000-01-2774.

[12] Abendroth, H., Haverkamp, M., Hoffrichter, W., Blaschke, P., Mauer, G. and Wernitz, B.: Current and new approaches for brake noise evaluation and rating, SAE International Journal of Passenger Cars - Mechanical Systems, Vol. 2, No. 2, pp. 32-45, 2010.

[13] Poletto, J. C., Neis, P.D., Ferreira, N.F., Masotti, D. and Matozo, L.T.: An experimental analysis of the methods for brake squeal quantification, Applied Acoustics, Vol. 122, pp. 107-112, ISSN 0003-682X, 2017.

[14] Zhang Y., Li Z., Gao J., Hong J., Villecco F. and Yunlong L.: A method for designing assembly tolerance networks of mechanical assemblies. Mathematical Problems in Engineering Vol. 2012, Article number 513958, 2012.

[15] Formato A., Ianniello D., Villecco F., Lenza T.L.L. and Guida D.: Design optimization of the plough working surface by computerized mathematical model, Emirates Journal of Food and Agriculture, Vol. 29, No. 1, pp. 36-44, 2017.

[16] Villecco F. and Pellegrino A.: Entropic measure of epistemic uncertainties in multibody system models by axiomatic design, Entropy, Vol. 19, No. 7, Article number 291, 2017.

[17] Capozzoli, M. and De Simone, M. C.: Overview of Shims/Insulators in Brake Vibration and Noise, International Journal of Mechanical Engineering and Industrial Design, Vol. 2, No. 1, pp. 1-7, ISSN:2280-6407, 2014.

[18] Yang, L., Li, Y., Ding, P., Zamankhan, P. and Cherng, J. G.: Integrated brake squeal with induced thermal stress analysis, in: *SAE 2017 Noise and Vibration Conference and Exhibition, NVC 2017*; 12-15.06.2017, DeVos Place Convention CenterGrand Rapids; United States, Code 128586.

[19] Sena, P., Attianese, P., Carbone, F., Pellegrino, A., Pinto, A. and Villecco, F., 2012, "A Fuzzy Model to Interpret Data of Drive Performances from Patients with Sleep Deprivation", Computational and mathematical methods in medicine.

[20] Pellegrino, A. and Villecco, F., 2010, "Design Optimization of a Natural Gas Substation with Intensification of the Energy Cycle", Mathematical Problems in Engineering, 294102.

[21] Kanehira, Y., Aoki, Y. and Nishizawa, Y.: Evaluation of an Energy Dissipation Mechanism by

Friction for Brake Shims, SAE Technical Paper 2017-01-2487, 2017.

[22] Jaeyoung K.: Automotive brake squeal analysis with rotating finite elements of asymmetric disc in time, Journal of Sound and Vibration, Vol. 393, pp. 388-400, 2017.

[23] Ghomshei, M., Villecco, F., Porkhial, S. and Pappalardo, M.: Complexity in Energy Policy: a Fuzzy Logic Methodology, in: *Proceeding of Sixth International Conference on, IEEE7 Fuzzy Systems and Knowledge Discovery, FSKD'09*., pp. 128-131, 2009.

[24] Lancaster, J.K.: Severe metallic wear, in: *Proceedings of the Conference on Lubrication and Wear*, 01-03.10.1957, London, pp. 1-7 or Paper 72.

[25] De Simone, M.C. and Guida, D.: Dry Friction Influence on Structure Dynamics, in: Proceedings of the 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2015), 25-27.05.2015, Crete Island, Greece, pp.4483–4491.

[26] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Instability Induced by Dry Friction, International Journal of Mechanics, Vol. 3, No. 3, pp. 44-51, 2009.

[27] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Dry Friction Influence on Cart Pendulum Dynamics, International Journal of Mechanics, Vol. 3, No. 2, pp. 31-38, 2009.

[28] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Dry Friction Influence on Inverted Pendulum Control, in: Programme and Proceedings of 3rd International Conference on Applied Mathematics, Simulation, Modelling (ASM'09), 29-31.12.2009, Vouliagmeni Beach, Athens, Greece, pp. 49-54.

[29] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Friction Induced Vibrations of a Two Degrees of Freedom System, in: Programme and Proceedings of 10th WSEAS International Conference on Robotics, Control and Manufacturing Technology (ROCOM '10), 11-13.04.2010, Hangzhou, China, pp. 133-136.

[30] Shabana, A. A.: Dynamics of Multibody Systems, Fourth Edition, Cambridge University Press, Cambridge, United Kingdom, 2013.

[31] Pappalardo, C.M.: A Natural Absolute Coordinate Formulation for the Kinematic and Dynamic Analysis of Rigid Multibody Systems, Nonlinear Dynamics, Vol. 81, No. 4, pp. 1841-1869,2015.

[32] Pappalardo, C.M., Yu, Z., Zhang, X. and Shabana, A.A.: Rational ANCF Thin Plate Finite Element, ASME Journal of Computational and Nonlinear Dynamics, Vol. 11, No. 5, pp. 1-15, 051009, 2016.

[33] Pappalardo, C.M., Wallin, M. and Shabana, A.A.: A New ANCF/CRBF Fully Parametrized Plate Finite Element, ASME Journal of Computational and Nonlinear Dynamics, Vol.12, No. 3, pp.1-13, 031008, 2017.

[34] Pappalardo, C.M., Wang, T. and Shabana, A.A.: Development of ANCF Tetrahedral Finite Elements for the Nonlinear Dynamics of Flexible Structures, Nonlinear Dynamics, Vol. 89, No. 4, pp. 2905-2932, 2017.

[35] Pappalardo, C.M., Wang, T. and Shabana, A.A.: On the Formulation of the Planar ANCF Triangular Finite Elements, Nonlinear Dynamics, Vol. 89, No. 2, pp. 1019-1045, 2017.

[36] Kulkarni, S., Pappalardo, C.M. and Shabana, A.A.: Pantograph/Catenary Contact Formulations, ASME Journal of Vibrations and Acoustics, Vol. 139, No. 1, pp. 1-12,011010, 2017.

[37] Ruggiero, A., Affatato, S., Merola, M. and De Simone, M. C.: FEM analysis of metal on UHMWPE total hip prosthesis during normal walking cycle, in: Proceedings of the XXIII Conference of the Italian Association of Theoretical and Applied Mechanics (AIMETA 2017), 4-7.09.2017, Salerno, Italy.

[38] De Simone, M.C., Russo, S., Rivera, Z.B. and Guida, D.: Multibody Model of a UAV in Presence of Wind Fields, in: Programme and Proceedings of the International Conference on Control, Artificial Intelligence, Robotics and Optimization (ICCAIRO 2017), 20-22.05.2017, Prague, Czech Republic.

[39] Concilio, A., De Simone, M.C., Rivera, Z.B. and Guida, D.: A New Semi-Active Suspension System for Racing Vehicles, FME Transactions, Vol. 45, No. 4, pp. 565–571, 2017.

[40] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Optimal Control Design by Adjoint-Based Optimization for Active Mass Damper with Dry Friction, in: Programme and Proceedings of 4th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering COMPDYN 2013, 12-14.06.2013, Kos Island, Greece, pp. 1-19.

[41] Pappalardo, C.M., Patel, M.D., Tinsley, B. and Shabana, A.A.: Contact Force Control in Multibody Pantograph/Catenary Systems, in: Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multibody Dynamics, Vol. 230, No. 4, pp. 307-328, 2016.

[42] Pappalardo, C. M. and Guida, D.: On the Dynamic Analysis of Rigid Multibody Mechanical Systems, Machines, 2018, accepted for publication.

[43] Pappalardo, C.M., Patel, M.D., Tinsley, B. and Shabana, A.A.: Pantograph/Catenary Contact Force Control, in: *Proceedings of the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2015*, 2-5.08.2015, Boston, Massachusetts, USA, pp. V006T10A028-V006T10A028.

[44] Villecco, F. and Pellegrino, A.: Evaluation of uncertainties in the design process of complex mechanical systems, Entropy, Vol. 19, No. 9, art. no. 475, 2017.

[45] Gao, Y., Villecco, F., Li, M. and Song, W.: Multi-scale Permutation entropy based on improved LMD and HMM for rolling bearing diagnosis, Entropy, Vol. 19, No. 4, art. no. 176, 2017

[46] Zhai, Y. et al.: The application of disturbance observer to propulsion control of sub-mini under–water robot, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 6016 LNCS (PART 1), pp. 590-598, 2010.

[47] Stevanović, I., Rašuo, B.: Development of a Miniature Robot Based on Experience Inspired by Nature, FME Transactions, Volume 45 No 1, pp. 189-197, 2017.

[48] Ilić, Z., Rašuo, B., Jovanović, M., Jovičić, S., Tomić, Lj., Janković, D. and Petrašinović, D.: The Efficiency of Passive Vibration Damping on the Pilot Seat of Piston Propeller Aircraft, Measurement, Vol. 95, pp. 21-32., 2017.

[49] Ilić, Z., Rašuo, B., Jovanović, M., Pekmezović, S., Bengin, A. and Dinulović, M.: Potential Connections of Cockpit Floor – Seat on Passive Vibration Reduction at Piston Propelled Airplane, Technical Gazette, Vol.21 No.3, pp. 471-478, 2014.

[50] Jazarević, V. and Rašuo, B.: Computation of acoustic sources for the landing gear during the take-off and landing, FME Transactions, Volume 41 No 3, pp 180-188, 2013.

[51] Guida, D., Nilvetti, F. and Pappalardo C.M.: Mass, Stiffness and Damping Identification of a Two-story Building Model, in: *Programme and Proceedings of 3rd ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2011)*, 25-28.05.2011, Corfu, Greece, pp. 25-28.

[52] Pappalardo, C.M. and Guida, D.: Experimental Identification and Control of a Frame Structure using an Actively Controlled Inertial-based Vibration Absorber, in: *Programme and Proceedings of the International Conference on Control, Artificial Intelligence, Robotics and Optimization (ICCAIRO 2017)*, 20-22.05.2017, Prague, Czech Republic.

[53] Guida, D., Nilvetti, F. and Pappalardo C.M.: On Parameter Identification of Linear Mechanical Systems. In: *Programme and Proceedings of 3rd International Conference on Applied Mathematics, Simulation, Modelling, Circuits, Systems and Signals. (WSEAS)*, 29-31.12.2009, Vouliagmeni Beach, Athens, Greece, pp. 55-60.

[54] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Parameter Identification of a Two Degrees of Freedom Mechanical System, International Journal of Mechanics, Vol. 3, No. 2, pp. 23-30, 2009.

[55] Guida, D. and Pappalardo, C.M.: Sommerfeld and Mass Parameter Identification of Lubricated Journal Bearing, WSEAS Transactions on Applied and Theoretical Mechanics, Vol. 4, No. 4, pp. 205-214, 2009.

[56] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Experimental Investigation On a New Hybrid Mass Damper. In: Programme and Proceedings of 8th International Conference on Structural Dynamics (EURODYN 2011), 4-6.07.2011, Leuven, Belgium, pp. 1644-1649.

[57] Pappalardo, C.M. and Guida, D.: Adjoint-based Optimization Procedure for Active Vibration Control of Nonlinear Mechanical Systems, ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 139, No. 8, pp. 1-11, 2017.

[58] Pappalardo, C. M. and Guida, D.: Control of Non–linear Vibrations using the Adjoint Method, Mec–canica, Vol. 52, No. 11-12, pp. 2503-2526, 2017.

[59] Quatrano, A., De Simone, M.C., Rivera Z.B. and Guida, D.: Development and Implementation of a Control System for a retrofitted CNC Machine by using Arduino. FME Transactions, Vol. 45, No. 4 pp. 578–584, 2017.

[60] De Simone M. C., Rivera Z. B. and Guida D.: Ultrasonic Sensors for Object Recognition by Using Neural Network Algorithms for ROS applications, Machines, 2018, accepted for publication.

[61] Guida, D. and Pappalardo, C.M.: Control Design of an Active Suspension System for a Quarter-Car Model with Hysteresis, Journal of Vibration Engineering and Technologies, Vol. 3, No. 3, pp. 277-299, 2015.

[62] Guida, D. and Pappalardo, C.M.: A New Control Algorithm for Active Suspension Systems Featuring Hysteresis, FME Transactions, Vol. 41, No. 4, pp. 285-290, 2013.

[63] Guida, D., Nilvetti, F. and Pappalardo, C.M.: Adjoint-based Optimal Control Design for a Cart Pendulum System with Dry Friction. In: *Programme and Proceedings of ECCOMAS Thematic Conference on Multibody Dynamics*, 1-4.07.2013, Zagreb, Croatia, pp. 269-285.

[64] De Simone, M.C. and Guida, D.: On the Develop–ment of a Low Cost Device for Retrofitting Tracked Vehicles for Autonomous Navigation, in: *Proceedings of the XXIII Conference of the Italian Association of Theoretical and Applied Mechanics (AIMETA 2017)*, 4-7.09.2017, Salerno, Italy.

[65] Guida, D. and Pappalardo, C.M.: On the use of Two-dimensional Euler Parameters for the Dynamic Simulation of Planar Rigid Multibody Systems, Archive of Applied Mechanics, pp. 1-19, 2017, DOI: 10.1007/s00419-017-1279-0.

[66] Guida, D. and Pappalardo, C.M.: Forward and Inverse Dynamics of Nonholonomic Mechanical Systems, Meccanica, Vol. 49, No. 7, pp.1547-1559, 2014.

[67] Ruggiero, A.; De Simone, M.C.; Russo, D. & Guida, D.: Sound pressure measurement of orchestral instruments in the concert hall of a public school, International Journal of Circuits, Systems and Signal Processing, Vol. 10(2016), pp. 75-812.

[68] Guo, C., Bao, J., Yin, Y. and Yang, S.: Research status on frictional vibration and noise of mechanical brake, Recent Patents on Mechanical Engineering Vol. 10, No. 1, pp. 39-50, 2017.

[69] Yue, Y., Allgaier, R., Jaber, N. and Wang, A.: Brake Noise Study (Part I) - Low Frequency Squeal, SAE Technical Paper 2006-01-0474, 2006.

[70] Giannini, O. and Massi, F.: Characterization of the high-frequency squeal on a laboratory brake setup, Journal of Sound and Vibration, Vol. 310, No. 1–2, pp. 394-408, ISSN 0022-460X, 2008.

[71] Spurr, R. T.: A Theory of Brake Squeal, Proceedings of the Institution of Mechanical Engineers: Automobile Division, Vol. 15, No. 1, pp. 33-52, 1961.

[72] Earles, S.W.E. and Soar, G.B.: Squeal noise in disc brakes, Paper C100/71, Proc. I.Mech.E. Conf. on "Vibration and Noise in Motor Vehicles, 1971.

[73] Earles, S. W. E. and Lee, C. K.: Instabilities arising from the frictional interaction of a pin-disc system resulting in noise generation, ASME J. Eng. Ind, Vol. 98, No. 1, pp. 81-86, 1976.

[74] Ćirović, V. and Dragan A.: Dynamic modeling of disc brake contact phenomena, FME Transactions Vol. 39, No. 4, pp. 177-183, 2011.

[75] Aleksendrić, D., Velimir C. and Velibor S.: Dynamic control of disc brake performance, SAE International Journal of Passenger Cars-Mechanical Systems 5.2012-01-1837, pp. 1266-1272, 2012.

NOMENCLATURE

$\boldsymbol{q}$	Lagrangian coordinates vector
T	kinetic energy
V	potential energy function
$\boldsymbol{Q}$	generalized external forces vector
$\boldsymbol{M}$	mass matrix
$\boldsymbol{K}$	stiffness matrix
$\boldsymbol{Q}_{pad}$	force field between disk and pads vector
$\boldsymbol{Q}_v$	quadratic velocity vector
μ	friction coefficient
$\boldsymbol{K}_p$	coupling stiffness between the disk and pads
k_n	normal elastic reaction parameter
λ	contact pressure parameter
ND	nodal diameter

АНАЛИЗА КОНАЧНИХ ЕЛЕМЕНАТА КОД ШКРИПАЊА ЖЕЛЕЗНИЧКИХ ВОЗИЛА

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Рад приказује резултате експерименталних истраживања буке изазване шкрипањем диск кочница на железничким возилима. Мерења, која очигледно показују облике нестабилности са почетком кочења, су вршена у реалним условима уређајем са сондом за мерење интензитета звука који емитује диск кочница. Коришћењем FFT идентификоване су најјаче фреквенције. Циљ рада је анализа таквих феномена помоћу FEA 3D CAD модела диска израђеног у софтверском окружењу Ansys Workbench FEM да би се боље разумело како стабилан систем постаје нестабилан. Анализирани систем се састоји од челичног диска и четири диск плочице поређане у низ цилиндара направљених од фрикционог материјала. Такав систем плочица је пројектован да би се поједноставила симулација под претпоставком да она има утицаја само на поједине тачке на површини диска. Нумерички резултати се подударају са експерименталним.