Preface

This report "balances our books" in railway mechanics at the establishment and start of the Competence Centre CHARMEC.

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Introduction

by Bengt Åkesson

Research in railway mechanics has been carried on at the Division of Solid Mechanics at Chalmers University of Technology since 1987. Among the achievements so far are five licentiate dissertations, two doctoral theses, and one docent award. The work has been done within two research groups under the supervision of Tore Dahlberg and Roger Lundén together with Bengt Åkesson. The present report summarizes the research work that has been published up to June 1995.

As of July 1995, a Centre of Excellence, or Competence Centre (in Swedish: Kompetenscentrum), in Railway Mechanics has been formally established at Chalmers University of Technology. An overview of this centre, called CHARMEC, is included at the end of the present report.

Today, 6 senior researchers holding a doctor’s degree and 8 doctoral students (they will soon be 10) are working within CHARMEC. Our research in railway mechanics has now been broadened to include not only the Division of Solid Mechanics but also the Division of Engineering Metals and the Division of Dynamics in Design at Chalmers. It is intended that the Competence Centre CHARMEC shall operate for a period of 10 years.

An overview of the period 1987-1991 was published under the title "Report of railway engineering research at Chalmers University of Technology in Gothenburg" in Proceedings IMechE, Part F: Journal of Rail and Rapid Transit, vol 206, no F2, 1992, pp 145-148. The present report incorporates most of the material in the IMechE paper.

Each one of the following two sections, authored by Tore Dahlberg and Roger Lundén, is meant to be self-contained. The reference lists in the following contain (with some duplications)

53	**R**esearch papers:	R01	to	R32	and	R51	to	R71
20	**O**ther articles:	O01	to	O16	and	O51	to	O54
20	**S**tudent reports:	S01	to	S10	and	S51	to	S60

Papers which are published internationally in scientific journals or conference proceedings are marked with an asterisk. There are 38 such papers. Reports and reprints can be obtained from the author(s).

Dynamic Train/Track Interaction

by Tore Dahlberg

General

Since 1988, the dynamics of the train/track system have been a research topic at the Division of Solid Mechanics at Chalmers University of Technology in Gothenburg, Sweden. Papers and articles published by the research group are surveyed in the following. References are given at the end of the present exposition. Abstracts of some papers are also given. Reports and reprints of published papers can be obtained from the author (Tore Dahlberg).

In the research reported here, the interacting train and track are both modelled as dynamic systems. The compound train/track system is treated as a whole.

The research papers are numbered R01 to R32. Other articles and reports are numbered O01 to O16. Student reports are numbered S01 to S10. A survey covering some literature on this subject before 1988 has been presented in reference R01.

Modelling of track structure and track components

Railroad track models often contain components which can be modelled as beams on elastic foundations. A method for calculating eigenfrequencies and eigenmodes of linear beam structures on a rather general linear elastic foundation has been developed, reference R06. The method is an extension of the so-called Wittrick and Williams algorithm. As special cases the foundation model contains the classical one-parameter Winkler model and the two-parameter Pasternak model.

A mathematical model of the vertical track dynamics has been established by use of beam elements. These may be connected to an elastic foundation, they may be generally viscously damped, and they may carry large static axial loads. In order to test the Rayleigh-Timoshenko beam models of sleepers and rails, measurements on free-free concrete railway sleepers and on pieces of railway rails have been performed, references R08 and R32. The dynamics of free-free and in-situ concrete railway sleepers have been (theoretically) investigated, reference R09.

Another two important components of the track structure are the railpads inserted between the rails and the sleepers and the ballast in which the sleepers are embedded. Until now the ballast has been modelled as a continuous distribution of springs and viscous dampers. Some extra mass has been added to the sleepers to take the ballast mass into account. The railpads are normally made of viscoelastic materials. For the constitutive description of these materials, a fractional derivative model has been tried, references R27, R28 and R29. Some experiments have been performed, references R26 and S05.

Modelling of vehicle

The vehicle model may contain the car body, secondary suspension, bogie frame, primary (wheelset) suspensions, unsprung masses (the wheelsets) and contact springs between wheel and rail. This model is non-linear and state-dependent and may also be time-dependent if necessary. The unsprung masses are connected to the rail via non-linear Hertzian springs having zero stiffness in tension. Algebraic equations ensure that the vertical wheel/rail contact force and the vertical velocity and acceleration at each wheel/rail contact patch become the same for the wheel as for the rail (as long as contact between wheel and rail is maintained). Initial irregularities on the wheel (out-of-roundness, undulations, wheelflats) and on the rail (corrugation, rail joints, and so on) are included in these algebraic equations. A possible loss of contact between wheel and rail is also handled.

Vehicle/track interaction

In an earlier investigation, structural responses to moving loads were studied. The dynamics of vehicle/bridge systems were investigated for simple mass-spring vehicle models, references R02, R03 and R04. In reference R05, a railway track was modelled as a finite beam supported by equally spaced mass-spring systems. The track was loaded by a force moving with constant speed.

In the research reported here a finite portion of a railway track structure is studied. A method has been developed for the solution of dynamic interaction problems including a non-linear dynamic system (a bogie) running at a prescribed time-dependent speed on a linear track or guideway. An extended state-space vector formulation for the solution of the full train/track interaction problem has been established, references R07, R10, R18 and R25. It allows for the analysis of structures containing both physical and modal components. The physical components model vehicles which are discretized into linear or non-linear mass-spring-damper systems, whereas the modal components model a linear continuous portion of a track. Dynamic forces between a bogie and the track structure are calculated. The computer program is documented in reference R19.

In a parametric study of a non-corrugated rail traversed by a perfectly round wheel, the influence of a number of parameters on the bending stresses in the sleepers and the rails has been investigated, reference R14. Parameters studied are, for example, vehicle speed, foundation stiffnesses (bed moduli), sleeper cross-section, rail cross-section, sleeper distance, pad stiffness and pad damping.

Wheel and rail irregularities

The solution technique developed can be used to study the influence of non-circular wheels or track irregularities in the vertical plane, reference R17. Also a study of the vertical time-dependent vehicle/track interaction force, taking a randomly irregular track profile into account, has been performed, references R11 and R12.

Corrugation that develops on the railhead causes high-frequency vibrations that generate noise, reference R21. Wear due to driven locomotive wheels has been investigated. The wear is assumed to be a function of creep and friction force. A semi-empirical relationship between creep, friction force and normal contact force based on rolling contact mechanics is employed. The normal contact forces between the moving wheels and the rail are determined by use of a time-stepping method. It has been found that the two wheelsets of a travelling bogie interact via the track, and that this phenomenon could play an important role in the development of the corrugation, reference R22.

Measurements

In order to verify the computational method developed, a full-scale measurement program was specified and planned by Chalmers and The Swedish National Rail Administration (Banverket). The measurements were accomplished in April 1993 on the newly built West Coast line in Sweden. Measurements of strains and accelerations in the track were made simultaneously with measurements on the train of rail/wheel contact forces and accelerations. The track measurements were performed by Banverket. The Swedish State Railroad Company (SJ) recorded contact forces using instrumented wheelsets mounted on a two-axle freight car. In July 1993 the same test site was used for similar measurements performed with the Swedish high-speed train X2000 at speeds up to 276 km/h. Measurement results have been reported in references R15, R16, R20, R30, R31, R32 and O13.

Partners and sponsors

A report summarizing the first three years of this research was presented in reference O02. The main partners and sponsors in the work reported here have been The Swedish National Rail Administration (Banverket) and Abetong Teknik AB (concrete sleeper manufacturer). During the first three years also The Swedish National Board for Technical Development (STU/NUTEK) and some other agencies sponsored.

Research papers with abstracts — Train/Track Interaction

Papers internationally published in scientific journals or conference proceedings are marked with an asterisk.

R01. T Dahlberg: *Dynamic interaction between train and track - A literature survey* (with 133 references). Report F120, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 21 pp, 1989

R02. T Dahlberg: *Vehicle-bridge interaction - Part 1*. Report F90, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 17 pp, 1984

R03. T Dahlberg: *Vehicle-bridge interaction - Part 2*. Report F92, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 29 pp, 1984

R04.* T Dahlberg: Vehicle-bridge interaction. *Vehicle System Dynamics*, vol 13, no 4, pp 187-206, 1984

> *Summary of references 2, 3, and 4*: With the emergence of high-speed trains, dynamic loads on bridges have changed. A method for estimation of the time-dependent vehicle-bridge interaction forces has been developed. The increase (or decrease) of the bridge response due to dynamic effects was determined. The moving constant-force problem was reviewed in some detail. Results obtained by the present method for the moving-mass problem were compared with existing experimental and theoretical results as reported in the literature. A parametric study of bridge responses was made. The parameters varied were the vehicle

speed, the ratio of vehicle mass to bridge mass, the ratio of vehicle eigenfrequency to bridge eigenfrequency, and the relative damping of the vehicle. Finally, the influence of an initial bridge deflection was discussed.

R05.* T Dahlberg: Structural responses to moving forces determined by reciprocity relations. *Vehicle System Dynamics*, vol 19, no 3, pp 113-130, 1990

Summary: Reciprocity relations are valid also for dynamic problems. In this paper, the reciprocity relation was first used to determine the response of a simply supported beam subjected to an arbitrarily time-varying force moving with constant speed. Then the reciprocity relation was used to determine the response of a beam-like structure (a beam on mass-spring supports, a model of a railway track) subjected to a moving constant force. Numerical solutions, including also a pair of moving forces, were given.

R06.* J C O Nielsen: Eigenfrequencies and eigenmodes of beam structures on elastic foundation. *Journal of Sound and Vibration*, vol 145(3), pp 479-487, 1991

Summary: A method for determining the eigenfrequencies of continuous structures containing beams in plane bending-shearing vibration was presented. Each beam member may rest on a general Winkler-type elastic foundation (including the Pasternak foundation as a special case) and may carry a large static axial load calling for use of a second-order theory. The method could preferably be implemented in the Wittrick-Williams bisection algorithm. A numerical verification was given for a repetitive structure where an alternative solution is available through the use of exact difference equations. Practical applications to a rail/pad/sleeper system on its ballast and roadbed were foreseen.

R07.* J C O Nielsen and T J S Abrahamsson: Complex eigensolutions used for beam structures on elastic foundation loaded by moving nonlinear dynamic systems. *Proceedings of the Ninth International Modal Analysis Conference*, 15-18 April 1991, Florence, Italy, vol 2, pp 1110-1116, Union College, Schenectady NY, 1991

R08. L Ågårdh: *Reinforced concrete sleepers. Determination of resonance frequencies, modal dampings and modal shapes by use of experimental modal analysis* (in Swedish), The Swedish National Testing Institute, Report SP-AR 1009-09, Byggnadsteknik, Borås, Sweden, 43 pp, 1990

R09.* T Dahlberg and J C O Nielsen: Dynamic behaviour of free-free and in-situ concrete railway sleepers. *International Symposium on Precast Concrete Railway Sleepers*, 8-11 April 1991, Madrid, Spain, Proceedings, pp 393-416, Colegio de Ingenieros de Caminos, Canales y Puertos, Madrid, Spain (also Report F138, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 17 pp, 1991)

Summary: The dynamic behaviour of free-free and in-situ concrete railway sleepers was studied. A method developed by Nielsen (reference R06 above) to calculate eigenfrequencies and eigenmodes of general beam structures on a general elastic foundation was used. Measurements on free-free concrete railway sleepers have been performed. Calculated and measured eigenfrequencies and eigenmodes in bending vibration in the vertical plane of the sleepers were compared. It was found, except for the lowest two bending mode eigenfrequencies, that the refined Rayleigh- Timoshenko beam theory was required for the eigenfrequency and eigenmode calculations. The natural frequencies of a beam on an elastic foundation (*i e*, the in-situ sleeper) will differ from those obtained for the free-free beam (sleeper). The foundation introduces two eigenfrequencies coupled to two almost rigid-body eigenmodes (translation and rotation) of the sleeper. The lower eigenfrequencies in bending are also influenced by the foundation stiffnesses, whereas higher eigenfrequencies are almost unaffected. Dynamic responses (bending moments) of a sleeper as a component in a track structure subjected to transient excitation were investigated. It was found that an irregular rail profile had a significant influence on the dynamic responses.

R10.* J C O Nielsen and T J S Abrahamsson: Coupling of physical and modal components for analysis of moving nonlinear dynamic systems on general beam structures. *International Journal for Numerical Methods in Engineering*, vol 33, pp 1843-1859, 1992 (also Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 22 pp, 1990)

Summary: A general, well-structured and efficient method is advanced for the solution of a large class of dynamic interaction problems including a nonlinear dynamic system running at a prescribed time-dependent speed on a linear track or guideway. The method uses an extended state-space vector approach in conjunction with a complex modal superposition. It allows for the

analysis of structures containing both physical and modal components. The physical components studied here are vehicles modelled as linear or nonlinear discrete mass-spring-damper systems. The modal component studied is a linear continuous model of a track structure containing beam elements which can be generally damped and which can be embedded in a three-parameter damped Winkler-type foundation. The complex modal parameters of the track structure are solved for. Algebraic equations are established which impose constraints on the transverse forces and accelerations at the interfaces between the moving dynamic systems and the track. An irregularity function modelling a given nonstraight profile of the nonloaded track or a noncircular periphery of the wheels is also accounted for. Loss of contact and recovered contact between a vehicle and the track can be treated. The system of coupled first-order differential equations governing the motion of the vehicles and the track *and* the set of algebraic constraint equations are *together* compactly expressed in one unified matrix format. A time-variant initial-value problem is thereby formulated such that its solution can be found in a straight-forward way by use of standard time-stepping methods implemented in existing subroutine libraries. Examples for verification and application of the proposed method are given. The present study should be of particular value in railway engineering.

R11. Å Fenander and A Igeland: *Nonlinear vehicles on randomly profiled tracks - Monte Carlo simulation of excitation and frequency analysis of response*. Report T127, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 21 pp, 1991

R12.* T Dahlberg, Å Fenander, A Igeland and J Nielsen: Railway vehicle on randomly profiled track. *Proceedings Scandinavian Forum for Stochastic Mechanics*, Department of Building Technology and Structural Engineering, University of Aalborg, Aalborg, Denmark (also Report F150, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 12 pp, 1991)

Summary: A method has been developed, implemented and applied for the study of the dynamic vertical interaction between a moving dynamic system (a vehicle) and a continuous beam structure (the track). The dynamic interaction problem is solved in a unified manner by use of an extended state-space vector approach. The time-variant initial-value problem is formulated in such a way that its solution can be found by use of a standard

time-stepping method. An initial random irregularity of the track height profile (an irregularity on the railhead) and/or an initial random out-of-roundness of the wheel may be handled. In this report the wheel/rail contact force is analysed when the rail height profile has a random irregularity.

R13. J C O Nielsen: *Nonlinear vehicles traversing a rail structure*. Thesis for the Degree of Licentiate of Engineering, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 1991, 4 pp and two appended papers

R14.* J C O Nielsen: Dynamic interaction between wheel and track - A parametric search for best performance of railway tracks. *Vehicle System Dynamics*, vol 23, no 2, pp 115-132, 1994 (also Report F147, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 22 pp, 1991)

Summary: The dynamic vertical interaction between a moving rigid wheel and a flexible railway track was studied. A round and smooth wheel tread and an initially straight and noncorrugated rail surface were assumed. A linear three-dimensional beam structure model of a finite portion of the track was suggested including rails, pads, sleepers and ballast with spatially nonproportional damping. The full interaction problem was numerically solved by use of an extended state-space vector approach in conjunction with complex modal superposition for the track. Transient bending stresses in sleepers and rails were calculated. The influence of seven selected track parameters on the dynamic behaviour of the track was investigated. A two-level fractional factorial design method was used in the search for a combination of numerical levels of these parameters making the maximum bending stresses a minimum.

R15.* M Fermér and J C O Nielsen: Wheel/rail contact forces for flexible versus solid wheels due to tread irregularities. *Proceedings of the 13th IAVSD Symposium on the Dynamics of Vehicles on Roads and on Tracks*, Chengdu, Sichuan, China, 23-27 August 1993, pp 142-157

R16.* J C O Nielsen and M Fermér: Vertical dynamic train/track interaction - Verifying a theoretical model by full-scale experiments. *Proceedings of the Twelfth International Modal Analysis Conference*, January 31 - February 3, 1994, Honolulu HI, vol 2, pp 1583-1590, Union College, Schenectady NY, 1994

Summary of 15 and 16: The vertical dynamic behaviour of a railway vehicle with flexible wheels is compared to that of a vehicle with standard solid wheels. Full-scale field experiments performed on a portion of a recently built railway track for high-speed trains are reported. Flexible and solid wheels without and with wheelflats were instrumented for measurement of transient vertical wheel/rail contact forces. Accelerations and strains in the track structure were measured in parallel. The location of the instrumented wheelset in relation to the instrumented portion of the track was determined at each instant of time. Flexible wheels are shown to considerably reduce the contact forces. A linear mathematical model of the track is suggested based on a previously reported technique for solving vertical interaction problems. Track parameters determined at the test-site are used as input to the model. Numerical results show acceptable agreement with measured responses.

R17.* J C O Nielsen and A Igeland: Vertical dynamic interaction between train and track - Influence of wheel and track imperfections. *Journal of Sound and Vibration*, vol 187(5), pp 825-839, 1995 (also Report F169, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 19 pp, 1993).

Summary: The vertical dynamic behaviour is investigated for a railway bogie moving on a rail which is discretely supported, *via* railpads, by sleepers resting on an elastic foundation. The transient interaction problem is numerically solved by use of an extended state-space vector approach in conjunction with a complex modal superposition for the track. Application examples are given in which the influences of three types of practically important imperfections in the compound vehicle/track system are investigated. The first is a sinusoidal corrugation of the railhead and the second a skid flat on the wheel tread (a wheelflat). The third imperfection is a case where a single sleeper has lost its support due to erosion of the ballast. Physical explanations of the calculated interaction behaviour are given.

R18.* J C O Nielsen: *Train/track interaction — Coupling of moving and stationary dynamic systems - Theoretical and experimental analysis of railway structures considering wheel and track imperfections*. PhD Dissertation, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 1993, 17 pp and five appended papers

R19. J C O Nielsen: *DIFF - A computer program for numerical analysis of vertical dynamic train/track interaction. Theory manual and User's manual*. Publication no 34, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 77 pp, 1994

R20.* M Fermér and J C O Nielsen: Vertical interaction between train and track with soft and stiff railpads - full-scale experiments and theory. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol 209, no F1, pp 39-47, 1995 (Report F175, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 30 pp, 1994)

> *Summary*: The vertical dynamic interaction between a running freight wagon and a tangent railway track has been investigated experimentally and numerically. Standard solid wheels without and with wheelflats were instrumented for measurement of transient vertical wheel/rail contact forces. Accelerations and strains in the track structure were measured in parallel. The location of the instrumented wheelset in relation to the instrumented portion of the track was determined at each instant of time. A portion of the track was equipped with railpads considerably stiffer than the soft ones used as standard in Sweden. The influence of train speed and axle load on dynamic responses was studied and compared for the two test sites. Track parameters determined at the test site were used as input to a mathematical model. Numerical results show reasonable agreement with measured responses. In the presence of wheelflats, measured dynamic contact forces were largely affected by pad stiffness and axle load. However, for some of the loading cases investigated, it was observed that soft pads did not always lead to lower contact forces. Maximum dynamic responses generally increased with increasing train speed.

R21. T Dahlberg: *Rail corrugation formation - A literature survey*. Report F158, Solid Mechanics, CTH, Gothenburg, 10 pp, 1993

R22. A Igeland: *Railhead corrugation growth on tangent tracks*. In Railhead corrugation on tangent tracks - Consequences and causes, Thesis for the Degree of Licentiate of Engineering, Report F173, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 24 pp, 1994

R23.* A Igeland: Dynamic train/track interaction can explain rail corrugation growth. *Proceedings of the 13th International Modal Analysis Conference*, Nashville TN, 1995, vol 1, pp 126-132, Union College, Schenectady NY, 1995 (condensed version of R22)

R24.* A Igeland: Railhead corrugation growth explained by dynamic interaction between track and bogie wheelsets. Accepted October 1995 for publication in *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*

Summary of references 22, 23, 24: Railhead corrugation growth on tangent tracks due to wear from driven locomotive wheels is investigated. The study sets out from an assumed random initial railhead irregularity. Measurements on a newly-built track are exploited. The wear is assumed to be a function of creep and friction force. A semi-empirical relationship between creep, friction force and normal contact force based on rolling contact mechanics is employed. Only longitudinal creep and creep forces are taken into account. The normal contact forces between the moving wheels and the rail are determined by use of a time-stepping method, allowing for a non-linear hertzian contact stiffness, and by use of complex modal superposition for the track structure. Numerical examples are given. It is found that the two wheelsets of a travelling bogie interact and should be considered in the same calculation. The bogie wheelbase is an important parameter.

R25.* A Igeland: Time domain solution of the dynamic interaction between railroad structures and moving loads. *The Third International Congress on Industrial and Applied Mathematics*, Hamburg, 3-7 July 1995, 4 pp

R26.* Å Fenander: *In situ stiffness of railway pads evaluated through comparison between measurements and calculations*. Report F160, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 8 pp, 1993

Summary: Eigenfrequencies have been measured in the laboratory for a free-free concrete railway sleeper with a piece of rail attached to the sleeper and with different railpads between sleeper and rail. In parallel, a finite element model of the sleeper with pad and rail has been developed and eigenfrequencies have been evaluated. The results of measurements and calculations are compared. By adapting the pad stiffness in the calculation model to reproduce the measured eigenfrequencies one may estimate the

real stiffness of different pads. The value of pad stiffness is found to have a great influence on some eigenfrequencies and less influence on others.

R27. Å Fenander: *Modelling damping by use of fractional derivatives*. Thesis for the Degree of Licentiate of Engineering, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 22 pp, 1994

R28.* Å Fenander: Modal synthesis when modelling damping by use of fractional derivatives. *Proceedings of 36th AIAA/ASME/ASCE/ AHS/ASC Structures, Structural Dynamics and Materials Conference,* New Orleans LA, April 10-13, 1995, vol 1, pp 221-230

R29.* Å Fenander: Modal synthesis when modelling damping by use of fractional derivatives. Accepted December 1995 for publication in *AIAA Journal*, 10 pp

Summary of references 27, 28, 29: The fractional derivative damping model is compared to other damping models used for mechanical systems. In some examples, which are solved in the Fourier domain, the influence of the different parameters in the fractional derivative model is studied. For large structures, modal synthesis can be used to solve the equations of motion in the time domain. A state-space vector, containing fractional derivatives of the displacement, is then introduced. The resulting system of equations is decoupled by use of the complex eigenvectors of the system. The solutions of the decoupled equations are superposed, weighted by the eigenmodes, to give the response of the structure. A method to reduce the computational effort is suggested.

R30.* T Dahlberg: Dynamic interaction between train and track - calculations and full-scale experiments. *Nordic Conference on Vehicle and Machine Vibrations*, September 6-8 1994, on board Silja Europa. Swedish Vibration Society WG2 SVIB-AU2, and the Royal Swedish Academy of Engineering Sciences IVA, 12 pp

R31.* T Dahlberg: Dynamic interaction between train and track - calculations and full-scale experiments. *Proceedings of the 3rd International Conference on Traffic Effects on Structures and Environment*, September 13-16 1994, The High Tatras (Strbské Pleso), Slovakia, vol I, pp 93-101

R32.* T Dahlberg: Vertical dynamic train/track interaction - verifying a theoretical model by full-scale experiments. *Proceedings of the 3rd Herbertov Workshop, Interaction of Railway Vehicles with the Track and Its Substructure*, September 19-23, 1994, Herbertov, Czech Republic. Supplement to *Vehicle System Dynamics*, Vol 24, pp 45-57, 1995. Swets & Zeitlinger, Lisse (also Report F176, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 13 pp, 1995)

Summary of 30, 31 and 32: A numerical method has been developed by which the dynamic behaviour of railway track and vehicle components may be investigated. Parameters such as speed, axle load, wheel base of a bogie, rail corrugations, wheelflats etc may be taken into account. In order to verify the computational method, a full-scale measurement program was accomplished on the West Coast line in Sweden. Test results are presented and compared to calculations. In order to investigate the influence of pad stiffness, the soft railway pads were replaced by stiffer pads along a limited portion of the track.

Other articles — Train/Track Interaction

International publication is marked with an asterisk.

O01 T Dahlberg and J Nielsen: *En studieresa till England*. Report F160, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 8 pp, 1993

O02 T Dahlberg: *Dynamic interaction between railway vehicle and track. Final report of a three-year railway engineering research program*. Report F140, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 20 pp, 1991

O03 T Dahlberg: Dynamisk interaktion mellan tåg och bana, *Modern Järnväg*, no 3, pp 14-15, 1991

O04 J Nielsen: *Spårmodeller för studium av vertikal samverkan mellan fordon och bana*. Dokumentation till doktorandkurs TC911, Samverkan fordon/bana, KTH, 8 pp, 1991

O05* T Dahlberg, R Lundén and B Åkesson: Report of railway engineering research at Chalmers University in Gothenburg, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol 206, no F2, pp 145-148, 1992

O06 T Dahlberg, R Lundén and B Åkesson: Railway engineering research at Chalmers, *Proceedings VTIs och TFBs Forskardagar*, Linköping, 8-9 January 1992, pp 234-240

O07 T Dahlberg and J Nielsen: Dynamic interaction between wheel and track - A parametric search towards an optimal design of rail structures, *Proceedings VTIs och TFBs Forskardagar*, Linköping, 8-9 January 1992, pp 242-250

O08* T Dahlberg, S Westberg and B Åkesson: Modelling the dynamic interaction between train and track, *Railway Gazette International*, vol 149, no 6, pp 407, 409 and 411-412, June 1993

O09 T Dahlberg: Dynamisk samverkan mellan tåg och spår, *CIC-Nytt* (Chalmers Innovationscentrum), vol 13, no 2, pp 36-38, 1993

O10 T Dahlberg: *Stokastiska svängningar - med speciell tillämpning på fordonsvibrationer*, Skrift U60, Chalmers hållfasthetslära, Göteborg 1993, 92 pp

O11 T Dahlberg, B Paulsson and B Åkesson: Dynamisk samverkan mellan tåg och spår - beräkningar och fullskaleexperiment, *Proceedings VTIs och KFBs Forskardagar*, Linköping, 12-13 January 1994, 7 pp

O12 J Nielsen: Forskning för bättre järnvägsspår, *SVEN* (Swedish Vehicular Engineering News Forum), no 1, 1994, p 7

O13* T Dahlberg, S Hammarlund and Å Jahlenius: Goose Hill measurements confirm X2000's low dynamic track forces, *Railway Gazette International*, vol 150, no 7, pp 439-444, July 1994

O14 T Dahlberg: Tåginducerade vibrationer i järnvägsspår - beräkningsmodell och fullskaleexperiment. *Nordisk Järnbane Tidskrift*, årg 120, no 1994:5, pp 16-17

O15 T Dahlberg: Järnvägsforskning vid Chalmers hållfasthetslära, *Modern Järnväg*, June 1995, pp 10-11

O16 T Dahlberg: Spårdynamik och höga axellaster, Konferensrapport från seminarium om *Gångdynamisk simulering och prediktering av underhållsrelaterade spårkrafter vid höga axellaster*, Banverket och Luleå tekniska högskola, Luleå, May 1995, 5 pp

Student reports — Train/Track Interaction

S01 G Johansson, P Skoglund and L-G Skötte: *Dynamic effects of a high speed train on a bridge* (in Swedish), Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 37 pp, 1983

S02 S Alfredsson, O Arnez, R Svensson and A Wibrink: *Interaction between vehicle and rail* (in Swedish), Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 36 pp, 1988

S03 A Andersson, L Bergman, M Enelund and R Malkolmsson: *Dynamic interaction between train and track* (in Swedish), Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 42 pp, 1990

S04 F Hansson, P Mellander, Y Saberi-Majd and A Shahdaei: *Non-linear vehicle on bridge with random road profile* (in Swedish), Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 50 pp, 1991

S05 P Johansson, C Linusson, U Lindstedt and L Zetterberg: *The role of rail pads in a railway model* (in Swedish), Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 31 pp, 1992

S06 P Govik, B Lennartsson, S Petersen, S Thynelius, E Tivesten and J Östberg: *Dynamic properties of railway tracks* (in Swedish), Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 63 pp, 1993

S07 M Ericson, J Frendin, L Nordström, P Sandberg and R Torsein: *Railway track vibrations – some dynamic models* (in Swedish), Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 48 pp, 1994

S08 A T A de Brito and D A Coelho: *Theoretical and experimental analysis of railway beams*, Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 28 pp, 1994

S09 D A Coelho: *Dynamic analysis of the overhead contact line (in electrically powered railway systems)*, Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 6 pp, 1994

S10 T Broberg, P Johansson, P A Jönsson, S Larsson and U Lång: *Railway track vibrations – a benchmark test and a sleeper vibration study*, Student Report, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 46 pp, 1995

Railway Wheelsets

by Roger Lundén

General

Since 1987, the mechanics of railway wheelsets has been an area of research at the Division of Solid Mechanics at Chalmers University of Technology in Gothenburg, Sweden. Papers and articles published by the research group are surveyed in the following. References are given at the end of the present exposition. Abstracts of some papers are also given. Reports and reprints of published papers can be obtained from the author (Roger Lundén).

The research papers are numbered R51 to R71. Other articles and reports are numbered O51 to O54. Student reports are numbered S51 to S60. The present report is an update of two previous reports, see references O51 and O52. A short information is also given in reference O53.

Railway wheelsets

Railway wheels normally have a service life of one or two million kilometres, and they can operate under very extreme climatic conditions. A proper design of wheelsets is important when considering some of the most crucial aspects on the competitive strength of railways, such as safety, noise, economy, speed and axle load. The aim of the research is to serve the development of wheelsets and related components to meet future demands.

Some specific aspects have been coped with. A shrink-fit assembly between wheel and axle has been used in Sweden with success since the 1940s. Diameter tolerances of the shrink-fit assembly have been studied, reference R51. Nowadays, higher axle loads for railway freight operations are required. The unsprung mass (including wheels, axles, brake discs, bearings and axle boxes) strongly contributes to the dynamic wheel/rail forces. Weight optimizations of axles, axle boxes, bearings and wheel discs have been performed, references S51 and S52. The durability of block-braked freight car wheels under increased axle load and speed has been investigated, reference R52. Further work on braking is reported in references R53, R54 and S53.

Disc brakes

Demands for higher speeds and better performance make disc brakes necessary in modern trains. Studies have been carried out on solid unventilated discs under normal (in Sweden) loading conditions. Analytical work and experimental studies have been performed, references S54, R55, R56, R57 and R58. For the experiments, a full-scale inertia dynamometer has been developed and constructed within the present project. It contains 12 locomotive wheels driven by a 250 kW electrical motor.

New wheel concepts

Increased axle loads in freight trains call for new concepts of wheelsets. One project has been dealing with flexible wheels. A proposed spoked wheel has been shown to improve both the tread braking performance and the dynamic characteristics, references R59 and R60. There are also indications that this wheel has a very low noise emission.

A solid "low-stress" freight car wheel has been designed by use of a modern optimization method, reference R61. The wheel is exposed to combined high contact forces and braking loads.

The work on *Disc brakes* and *New wheel concepts* constitutes a PhD dissertation, reference R62. The five papers of the dissertation have all been published internationally, references R55, R56, R59, R60 and R61. Also references R63 and O54 are related to this dissertation.

Wheel materials

Effort has been focused on wheel materials. A group of specialists in solid mechanics and material sciences has been set up. Two important aspects have been the optimum choice of material parameters and the selection of new materials. The steel process involving phenomena such as hydrogen embrittlement is essential, reference S55. Cooperation with the Division of Engineering Metals at Chalmers University of Technology has been fruitful and it will expand within the new "Competence Centre" CHARMEC.

Wheel flats

A major study on martensite formation in the wheel/rail contact area as caused by unintentional sliding between the wheel and the rail is presently being performed, references R64, R65, R66 and R67. The work includes finite element analysis of both thermomechanical phenomena and phase transformation phenomena during the development of a wheel flat.

Fatigue of the brittle martensite formed by the thermal shock is being studied. The results are expected to have a bearing on the future selection of wheel materials and maintenance procedures. Two introductory studies, partially experimental, in this field were performed, references S56 and S57.

Wheel/rail contacts

Higher axle loads for railway operations give rise to wear and shelling of the wheels. This damage is governed by the conditions in the wheel/rail contact zone. The combined effect of the wheel/rail contact load and the braking load on the service life of the wheel tread has been investigated, reference R68. In another study, a three-dimensional finite element analysis of the elastoplastic response to rolling contact was performed on a supercomputer, reference S58. Further, the problem of wheel subsurface crack initiation and growth due to rolling contact load has been considered, reference R69. Here, practical experience and also results from existing rolling bearing technology are employed.

During 1994 an extensive work was started to develop a lifetime prediction method for the wheel tread, references R70 and R71. Fatigue, plastification, thermal effects and wear are considered in this project. Theory, verified by experiments and data from the field, will be implemented in a computer code. The method should be useful in design and tendering work and also in optimization of wheel maintenance.

Vibration and noise

Vibration and noise from railway traffic are receiving increased attention. Higher speeds and axle loads tend to aggravate these problems while the public is demanding a better comfort and environment. The wheel is an important source of vibration and noise, mostly related to the rolling contact and the braking.

Two introductory studies on vibration and noise have been performed, references S59 and S60.

Two research students have recently been employed at the Division of Solid Mechanics to work with problems related to vibration and noise. This work is partly performed within a NUTEK-financed project (NUTEK = the Swedish National Board for Technical Development) and, from January 1996, also within the BriteEuRam III projects "EuroSabot" and "Silent Freight".

Partners and sponsors

The work described above is part of two joint projects between, on one hand, the Division of Solid Mechanics at Chalmers University of Technology, and, on the other, the Swedish wheel manufacturer ABB Sura Traction AB and the Swedish State Railroad Company (SJ), respectively.

Research papers with abstracts — Wheelsets

Papers internationally published in scientific journals or conference proceedings are marked with an asterisk.

R51. R Lundén: *Järnvägshjul med krympförband – beräkningar och experiment för verifiering av toleranser* (*Railway wheels with shrink-fit assembly – calculations and experiments*, in Swedish). A joint project with ABB Sura Traction AB. Report F110, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 39 pp, 1988

R52.* R Lundén: Fatigue durability of railway wheels — on admissible combinations of axle load, train speed and signalling distance. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol 205, no F1, pp 21-33, 1991 (the paper is a condensed version of Report F112, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 37 pp, 1989)

Summary: A mathematical model for the prediction of relative lifetimes of railway wheels exposed to block braking under stop braking cycles is presented. Analytical and finite element thermoelastic calculations are employed together with a model for low-cycle fatigue. Durability curves are established describing limiting combinations of axle load and train speed for given combinations of signalling distance and required wheel lifetime. Application of the method is demonstrated on an existing freight car wheel that conforms to UIC standards. The numerical results should also be useful for other wheels.

R53. J Jergéus and R Lundén: *Thermally damaged railway wheels detected through a later measuring of residual deformations*. A joint project with ABB Sura Traction AB. Report F146, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 32 pp, 1992

R54. T Vernersson and R Lundén: *Stresses in Rc-locomotive tyres - On the influence of shrink-fit and braking stresses on rolling contact fatigue.* A joint project with ABB Sura Traction AB. Report F183, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 45 pp, 1995

R55.* M Fermér and R Lundén: Transient brake temperatures found by use of analytical solutions for finite hollow cylinders. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* vol 205, no C3, pp 189-200, 1991 (also Report F134, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 29 pp, 1990)

> *Summary*: A linear analytical model for calculating transient axisymmetric temperature distributions in finite hollow cylinders is established and adapted for practical use. A homogeneous isotropic material with temperature-independent thermal properties is assumed. Among possible applications are brake discs, brake drums and block braked railway wheels. The thermal power from braking is applied as prescribed heat influxes over parts of the lateral and radial surfaces of the cylinder. Bessel series solutions to the heat conduction equation are found where Newton’s law for heat transfer is used in the boundary conditions. In addition to convection, prescribed surface temperatures and insulated surfaces are also studied. Arbitrary thermal loading histories are treated by use of Duhamel’s principle where step loadings are superposed. Convergence and limitations of the method and required computer times are discussed. Calculated numerical results for some typical braking operations are compared with those of other studies.

R56.* M Fermér: Brake discs for passenger trains – a theoretical and experimental comparison of temperatures and stresses in solid and ventilated discs. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* vol 206, no F1, pp 37-46, 1992 (Report F139, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 16 pp, 1991)

Summary: The ventilated brake discs currently used in passenger trains can be replaced with solid discs when there is no need to design for drag braking of long duration. This is a conclusion arrived at in the present study where transient temperatures and stresses induced in the disc during drag braking and during single and repeated stop braking are calculated by use of a previously established analytical model. The results are verified through full-scale experiments carried out on a recently built inertia dynamometer. A forged solid steel disc is compared with a standard ventilated cast iron disc. Measurement techniques and various observations are discussed.

R57. M Fermér: *Transient brake temperatures - theory and experiments*. Thesis for the Degree of Licentiate of Engineering, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 52 pp, 1991

R58. M Fermér: *User's manual for AXITEMP - a computer program for calculating transient axisymmetric temperature distributions in finite hollow cylinders*. A joint project with ABB Sura Traction AB. Report F141, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 17 pp, 1991

R59.* M Fermér: Flexible wheels for railway freight cars considering thermal and mechanical aspects of block braking. *Proceedings of the Tenth International Wheelset Congress*, Sydney, Australia, pp 277-281, 1992

Summary: A railway wheel with flexible steel elements between the hub and rim is suggested. Twelve S-shaped steel spokes as studied here is one possibility. Transient temperatures and thermoelastoplastic strains and stresses in the wheel exposed to block braking are calculated by use of finite elements and are compared to those for a standard solid freight car wheel. The results are verified through experiments on a full-scale inertia dynamometer. Based on the present study, several advantages are foreseen for the suggested wheel. Because of its low unsprung mass, the wheelset can carry a higher axle load with preserved lifetimes of the vehicle and track. No thermally induced residual stresses from block braking will occur in the wheel tread. The wheel was also found to radiate less noise than a standard solid wheel as used on passenger and freight trains today.

R60.* M Fermér and J C O Nielsen: Wheel/rail contact forces for flexible versus solid wheels due to tread irregularities. *Proceedings of the 13th IAVSD Symposium on Dynamics of Vehicles on Roads and on Tracks*, Chengdu, Sichuan, China, 23-27 August 1993, pp 142-157 (see also R16)

Summary: The vertical dynamic behaviour of a railway vehicle with flexible wheels is compared to that of a vehicle with standard solid wheels. Full-scale field experiments performed on a portion of a recently built railway track for high-speed trains are reported. Flexible and solid wheels without and with wheel flats were instrumented for measurement of transient vertical wheel/rail contact forces. Accelerations and strains in the track structure were measured in parallel. The location of the instrumented wheelset in relation to the instrumented portion of the track was determined at each instant of time. Flexible wheels are shown to considerably reduce the contact forces. A linear mathematical model of the track is suggested based on a previously reported technique for solving vertical interaction problems. Track parameters determined at the test-site are used as input to the model. Numerical results show acceptable agreement with measured responses.

R61.* M Fermér: Optimization of a railway freight car wheel by use of a fractional factorial design method. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* vol 208, no F2, pp 97-107, 1994 (Report F170, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 17 pp, 1993)

Summary: The performance of a ’low-stress wheel’ exposed to vertical and lateral contact forces and to thermal braking loads is investigated. Based on finite element calculations, a two-level fractional factorial design method is used to quantify the influences of rim thickness, disc thickness and hub-rim offset on thermal and mechanical stresses, on axial rim displacement, and on wheel mass. A number of approximating linear empirical formulas have been obtained. They offer a powerful tool in designing and optimizing railway wheels. The most effective measure to reduce thermal and mechanical stresses is found to be a hub-rim offset but the penalty is a thermoelastic axial rim displacement during heating. This displacement can be minimized by using as large an offset as possible within geometrical limits.

In contrast to the standard type of wheel, no residual deformations and large stresses are induced in the offset wheel after heavy block braking. Full-scale dynamometer brake tests performed on a new prototype wheel are reported. The test results support the calculation model used.

R62. M Fermér: *Railway wheelsets – Theory, experiments and design considering temperatures, stresses and deformations as induced by braking loads and contact forces*. PhD Dissertation, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 1993, 20 pp and five appended papers

R63.* M Fermér and J C O Nielsen: Vertical interaction between train and track with soft and stiff railpads – full-scale experiments and theory. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol 209, no F1, pp 39-47, 1995 (also Report F175, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 30 pp, 1994)

Summary: The vertical dynamic interaction between a running freight wagon and a tangent railway track has been investigated experimentally and numerically. Standard solid wheels without and with wheelflats were instrumented for measurement of transient vertical wheel/rail contact forces. Accelerations and strains in the track structure were measured in parallel. The location of the instrumented wheelset in relation to the instrumented portion of the track was determined at each instant of time. A portion of the track was equipped with railpads considerably stiffer than the soft ones used as standard in Sweden. The influence of train speed and axle load on dynamic responses was studied and compared for the two test sites. Track parameters determined at the test site were used as input to a mathematical model. Numerical results show reasonable agreement with measured responses. In the presence of wheelflats, measured dynamic contact forces were largely affected by pad stiffness and axle load. However, for some of the loading cases investigated, it was observed that soft pads did not always lead to lower contact forces. Maximum dynamic responses generally increased with increasing train speed.

R64. J Jergéus: *Wheel flats and martensite formation in railway wheel treads - a literature survey*. Report F156, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 19 pp, 1992

R65. J Jergéus. *Martensite formation in railway wheel flats*. Thesis for the Degree of Licentiate of Engineering, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 48 pp, 1994

R66.* J Jergéus, R Lundén and P Gullers. Martensite formation around railway wheel flats. *Proceedings of the 11th International Wheelset Congress*, Paris, France, June 1995, pp 53-58

Summary: A railway wheel flat is a flat spot on the rolling surface of a wheel caused by its unintentional sliding on the rail. Under certain sliding conditions, martensite, which is a brittle phase of carbon steel, will form around such a flat. The presence of martensite often leads to cracking and spalling of the material in the tread of a rolling wheel having a flat. In Sweden, flat induced cracks and spalls lead to excessive wheelset maintenance costs. It is believed that a better knowledge about the process of formation of martensite around wheel flats will facilitate money saving improvements in wheelset operation and maintenance.

In this paper, the development of a railway wheel flat is studied by use of the finite element method. A material model is established through which the interaction between temperature and microstructure can be followed in space and time. Phase transformations are modelled by use of IT-diagrams and transformation laws. Phase contents for different thermal loading cases are calculated. The numerical results are compared with data from physical experiments. Also wheels that have been damaged in revenue railway traffic are examined. Improved wheel materials and other means of avoiding wheel flats are discussed in the paper.

R67. J Jergéus. *Martensite formation and residual stresses around railway wheel flats.* In preparation. To be submitted for international publication

R68.* R Lundén: Contact region fatigue of railway wheels under combined mechanical rolling pressure and thermal brake loading. *Wear*, vol 144, no 1-2, pp 57-70, 1991 (this issue of *Wear* constitutes *Proceedings of the 3rd International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, Cambridge, UK, July 1990) (also Report F135, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 18 pp, 1991)

Summary: The combined effect on railway wheels of a periodically varying contact pressure and an intermittent thermal brake loading is investigated in this paper. The development and redistribution of residual stresses in the wheel rim are clarified. Elastoplastic strain cycles are calculated for some often occurring loading histories. These cycles are used as input to a damage mechanics model where the relative lifetime of the wheel rim can be estimated. Shakedown, cyclic plasticity and ratchetting are central phenomena discussed in the paper. A commercial FEM computer program for thermoelastoplastic analysis is employed. Temperature-dependent material data for a real wheel steel are used. Simulations with varying material data are carried out and measures to increase the lifetime of railway wheels are discussed.

R69.* R Lundén: Cracks in railway wheels under rolling contact load. *Proceedings of the 10th International Wheelset Congress*, Sydney, Australia, pp 163-167, 1992

Summary: Crack initiation and crack propagation in the contact region of a railway wheel are studied by use of analytical and numerical methods assuming a Hertzian contact pressure without and with friction. Triaxial contact and residual stresses are considered in a three-dimensional model for crack initiation. Crack propagation is considered in a simplified model mainly involving mode II cracks. Stress intensity factors are computed for plane conditions. The numerical results obtained are compared with experimentally found threshold values for a real wheel material. Observed cracks in wheels exposed to service loads are investigated and the allowable size of such defects is discussed.

R70.* A Ekberg, H Bjarnehed and R Lundén: A fatigue life model for general rolling contact with application to wheel/rail damage. *Fatigue & Fracture of Engineering Materials & Structures*, vol 18, no 10, pp 1189-1199, 1995 (also Report F177, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 17 pp, 1995)

Summary: A high-cycle fatigue model for the prediction of component lifetime in elastic rolling contacts is developed and applied. Varying magnitudes and positions of the contact loads are described by use of discretized statistical distributions. Longitudinal and lateral adhesion is included. The Hertzian contact pressures are analytically found, and the corresponding subsurface stresses are calculated using a numerical integration scheme starting from the exact point force solutions of Boussinesq and Cerruti. Triaxial fatigue with rotating directions of principal stresses is studied using the Dang Van fatigue initiation criterion, together with the Palmgren-Miner damage accumulation law. The full model has been implemented in a computer code. A wheel/rail contact problem is treated and the results are compared to previous numerical and experimental data.

R71. A Ekberg and H Bjarnehed: *Rolling contact fatigue of wheel/rail systems - a literature survey*. A joint project with ABB Sura Traction AB and the Mechanical Systems Division of ABB Traction AB. Report F182, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 50 pp, 1995

Other articles — Wheelsets

International publication is marked with an asterisk.

O51.* T Dahlberg, R Lundén and B Åkesson: Report of railway engineering research at Chalmers University in Gothenburg, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol 206, no F2, pp 145-148, 1992

O52. T Dahlberg, R Lundén and B Åkesson: Railway engineering research at Chalmers, *Proceedings VTIs och TFBs Forskardagar*, Linköping, 8-9 January 1992, pp 234-240

O53. Brochure from ABB Sura Traction, Surahammar, Sweden, 8 pp, 1995

O54.* T Dahlberg, S Hammarlund and Å Jahlenius: Goose Hill measurements confirm X2000's low dynamic track forces, *Railway Gazette International*, vol 150, no 7, pp 439-444, July 1994

Student reports — Wheelsets

S51. A Ahlm, P Fejde, K Grundberg and R Langer: *Axlar, lager och lagerboxar till järnvägsfordon* (*Axles, bearings and axleboxes for railway vehicles,* in Swedish). A joint project with ABB Sura Traction AB. Student Report T112, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 58 pp, 1988

S52. F Berghel, E Grundberg, J Jergéus and Ö Johansson: *Optimal utformning av skiva hos järnvägshjul* (*Optimal design of disc of railway wheel*, in Swedish). A joint project with ABB Sura Traction AB. Student Report T120, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 43 pp, 1990

S53. L Mähler: *Fracture of railway wheels exposed to high braking temperatures*. A joint project with the Swedish State Railroad Company (SJ) and ABB Sura Traction AB. Student Report T132, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 35 pp, 1992

S54. J Bergström and L Granlund: *Brake discs for rail vehicles*. A joint project with ABB Sura Traction AB. Student Report T113, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 54 pp, 1988

S55. J Ahldén, K Mehtola, A Normén and S Sjödin: *Hydrogen embrittlement of railway wheels*. A joint project with ABB Sura Traction AB. Student Report T134, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 48 pp, 1994

S56. K Andersson, K Johnsson, H Simonsen and E Wang: *Martensite formation in railway wheel treads*. A joint project with ABB Sura Traction AB. Student Report T126, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 40 pp, 1991

S57. S Berglund, R Karlsson, P-A Olsson and C Stübner: *Formation of wheel flats and martensite in railway wheel treads*. A joint project with ABB Sura Traction AB. Student Report T131, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 48 pp, 1992

S58. J Jergéus: *Wheel/rail contact problems modelled with three-dimensional finite elements in a supercomputer*. A joint project with ABB Sura Traction AB. Student Report T125, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 40 pp, 1991

S59. O Cato, T Göransson, P Johansson and A Lindberg: *Acoustically short-circuited railway wheels - a preliminary experimental study*. A joint project with ABB Sura Traction AB. Student Report T135, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 39 pp, 1995

S60. O Kämmerling: *Vibrational modes of railway wheels*. Student Report T137, Division of Solid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 32 pp, 1995

CHARMEC — Chalmers Railway Mechanics

by Bengt Åkesson, Tore Dahlberg and Roger Lundén (December 1995)

A Centre of Excellence, or Competence Centre (in Swedish: Kompetenscentrum), in Railway Mechanics has been established at Chalmers University of Technology. The formal agreement was signed at The Swedish National Board for Industrial and Technical Development (NUTEK) in Stockholm on 7 July 1995. The three parties to the agreement are

1. *The Industrial Interests Group*

   ABB Sura Traction AB: an ABB Traction subsidiary and wheelset manufacturer located in Surahammar

   Abetong Teknik AB: a Euroc Group company and concrete sleeper manufacturer with headquarters in Växjö

   Banverket Huvudkontoret: the Swedish National Rail Administration (infrastructure authority) with headquarters in Borlänge

   SJ Maskindivisionen: the Swedish State Railways (rolling stock operator) with Machine Division headquarters in Stockholm

2. *Chalmers University of Technology*

3. *The Swedish National Board for Industrial and Technical Development (NUTEK)*

Joint funding of stage 1 (1 July 1995 to 30 June 1997) with a sum of 20.5 MSEK has been agreed upon. It is intended that the Centre shall operate for a period of 10 years.

Board, head and researchers

Anders Sjöberg, President of Chalmers University of Technology, in consultation with the Industrial Interests Group and NUTEK, appointed the following to be members of the Board of the Competence Centre on 4 September 1995:

Björn Paulsson (chairman)	Banverket Huvudkontoret
Lennart Nordhall	ABB Sura Traction AB
Stefan Westberg	Abetong Teknik AB
Hugo von Bahr	SJ Maskindivisionen
Evert Andersson	The Royal Institute of Technology (KTH), Railway Engineering, Stockholm

Hans Andersson	The Swedish National Testing and Research Institute (SP), Borås
Lars Sjöstedt	Chalmers University of Technology, Transportation and Logistics, Göteborg

Bengt Åkesson is Head of the Competence Centre. Other persons at present employed at Chalmers Solid Mechanics and working in the field of railway mechanics are Dr Tore Dahlberg and Dr Roger Lundén, Associate Professors, Ms Åsa Fenander, Ms Annika Igeland and Mr Johan Jergéus, all with licentiate degrees in engineering, and Mr Anders Ekberg, Mr Tore Vernersson, and Mr Martin Petersson, all with master's degrees in engineering. In addition there is the total competence available within the whole Division of Solid Mechanics at Chalmers University of Technology.

At their first meeting on 29 November 1995, the Board decided to launch new railway mechanics projects also engaging Dr Birger Karlsson (Professor) and Mr Johan Ahlström at Chalmers Engineering Metals, Dr Sven Ohlsson (Associate Professor) and Mr Johan Jonsson at Chalmers Dynamics in Design, and Dr Kenneth Runesson (Professor), Mr Johan Oscarsson and Mr Lars Jacobsson at Chalmers Solid Mechanics. This means that, in total, five supervisors and ten doctoral students are involved in the research directed and financed by the Competence Centre.

In the following four sections will be presented the Operational Plan for the activities of the Competence Centre as set out in the agreement drawn up by the parties involved.

Vision and goals

Within its area of competence the Centre will work for a long-term build-up of knowledge that is relevant to the needs of the industry as regards railway infrastructure and rolling stock. The choice and orientation of the individual research projects will be decided on the basis of overall assessments of technology, economy, safety and environmental factors.

The overall goal of the Competence Centre is to achieve increased quality in railway transportation and at the same time to lower production, maintenance, operational and environmental costs. The interaction of various railway mechanical components will be given special consideration. Specific goals are life-cycle optimized components and systems for track structure and running gear. These should result in slower degradation of ballast, increased lifetime of sleepers and pads, improved track alignment stability, reduced rail and wheel wear, and lower levels of vibration and noise in trains and tracks and in their surroundings.

National and international cooperation with parallel and supporting competences will continue and will be increased. In the Centre it will be possible to make contributions to areas that are central and basic to railway mechanics in which up to now none of the individual members of the Industrial Interests Group together with the University has been able to shoulder total responsibility.

Quality assessment and knowledge transfer

The scientific quality of research results will be assured through public exposure and criticism at national licentiate seminars and defence of doctoral theses, as well as through presenting papers at recognised international conferences and publishing papers in recognised international journals.

The transfer of knowledge to industry is to take place by means of regular personal contacts and exchange of staff, through orientation and summarizing at seminars, and through informative reports and the handing over of test results and computer programs. An extremely important aspect of this transfer of knowledge will be the employment in the industry of those who have gained licentiate's and doctor's degrees at the University.

Core activities at Chalmers Solid Mechanics

The core activities of the Competence Centre are to be located at Chalmers University, and in particular at its Division of Solid Mechanics. Activities will be renewed and broadened by an extension of research into other disciplines than solid mechanics that are represented both within and outside Chalmers.

Each individual research project within the Centre should correspond to work for a licentiate or doctoral thesis. This is to be formulated in general terms as regards orientation and goals. A detailed specification of each step of a project (such as when an agreement is drawn up for ordering project work or when consultancy services are purchased) should be avoided.

Programme areas

The Competence Centre is to work within three overall programme areas, as set out below. The choice of projects within each area is to be decided by the Board of the Centre.

Programme area 1: Interaction of train and track

A rolling train is a mobile dynamic system that interacts with the stationary track structure, which in its turn is a dynamic system. This interaction is a key area within all railway research. The mechanisms behind vibration, noise and wear depend on the interplay of the rolling train and the track structure. The activities of this programme area will be directed towards being able to better understand, model and predict the dynamic interaction for different types and conditions of trains, tracks and operations. Theoretical, numerical and experimental methods will be required.

Programme area 2: Vibration and noise

A considerable reduction in vibration and noise from railway traffic seems to be of crucial importance for future acceptance of this type of transportation. The generation and spreading of vibrations in trains and tracks and the emission of noise are phenomena that are both theoretically and experimentally difficult to approach. The activities of this programme area will be directed towards being able to better understand the underlying mechanisms. Advanced analytical and numerical tools as well as laboratory and field experiments and measurements will be required. The goal is to be able to put forward effective modifications and counter-measures against vibration and noise in both train and track.

Programme area 3: Materials and maintenance

Suitable and improved materials for axles, wheels, rails, pads, sleepers, ballast and embankment are a prerequisite for good mechanical performance, reduced wear, lower maintenance costs and increased technical/economic lifetime of the components mentioned. The activities of this programme area will be directed towards analysing existing materials and developing new materials. There will be created a knowledge base for the rational maintenance of train and track components. Cooperation between several different competences will be required for this research.

Present state of railway research

Railway research has been carried on since 1987 under the supervision of Professor Bengt Åkesson and Associate Professors Tore Dahlberg and Roger Lundén. This research has been funded through separate agreements with NUTEK and the Swedish Council for Building Research (BFR), as well as with ABB Sura Traction AB, Abetong Teknik AB, Banverket Huvudkontoret and SJ Maskindivisionen. During the 1994/95 academic year five doctoral candidates have been involved in our railway research programmes. Today (December

1995) we have altogether nine researchers with doctor's degrees and twelve doctoral candidates working at Chalmers Solid Mechanics. Two new doctoral candidates are being recruited for the railway programme in our Division and will start their work in January/February 1996. The broadening of the railway mechanics research to Chalmers Engineering Metals and Chalmers Dynamics of Design has been described above.

Doctoral theses and licentiate dissertations

The following persons have so far gained research degrees (in Swedish: teknologie doktor, teknologie licentiat) at Chalmers Solid Mechanics within the field of railway mechanics:

Jens Nielsen Tech Lic in February 1991 and D Eng in December 1993. Doctoral thesis: Train/track interaction - coupling of moving and stationary dynamic systems - theoretical and experimental analysis of railway structures considering wheel and track imperfections. Faculty opponent: Professor Klas Knothe, Technische Universität Berlin

Mikael Fermér Tech Lic in April 1991 and D Eng in December 1993. Doctoral thesis: Railway wheelsets - theory, experiments and design considering temperatures, stresses and deformations as induced by braking loads and contact forces. Faculty opponent: Professor Karl-Olof Olsson, Linköping Institute of Technology, Machine Design

Åsa Fenander Tech Lic in September 1994. Licentiate dissertation: Modelling damping by use of fractional derivatives. Discussion leader: Dr Thomas Abrahamsson, Saab Military Aircraft

Annika Igeland Tech Lic in October 1994. Licentiate dissertation: Railhead corrugation growth on tangent tracks - consequences and causes. Discussion leader: Professor Georg Lindgren, Lund Institute of Technology, Mathematical Statistics

Johan Jergéus Tech Lic in November 1994. Licentiate dissertation: Martensite formation in railway wheel flats. Discussion leader: Dr Lars-Erik Lindgren, Luleå Institute of Technology, Computer-Aided Design

Since the 1971/72 academic year, 31 persons have been awarded doctor's degrees at Chalmers Solid Mechanics. Since 1985/86, 23 licentiate's degrees have been awarded. The number of persons acquiring a standard of competence as associate professor (in Swedish: docent) is 12, and one of these is in railway mechanics (Roger Lundén in 1992/93).

Project and degree work

Some hundred engineering undergraduates have been involved over the years in project and degree work within the field of railway mechanics. One of the latest works is

Olof Cato, Tomas Göransson, Peter Johansson and Anders Lindberg: Acoustically short-circuited railway wheels - a preliminary experimental study (supervisors Roger Lundén and Bengt Åkesson). A joint project with ABB Sura Traction AB. *Chalmers University of Technology, Division of Solid Mechanics*, Report T135, Gothenburg 1995, 39 pp

International publications

Some forty works in railway mechanics have, over the years, been published internationally in scientific journals or been presented at scientific conferences. In addition a number of articles of a more popular nature have been published.

Research in progress

Four representative papers just published (December 1995) are

Tore Dahlberg: Vertical dynamic train/track interaction - verifying a theoretical model by full-scale experiments, *Vehicle System Dynamics Supplement*, vol 124, pp 45-57 (1995)

Mikael Fermér and Jens Nielsen: Vertical interaction between train and track with soft and stiff railpads - full-scale experiments and theory, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol 209, no F1, pp 39-47 (1995)

Anders Ekberg, Hans Bjarnehed and Roger Lundén: A fatigue life model for general rolling contact with application to wheel/rail damage, *Fatigue & Fracture of Engineering Materials & Structures*, vol 18, no 10, pp 1189-1199 (1995)

Jens Nielsen and Annika Igeland: Vertical dynamic interaction between train and track - influence of wheel and track imperfections, *Journal of Sound and Vibration*, vol 187(5), pp 825-839 (1995)

The future

The Board of the Competence Centre will determine which research projects in railway mechanics are to be carried out within the Centre at Chalmers Solid Mechanics and at other divisions and departments within and outside Chalmers University.

New measurements at Goose Hill

Comprehensive full-scale field measurements were carried out in April 1993 on a newly built stretch of the Swedish West Coast Line at Goose Hill (Gåsakulla) between Varberg and Falkenberg in a joint project between Banverket Huvudkontoret, SJ Maskindivisionen, ABB Sura Traction AB and Chalmers Solid Mechanics, with a total budget of about 2.3 MSEK. Results have been published internationally. Additional measurements (without rolling test trains) have been carried out during September/October 1995 on the same stretch of track provided with test instrumentation in cooperation between Banverket Huvudkontoret and Chalmers Solid Mechanics. Pandrol International Ltd, UK, did also participate in the measurements.

International contacts

Over the years the railway group at Chalmers Solid Mechanics has built up a comprehensive contact network through conference participation, joint seminars, working groups and personal visits. Present contacts are especially with universities, research institutes, public bodies and manufacturers in Denmark, Great Britain, France, Germany, the Netherlands, Poland, the Czech Republic, USA, Australia, Japan and China.

EU R&D projects

Chalmers Solid Mechanics participated in March 1995 in three applications concerning railway mechanics for a total sum of 14 MECU (our projected share was 0.4 MECU) to Brite-EuRam III within the Fourth Framework Programme. At the time of writing (December 1995) approval has been granted (with a certain reduction of the sum involved) for two of these projects (Silent Freight and EuroSabot), which had both ended up in category A1 (highest priority). The third project (Silent Track) ended up in category A2 and will probably also be realized. All three projects concern quieter train traffic.