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SIGNAL ANALYSIS TECHNIQUES FOR RAIL VEHICLE MODEL VALIDATION

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Abstract: *The recent improvements in computer technology and a better understanding of mathematical problems lead to the creation of very complex models. One of the more important steps in the model development process is the model validation and verification, especially if the model should be used to support decision making. A desire to explain and predict a system behavior in the past decades in the literature has led to development of several validation techniques and validation metrics. The categorization of validation techniques as well and description of different validation metrics have been presented in this paper. The discussion on advantages and disadvantages several validation metrics on an example of validation of rail vehicle have been presented in this paper.*

INTRODUCTION

Experimental investigation of railway vehicles is the most reliable way to determine their properties and the crucial criteria for the approval of their exploitation. However, experimental investigations are extensive, time-consuming and expensive so alternative methods, used in the design of vehicles are of greatest interest. Numerical simulations of the railway vehicle running behavior, which allows the calculation of dynamical quantities in the time and frequency domain based on the mathematical models of the vehicle and track, are developed in that purpose.

Taking into account that numerical models are used in all stages of the vehicle design and development, the verification and validation of the simulation models represent the crucial point for future usage of the simulation process in the development phase of the railway vehicles. Today, model validation is used only for particular case or for particular vehicle. The results of the validation and validated model are not used in the future process of the development of new vehicles.

Validated models of the railway vehicles may be used for prediction of the vehicle behavior, for virtual prototyping, virtual testing and as decision making support. The future usage of the validated models in the process of design and development of new rail vehicles has been explained in “DYNOTrain” project. The results of the simulation, obtained from the validated model of the rail vehicle, may be used in design phase for the new vehicle.

This approach will significantly reduce the cost of the experimental investigation and will give the opportunity to designers to reduce the time and cost and researchers to examine the vehicle behavior even before the vehicle is built.

In order to perform the verification and validation of the numerical model, the significant signal and data processing need to be performed.

VALIDATION AND VERIFICATION

The process which determines or perform evaluation of agreement of the experimental results with the results obtained by numerical simulation is called the process of model validation and verification.The basic methods for verification and validation were developed on 1979 by the Society for Computer Simulation and it may be presented in the form of “Sargent Circle” [1], as it is shown in Figure 1.The basis of the process of validation is comparison of the results of simulation and results obtained from experiment. The validation may be defined:

- According to**Jack P.C. Kleijnen** – *validation* as determining whether the simulation model is an acceptable representation of the real system - given the purpose of thesimulation model
- **S.Ferson, W.L.Oberkampf, L.Ginzburg**defining *validation*as assessment of model accuracy by comparison of prediction against experimental data
- **W.L.Oberkampf** - *Validation* provides evidence that the mathematical model accurately relates to experimental measurements.

Generally, the model validation is the process where is possible to determine the degree that a model is an accurate representation of the real system [2], [3].

The verification process is focused on the identification and elimination of errors in the development of mathematical and computer models [1].

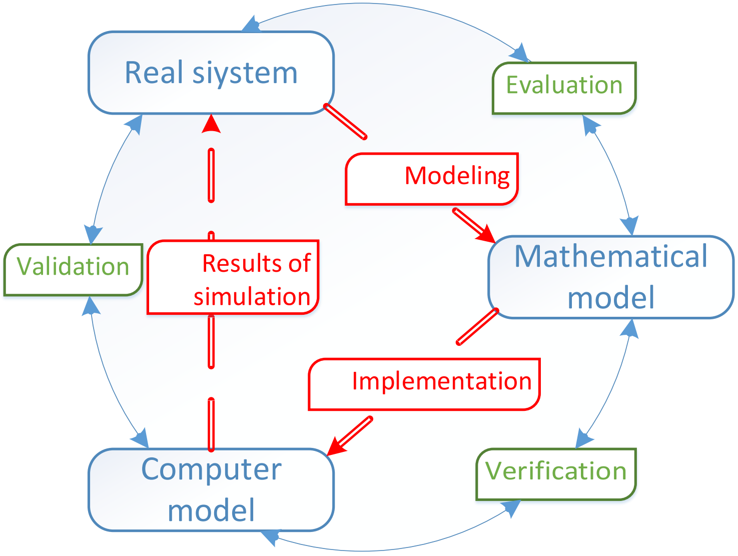

Figure 1. Graphical representation of the verification and validation process

The process of validation contain several type of model and as well and several process which need to be performed during the process of validation and verification. The mathematical model comprises the conceptual model, mathematical equations, and modeling data needed to describe real system [1], [2], [3].The computer model represents encapsulation of the mathematical model in the form suitable for execution on a computer [1]. The process of the verification establishing relations between mathematical model and computer model and validation compares the outcomes of the computer simulation with results of the experimental investigations, as it is shown in Figure 1.

VALIDATION TECHNIQUES

The methodology for evaluation of the agreement between the results obtained by simulation and experimental investigation has not been defined in the field of the railway vehicle dynamics. The model validation, applied from different authors [4], [5], [6], [7], [8] was performed by comparing the characteristic parameters, such as accelerations in vertical and horizontal plane and forces in the wheel-rail contact, in time and/or frequency domain.

The model validation may be performed using five different approaches, as it is shown in Figure 2.

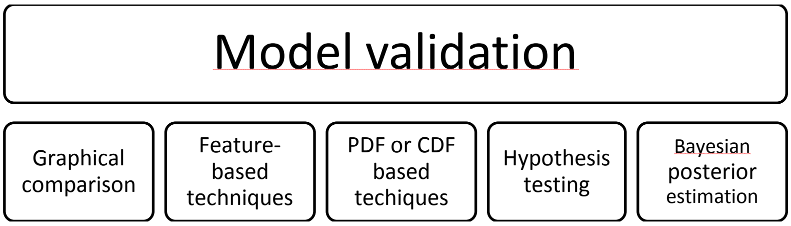

Figure 2. Model validation techniques

Graphical methods are based on the comparison of various graphs. The results of simulations are plotted together with the results from experiments on the same graph, as it is shown in Figure 3. This method does not provide quantitative measure of matching between the results obtained by simulations and experiments. The model validation performed by this method is highly subjective and depends on the experience of the reviewer. In the field of railway vehicle dynamics, graphical comparison of different parameters is the most common method used for model validation.

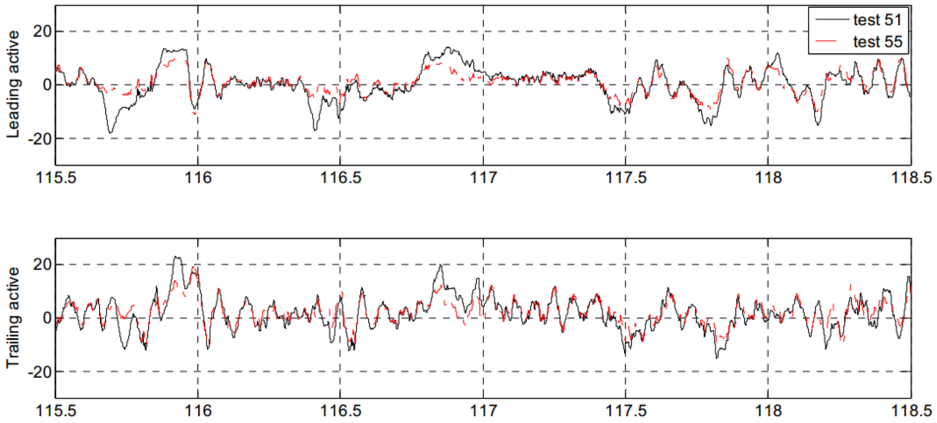

Figure 3. Model validation based on graphical comparison of chosen parameters

Feature-based techniques draw conclusions on the model validation based on the difference between characteristic features of the obtained results, such as magnitude, shape, phase, etc. Various metrics are used as a measure of the difference. One of the most known metrics is defined by Sprague and Geer [7], and it is based on the difference between magnitudesand phasesof the results of simulations and experiments. Sprague and Geer validation metrics may be expressed as following:

$$\textit{Magnitude error - } M_{SG} = \sqrt{\frac{v_{ss}}{v_{pp}}} - 1 \qquad (1)$$

$$\textit{Phase error - } P_{SG} = \frac{1}{\pi} cos^{-1}\left(\frac{v_{ps}}{\sqrt{v_{pp}\, v_{ss}}}\right) \qquad (2)$$

$$\textit{Compressive error factor - } C_{SG} = \sqrt{{M_{SG}}^{2} + P^{2}} \qquad (3)$$

The Russell metrics [10, 11] are very similar to the SG metric. EARTH metrics [12] take into account the shape of scalar series, which is not the case with SG and Russell metrics.

This method don't have defined appropriate limits for model acceptance. The experience of the experts may be incorporated into this methodology by defining the limiting values. However, very often results of the model validation obtained by other methods are not compliant with results of this methodology.

Model validation based on PDF (the probability density function) or CDF (the cumulative density function) techniques draw conclusions based on the difference between PDF or CDF functions of the obtained results. During the last fifty years, researchers have developed several validation metrics for comparison of PDF/CDF functions. The Kolmogorov-Smirnov metric [11] is one of the most used metrics for model validation. It measures the distance between two CDF functions along the ordinate axis, as it is shown in Figure 4. Validation metrics may be expressed as following:

$$d_{SG} = sup\left|F_{1,n}(x) - F_{2,n}(x)\right| \qquad (1)$$

Where $F_{1,n}(x)$ and $F_{2,n}(x)$ represent cumulative functions obtained from simulation and experimental investigation.

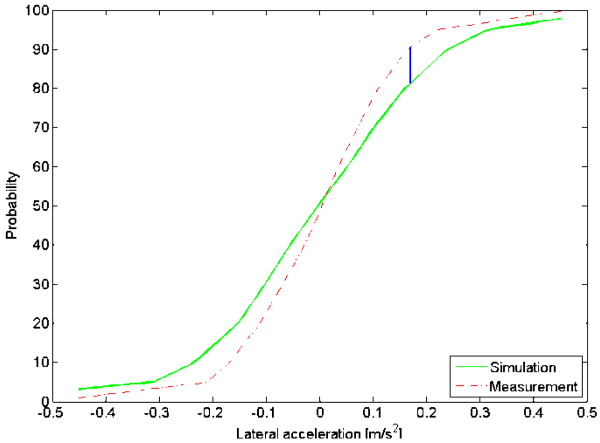

Figure 4. Graphical representation of Kolmogorov-Smirnov validation metrics

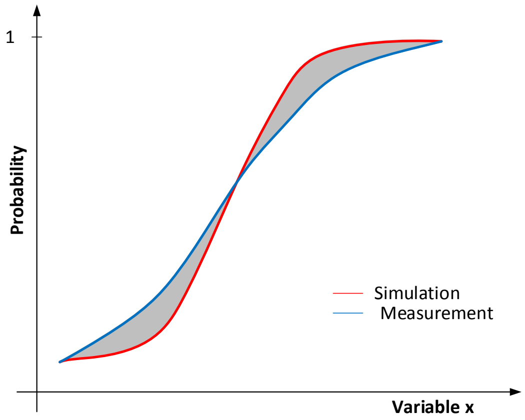

Figure 5. Area validation metrics

Anderson–Darling [13] validation metric is very similar to Kolmogorov-Smirnov metric. However, instead the distance along ordinate, Anderson–Darling metric has introduced the weighted quadratic CDF statistic to measure the distance between the two CDF functions. It was shown that the Anderson-Darling validation statistic had more power than the Kolmogorov-Smirnov metrics [11]. These two validation metrics draw conclusion based on the comparison of cumulative function in one point.

In order to cover a larger number of points of the cumulative functions the third validation metrics – Area validation metrics is based on the calculation of the area between the two CDF functions [13], shown in Figure 5. The area metrics depend on the scale used to present the distributions, and any kind of normalization would destroy the meaning of the metrics [13].

The CDF/PDF methods for model validation are based on comparison only two cumulative function, one obtained from simulation and second achieved from experimental investigation. The multiple validation experiments and simulations results may be compared using U-pooling methodology [14], which is shown in Figure 7.

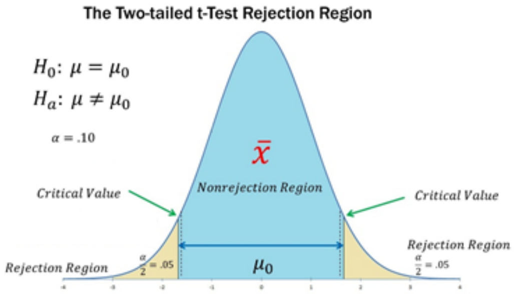

Figure 6. Hypothesis testing – t-test

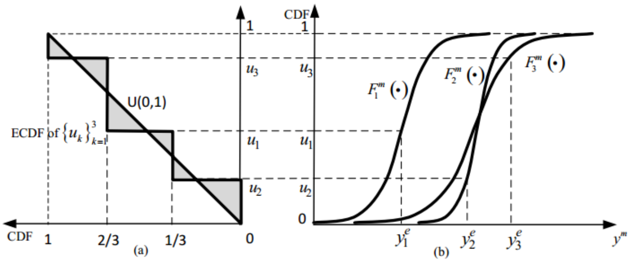

Figure 7. Area validation metric in the case of the multivariate data

The area validation metric does notinclude any limiting value of accepting the model, but only quantifiesthe difference between two CDF/PDF functions. Model acceptance will be determined for each individual problem.

Hypothesis testing is the procedure which is often used for model validation. Model validation in this case is based on the acceptance of the one of two opposite statements, which is based on the several tests. Depending on the features which are chosen for comparison (difference between mean values, deviations, normality test, etc.), on the underlying assumption and simple size several tests may be used, such as T-test, r^2 –test, F-test, ANOVA test. All those test are based on calculation of the test statistics parameters which is compared to critical value. Usually,if the value of the test statistic is greater than critical value model is not validated.

The Bayes posterior estimation for model validation is based on the Bayes hypothesis testing. The statistical parameters (e.g., mean and/or standard deviation) of the distribution obtained by simulation are treated as random variables and can be updatedvia the observed physical data [14]. The validation metrics may be calculated as the ratio of posterior distribution of the null and alternative hypothesis, which can be expressed by following equation:

$$Pr(C|d) = \frac{Pr(d|C)Pr(C)}{Pr(d)} \tag{4}$$

Where *Pr(C|d)* is posterior probability of the model C for data d and Pr(*d*|C) represent a likelihood -probability that some data are produced under the assumption of this model*C*.

The Bayes approach for model validation requires a lot computational time. Hypothesis testing and Bayes estimation usually show confidence that hypothesis is not rejected, or confidence that model is suitable to be used for prediction. The level of agreement between the results achieved by simulation and experimental studies is not available.

CONCLUSION

The validation of models is very important for building the confidence in model prediction. There is no golden rule for model validation. Validation process is defined from case to case. For validation of the model may be used several different validation techniques.

Most in use are the graphical comparison method for model validation. Taking into account that this methodolgy is based on comparing graph, in most cases the process of validation is based on subjective judgment of experienced reviewers.

From presented methodology it can be concluded that validation process and limits for model acceptance are not defined in the field of railway vehicles.Future research should be focused on definition of the validation methodology for rail vehicles which will provide the validation metrics as well and limiting values which can clearly define the validation process for rail vehicle simulation models.

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ТЕХНИКИ ЗА АНАЛИЗ НА СИГНАЛИ ПРИ ВАЛИДИРАНЕ НА МОДЕЛИ НА ЖЕЛЕЗОПЪТНИ ВОЗИЛА

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Ключови думи: *валидиране, проверка, моделиране, обработка на сигнала*

Анотация: *Най-новите подобрения в областта на компютърните технологии и по-доброто разбиране на математически задачи доведоха до създаване на много сложни модели. Една от най-важните стъпки в процеса на развитие на модела е валидирането му и проверката, особено ако той трябва да се използва за подпомагане при вземане на решения. Желанието да се обясни и предскаже поведението на системата в литературата през последните десетилетия е довело до развитието на няколко техники за проверка и измерване при валидирането. Докладът представя категоризацията на техниките за валидиране, както и описание на различни показатели. Представена е дискусията за предимствата и недостатъците на няколко измерителни системи за валидиране чрез използване на пример за валидиране на модел на железопътно возило.*