EVALUATION OF LOADED ROLLING TYRE THERMAL FIELDS USING A FAST SCANNING INFRARED LINE CAMERA

I. Kopal[1], M. Mokryšová[1], Z. Mošková[1], J. Kučerová[1], I. Ružiak[1], N. Krečmer[2], S. Rusnáková[2],

[1]Trenčin University of Alexander Dubček in Trenčín, Institute for Material and Technological Research, Púchov, Slovakia, E-mail : kopal@fpt.tnuni.sk

[2]Trenčin University of Alexander Dubček in Trenčín, Department of Physical Engineering of Materials, Púchov, Slovakia

ABSTRACT
Infrared thermography is a well-established technique for evaluating material properties and products quality through contact-less and non-descructive thermal measurements. The paper presents the investigation results of a loaded rolling tire-casing external surface temperature distribution via a fast scanning infrared line camera for industrial temperature measurements. An efficiency approach is developed to an automated image processing of the large digital thermograms set. An analytical model of a maximum external tire-casing surface temperature time history during its rotation is identified and its parameters are estimated with very high reliability.
Keyvords: infrared thermography, rolling tyre, exponential model

1. INTRODUCTION

The car tyres construction and materials employed at their manufacturing markedly affect the heat production and the heat balance in them, as well as heat exchange with surrounding environment in every motor-car operation. Thermal processes inside tyres, rotating on roads, essentially affect not only their operating life, but also the road traffic safety. Nowadays, one of a few possibilities of experimental investigation of thermal processes inside the rotating car tyres represents infrared thermography via high-speed termovision cameras and infrared line scanners, which are very efficient at recording dynamic thermal fields on rotating and quickly moving object surfaces.

Modern termovision cameras and last generation infrared line scanners, working with high frequency rates, in every acquisition cycle return such a big amount of data, presented by means of robust digital thermograms set, which often precludes their direct understanding. Hence, it is usually necessary to reduce the acquired experimental data set, without a stronger deformation eventually without a loss of relevant information, and then to present results of this data reduction in the most compact form – generally in one or two thermal images or graphs which are favourable for further analysis. Thermovision diagnostics are so largely loaded by the problem of a post-experimental image processing in the form of robust digital thermograms series processing. Basically, the effectual solving of this problem it is possible only via an sufficiently powerful computer technique and by a meaningful implementation of modern software technologies. The paper lays stress on the identification of the loaded rolling tyre thermal system and its parameters estimation on the basis of the reduced experimental data set acquired in the form of a sizable digital thermograms time series registered by a very fast infrared line scaner.

2. EXPERIMENTAL PROCEDURE

The experimental thermal data set was completed by scanning of the whole external surface of a radial car tyre – rotating on the *HASBACH* test machine with constant velocity of *60 km/h*, constant compressive force *4,83 kN* and a zero slope to its rotary drum – by high-speed infrared line scanner *DIAS Infrared Systems HRP – 250*. After the stabilisation of an initial thermal field on tire-casing surface at the velocity of *40 km/h* this was increased to the aforementioned testing value. The thermal data where acquired during an one-hour test at sampling frequency of *3000 Hz* and in one-minute intervals they were sent from the camera's memory into the collaborative personal computer. A specialized camera's firm-ware enabled transformation of complete time series of *60* acquired thermograms into the text files in the format compatible with the standard matrix oriented software environments. Consequently, all transformed thermograms were imported into the *Matlab*® system workspace for further analysis.

All imported thermograms were converted into scaled intensity thermal images, representing a *2-D* matrix series of floating-point numbers in a double precision format according to the *IEEE 754* standard, and then they were arranged into a *3-D* matrix like *T(row, column, time)*, which is a *3-D* temperature function of spatial coordinates and of an observation time of equivalent thermogram. This arrangement makes it possible a very unassuming and effective simultaneous manipulation with the whole data set of arbitrary selected rectangular regions of any time history interval of the acquired thermal fields in all three directions. The created *3-D* matrix object enables to computerize the analysis of aquired thermal fields in both, the cross and the circiut direction of the tire-casing, as well as in the time. A more detailed description of realised experiment, as of the thermogram series treatmant and automatized data reduction procedure were published in the previous work [1].

3. DATA PREPROCESSING

Whereas for the tyre safety in the road traffic above all a maximum temperature of the tire-casing and the time of its achieving is essential, a maximum temperature time history was extracted from the *3-D* matrix *T(row, column, time)*. Strictly speaking, the thermal field registered at each termogram was characterised by its maximum temperature presenting a maximum value of spatial distribution of mean temperatures exported by used infrared scaner in relevant time interval. The time history was created namely from these temperatures, what aloowed to reduce the acquired sixty thermograms time series into a particular functional dependence (Figure 1).

Temperatures from the time interval of firs *180 seconds* of the whole time history correspond to the thermal fields registered by continually rising velocity of testing machine rotary drum before its stabilization, therefore they where used just to initial temperature of the tire-casing identification and subsequently they were excluded from the next analysis (Fig. 2). Because the selected thermal data set accounts some dispersion, associated above all with a typical infrared thermography noise [2], at first it was adequately smoothed (Fig. 3), namely by a robust smoothing procedure by using a locally weighted linear least squares regression with a quadratic polynomial regression model [3]. The robust smoothing procedure with a span of *50 %* of all smoothed data provided a resistance of the smoothing process to all outliers and misplaced data.

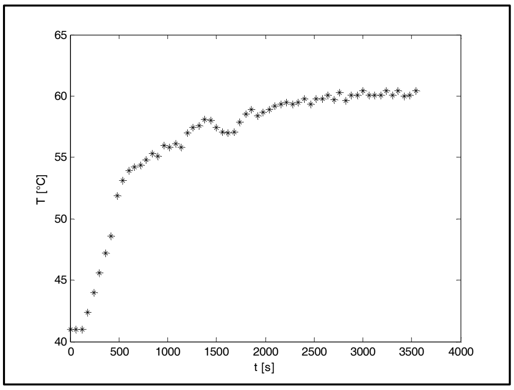

Figure 1. The experimental time history of the maximum tire-casing temperature

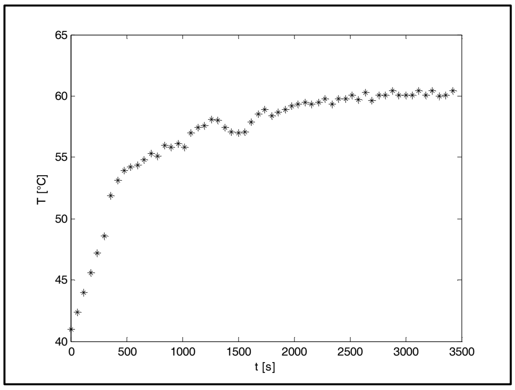

Figure 2. The experimental data selected for next analysis

The goodness of smoothing was checked by a randomness distribution of residuals, ergo by the difference between the observed data T and smoothed data T_s [4]. The residuals oscillate around very low mean value of *0,037°C*, within a sufficiently narrov temperature interval of *[– 0,848, 1,743] °C*, with a standard deviation of *0,533 °C*, what documents a suitable result. The randomness distribution of residuals is yet corrupt only in the surrounding of the time of *400 seconds* (Figure 4).

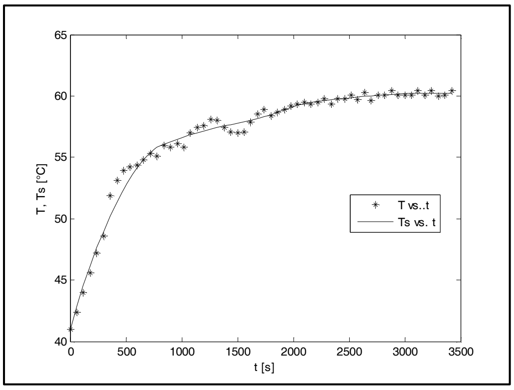

Figure 3. The smoothed curve (solid line) of selected data se.

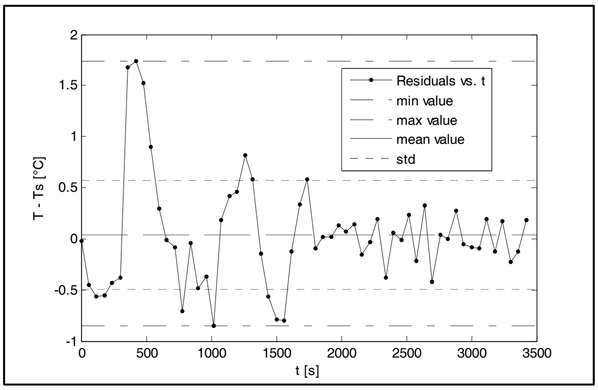

Figure 4. Residuals of smoothing process with monitored statistical parameters

4. PARAMETER ESTIMATION

Following the smoothed time history waveform and considering the thermophysical basis of investigated process – which presents a transient thermal transport from the tyre insides into the environment – its analytical model in the form of

$$T(t) = T_0 + \left(T_{eq} - T_0\right)\left(1 - \exp\left(-t/\tau\right)\right) \tag{1}$$

was idetified in the process of parametric fitting of smoothed experimental curve by several nonlinear and exponential functions. Just data produced by function (1) are in one of the best accordance with an experimental data regression curve. The parametric fitting represents a finding of true but unknown parameters of a suitable analytical model of experimental data. Basicaly, the numerical values of the model parameters are estimated by various methods. The *trust-region* algorithm for a nonlinear constrained minimization problem was used in the described case since it can solve difficult nonlinear problems more efficiently than the other standard algorithms [5].

The parametric fitting procedure produces coefficients that describe the experimental data globally, so they usually have a physical meaning. Thereby, parameter T_0 represents an initial tire-casing temperature, parameter T_{eq} its equilibrium temperature and τ is a time constant of the rotating tire-casing dynamic thermal system [6]. However, the model (1) is going to have an objective physical reason just then if all three searched parameters in the fiting process of its estimation will be constrained by an interval of positive numbers, at which T_0 can have besides a zero value.

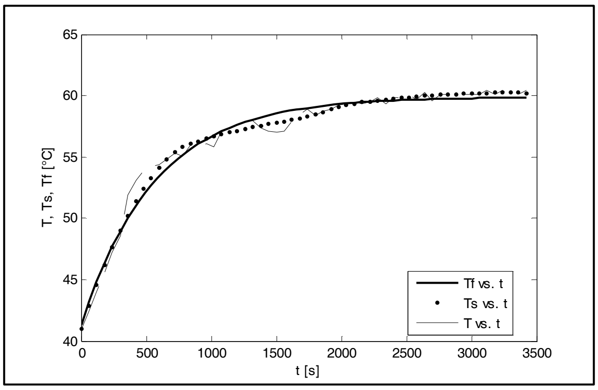

Figure 5. The experimental data (dotted line), smoothed curve (dash line) and fitted data (solid line)

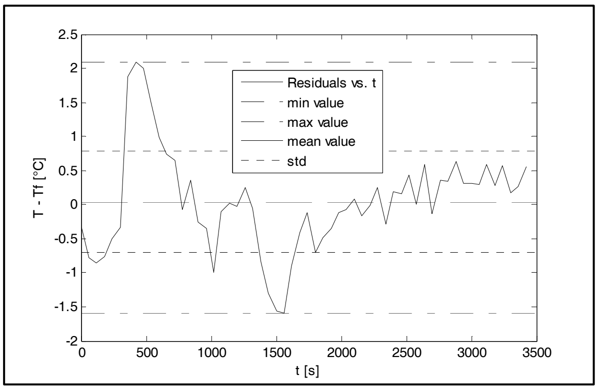

Figure 6. Residuals of fitting process with monitored statistical parameters

The result of the fitting process one can see on the Figure 5. The fitting residuals, hence the difference between the smoothed data T_s and the fitted data T_f produced by equation (1), oscillate around a very low mean value of *0,041 °C*, within temperature interval of *[– 1,588, 2,092] °C*, with a standard deviation of *0,748 °C* (Figure 6). Numerical values of estimated parameters along with their *95 %* confidence intervals [7] are presented in the Tab. 1. A very strong coincidence between both estimated temperature parameters and experimental values, documented by a non-dimensional coefficient σ_{rel} or percentage error of its comparison, is evident.

Table 1. Numerical values of estimated parameters with confidence intervals, experimental values and with the percentage error of its comparison.

Parameter	Experiment	Model	95 % CI	σ_{rel} [%]
T_0 [°C]	41,0	41,33	40,92 – 41,74	– 0,805
T_{eq} [°C]	60,4	59,89	59,89 – 60,04	0,844
τ [s]	–	569,90	551,20 – 586,80	–

5. MODEL VALIDATION

All estimated parameters of analytical models are asssociated with some uncertainties. The model will be sufficient for experimental data only in that case if its parameters uncertainties are still acceptable. The goodnes of fit was controlled by following statistics indicators: *CI* – the confidence interval, *SSE* – the sum of squares due to error, *R-square* – the coefficient of multiple determination, *AdjR-square* – the degree of freedom adjusted R-square and *RMSE* – the root mean squared error [8]. The goodness of fit statistics indicators values, except confidence intervals which are in the Table 1, are presented in the Table 2.

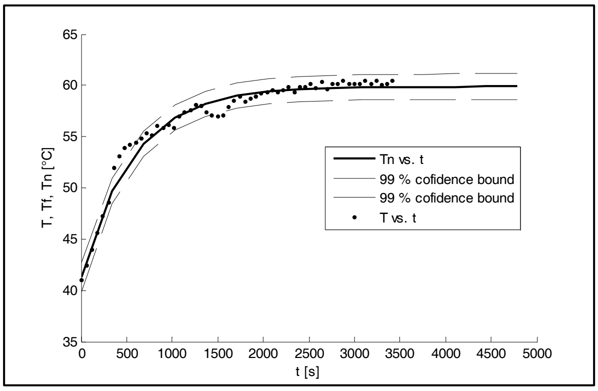

Figure 7. The comparisons of the experimental data (dotted line) with predicted data of a future experiment (solid line) and 99% confidence bounds of prediction

Table 2. Goodness of fit statistics indicators

SSE	R-square	AdjR-square	RMSE
11,32	0,9908	0,9907	0,4497

On the Figure 7 it is presented a comparison of experimental data with predicted data T_n produced by model (1) as an extrapolated prediction of result for a future experiment, as well as *99 %* confidence bounds which indicates a *99%* reliability that the future experimental data will be found just between this bounds [9]. The maximum width of confidence bounds of *2,7 °C*, as all monitored goodness of fit statistics indicators values document that the analysed experimental maximum tire-casing surface temperature time history can be described with high reliability just by the analytical model (1), which present a simple first-order exponential model of the heating solid with constant internal heat sources.[10]. It is important conclusion because it allows to suppose the investigated rotating car tyre as a first-order dynamic thermal system characterized by the exponential thermal function of the heating solid system with constant internal heat sources.

6. CONCLUSIONS

The reduction procedure of the acquired experimental data set in the form of sizable digital thermograms series via extraction of maximum tire-casing surface temperature time history allowed the system identification of investigated loaging rotating car tyre as the first-order dynamic thermal system, describable analytically with high reliability by simple first-order exponential model of heating solid with constant internal heat sources. The parameters of the model were estimated in the process of parametric fitting of the reduced experimental data regression. The estimated time constant of the system yet allows to determine the tire-casing surface temperature of the loaded rotating tyre in an arbitrary time instant or predict the time needed to achieving of certain temperature, what pays very important role in the road traffic safety.

7. REFERENCES

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