Application of movable approximation and wavelet decomposition to smoothing-out procedure of ship engine indicator diagrams

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ABSTRACT

In this paper - on the basis of indicator diagram processing taken as an example - were shown possibilities of the smoothing-out and decomposing of run disturbances with the use of the movable multiple approximation based on the least squares criterion. The notion was defined of movable approximating object and constraints used to form approximation features. It was demonstrated that the multiple approximation can be used to decompose disturbances out of an analyzed run. The obtained smoothing-out results were compared with those obtained from full-interval approximation of runs by means of splines as well as wavelet decomposition with using various wavelets, Wavelet Explorer and Mathematica software. Smoothing-out quality was assessed by comparing runs of first derivatives which play crucial role in the advanced processing of indicator diagrams.

Keywords : smoothing-out the runs, least squares method, full-interval approximation, movable approximation, decomposition of disturbances, cut constraints, glued constraints, riveted constraints, broken constraints, weighting factors, wavelet decomposition.

INTRODUCTION

Advanced acquisition of diagnostic information from indicator diagrams is associated mainly with determination of first derivative necessary for determining heat emission characteristics. For certain purposes also determination of second derivative and even third one may be necessary.

With determination of derivatives the necessity of smoothing-out indicator diagrams is associated. A. Ralston has defined the notion of smoothing-out in such a way that if an approximation maintains information on function resulting from measurements and fades away disturbances then it is said that it smooths out (levels) measurement data [8].

In this work - to compare effectiveness of various approximation methods – the indicator diagram (shown in Fig. 1, 2) was used; it was obtained from measurements performed in a cylinder of Sulzer 6AL20/24 ship medium-speed engine for the loading parameters : n = 750 rpm, p_i = 1.8 MPa. Beginning from the instant of ignition up to the end of combustion process, on the run of the pressure **p** can be observed pressure oscillations of large values generated by a short measuring channel (10 mm long) between the combustion chamber and gauge membrane. The indicator diagram of **p** was recorded with 0.1°owk angular resolution and 12 bit amplitude resolution.

FULL-INTERVAL APPROXIMATION OF RUNS BY USING THE LEAST SQUARES METHOD

Measurement data processing is aimed at assessing real values of measured quantities or searching for functional relationships whose mathematical model is either known or searched for. To this end, is usually applied the least squares method whose essence consists in the determination of minimum of the following functional :

$$\mathrm{MIN}(S) = \mathrm{MIN}\left[\sum_{1}^{N} (\tilde{y}_i - \hat{y}_i)^2\right] \qquad (1)$$

where :

MIN – operator of minimum value
N – number of elements of a measurement set
S – sum of squares of deviations
$\tilde{y}_i$ – measured values
$\hat{y}_i$ – approximated values.

Relations between measured, real and approximated values are determined by the equality :

$$\tilde{y}_i = y_i + \varepsilon_{Ri} = \hat{y}_i + \varepsilon_a = \hat{y}_i + \varepsilon_{Mi} + \varepsilon_{Ri} \qquad (2)$$

where :

y_i – real value of measured quantity
ε_{Ri} – measuring error
ε_a – approximating error
ε_{Mi} – modelling error.

If to find an adequate mathematical model of measured quantity run is not possible then it is usually approximated by means of a linear combination of selected elementary functions. As an orthogonal basis power polynomials or trigonometric ones are most often used; the latter - in the cases where periodic runs are analyzed. Sometimes non-linear models may be linearized or their parameters determined by using the theory of experiments.

The known difficulties in performing the full-interval approximation with the use of power polynomials are tried sometimes to be overcome by using splines.

A drawback of such functions is their high suceptibility to generate oscillations appearing especially in runs of derivatives derived from measurement data [6] (see e.g. Fig.1).

As it results from comparison of the runs of the derivative p'_{60} and p'_{F3}, the symptoms S_{CK} and S_R have been smoothed out for the number of nodes equal to 60. For the number of nodes equal to 180, the symptoms S_{CK} and S_R appeared - but with significant oscillations - on the run of p'_{180}.

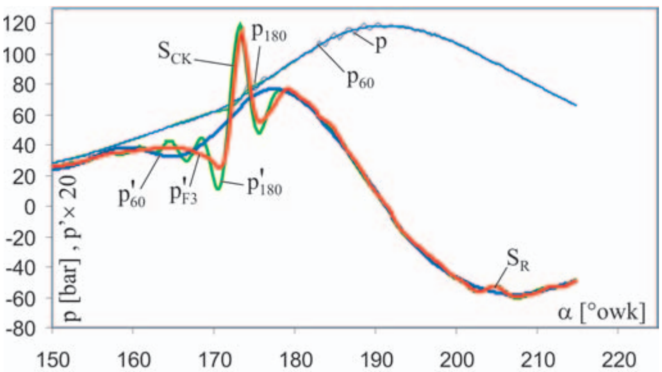

*Fig. 1. Comparison of smoothing-out quality of the indicator diagram **p** by means of glued 5th order polynomials and movable approximation with the use of the object F3 (Fig.2). **Notation** : p_{60}, p_{180}, p'_{60}, p'_{180} – runs and their derivatives obtained by approximating the run **p** with the use of the glued 5th order polynomial for the number of nodes given by their respective indices, p'_{F3} – first derivative derived from the run **p** by means of the movable approximation by making use of the object F3, S_{CK} – kinetic combustion symptom, S_R – fuel re-injection symptom, α - crankshaft rotation angle [°owk]*

The oscillations are increasing along with constraint number increasing. As proved, no such number of nodes exists that the first derivative run obtained for which, could be considered matching the run p'_{F3}.

Worth mentioning that the smoothing-out quality of pressure run itself in the form of the runs p'_{60}, p'_{180} can be considered sufficient for certain purposes despite that the quality of determination of first and higher derivatives is insufficient. In the case of rather non-dynamical runs (such as e.g. those of pure compression, sinusoid, etc), by applying the full-interval approximation with splines a sufficient smoothing-out quality can be obtained also in the aspect of determining derivatives, but usually can not in the case of the indicator diagrams of combustion process.

SMOOTHING-OUT THE RUNS AND DECOMPOSITION OF DISTURBANCES BY MEANS OF THE MOVABLE MULTIPLE APPROXIMATION METHOD

An obvious way for diminishing the errors occurring at application of the full-interval approximation method is to split a given data interval into smaller ones, that leads to the movable approximation process.

The movable approximation consists in determining – in every point **n** of measurement series – a value approximated over a movable approximation interval of a given width. The point **n** of movable approximation is called the control point.

If the minimum value of sum of squares of deviations is assumed the approximation criterion then for P-th step (repetition) of approximation the criterion can be written as follows :

$$\mathrm{MIN}(S_{Pn}) = \mathrm{MIN}\left[\sum_{i=n-k_{lP}}^{i=n-k_{rP}} (\hat{y}_{(P-1)i} - \hat{y}_{Pi})^2\right] \qquad (3)$$

where :

MIN – operator of searching for minimum
S_{Pn} – sum of squares of deviations in the point n for P-th step of approximation
$\hat{y}_P$ – values obtained from approximation for its step P
$\hat{y}_{0i} = \tilde{y}_i$ – measured values
k_{lP} , k_{rP} – parameters of the left and right end of interval of approximation for its step P.

Usually the central intervals of approximation, i.e. $k_{lP} = k_{rP} = k$, are applied.

The simplest example of the movable approximation is the movable average method. A natural generalization of the movable average method has been the algorithms of movable least squares approximation with the use of higher-order power polynomials, elaborated by Savitzky and Golay [9]. In this work the algorithms of movable approximation with power polynomials elaborated by this author [2, 3, 5], were applied; they were next extended by applying the approximating objects with constraints [4, 7].

In Fig.2 are shown results of the multiple approximation of the indicator diagram **p** with the use of the approximating object F3 being a power polynomial of 3rd order. To obtain a sufficiently smooth run of the first derivative p'_{F3} the approximation by using

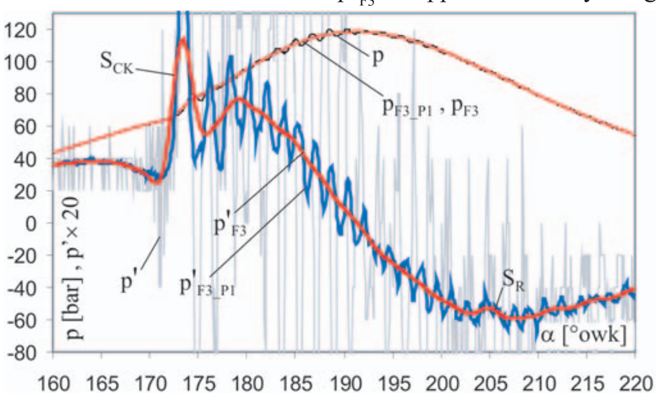

*Fig. 2. Illustration of smoothing-out effectiveness of the indicator diagram **p** with the use of the approximating object F3. **Notation** : F3 – 3rd order power polynomial - central object, k = 16, P = 5; p' – first derivative determined as linear increments of the run p; p_{F3_P1} , p'_{F3_P1} – the smoothed-out run and first derivative after 1st step of approximation; p_{F3} , p'_{F3} – the smoothed-out run and first derivative after 5th step of approximation ($p_{F3} = p_{F3\_P5}$, $p'_{F3} = p'_{F3\_P5}$); S_{CK} – kinetic combustion symptom, S_R – fuel re- injection symptom.*

the object F3 was performed five times for the same value of k = 16. The run of the first derivative p' (Fig.2), determined as linear increments of the curve **p**, illustrates the scale of difficulty which is to be overcome to obtain a smooth derivative run not loaded by dynamic errors, such as the run p'_{F3} (Fig.2) assumed in this work for the quality assessment of smoothing-out the run **p** with the use of other approximating objects and methods. To this end, in Fig.2 were distinguished the peaks (symptoms) S_{CK} , S_R ; on their runs conclusions as to dynamic features of the considered approximation method, can be based.

The multiple approximation method can be also applied to decompose disturbances. The total deviation of n-th sample of measurement series after performance of P-th approximation, is equal to :

$$D\hat{y}_{Pn} = \tilde{y}_n - \hat{y}_{Pn} \qquad (4)$$

The deviation can be presented in the form of component deviations for distinguished steps of approximation. If the steps 1, g, u, P are distinguished this is equivalent to four decomposition levels at which four runs of deviations which satisfy the below given equation, can be obtained :

$$Dy_{Pn} = Dy_{01n} + Dy_{1gn} + Dy_{gun} + Dy_{uPn} \qquad (5)$$

Other number of decomposition levels (steps) can be also assumed or to perform decomposition of disturbances after ending the approximation. Hence, auxiliary steps and main ones of the approximation have been distinguished. In order to achieve final smoothing-out to perform the auxiliary steps is not necessary.

Selection of decomposition parameters as well as assessment of its results depends on expectations, i.e. on knowledge of a physical character of achieved results - otherwise they may be of no subject-matter merit.

The high-frequency disturbances Dp_{F01}, Dp_{F12} of the run **p** (Fig. 2) determined in two auxiliary steps of the approximation with the use of the approximating objects F3a and F3b, are shown in Fig.3.

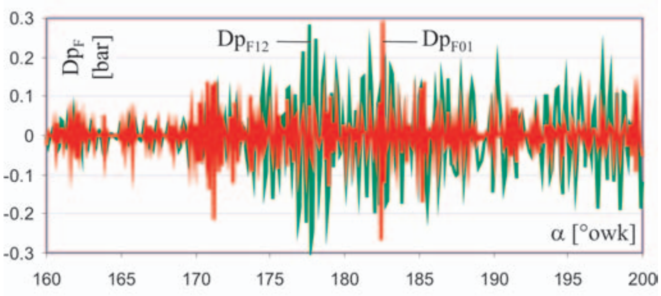

Fig. 3. *The disturbances Dp_{F01} , Dp_{F12} separated in two auxiliary steps of the approximation of the run **p** (Fig.2) with the use of the objects F3a and F3b. **Notation** : F3a – 3rd order power polynomial, k = 2; F3b – 3rd order power polynomial, k = 4; $Dp_{F01} = p - p_{F3a}$, $Dp_{F12} = p - p_{F3b}$; where: p_{F3a} – the run determined from the run **p** with the use of the object F3a, p_{F3b} – the run determined from the run **p** with the use of the object F3b.*

The disturbances Dp_{F01} , Dp_{F12} are composed of A/D processing errors, disturbances within measuring lines, measuring gauge errors and high-frequency components involved by gas passages.

The disturbances separated from the run **p** in five main steps of the approximation with the use of the object F3 are shown in Fig. 4.

The runs of disturbances shown in Fig. 4 result mainly from interaction of the gas channel between the cylinder working space and gauge membrane, as well as they may contain a part of useful signal due to inadequacy of the approximating object's model.

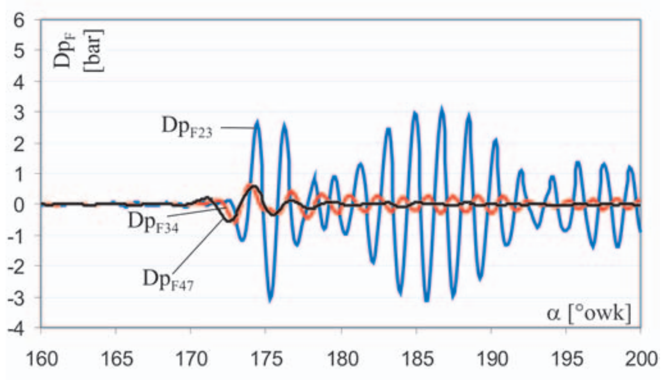

Fig. 4. *The disturbances Dp determined in five main steps of smoothing-out the indicator diagram **p** by using the object F3. **Notation** : $Dp_{F23} = p_{F3\_P1} - p_{F3b}$, $Dp_{F34} = p_{F3\_P2} - p_{F3\_P1}$, $Dp_{F47} = p_{F3\_P5} - p_{F3\_P2}$, where : p_{F3b} (Fig. 3), p_{F3_P1} ,..., p_{F3_P5} – the runs determined in result of approximation of the run **p** by using the object F3 (Fig.2).*

The run of the deviations Dp_{F47} can be represented by their three components [1]. The deviations were summed – up with taking into account their similarity.

In the smoothing-out process of the run **p** the objects F3a and F3b were not used for determining the derivative p'_{F3} (Fig.2). However if to include the objects into the smoothing-out process of the run **p** then in the example in question the first derivative determined this way will be almost identical - the differences will not exceed ±0.01% of the maximum value of p'_{F3} . Number of possible decompositions of deviations of measured run from that smoothed-out is very high for the example in question but such decompositions may be of no physical sense.

MOVABLE APPROXIMATING OBJECTS WITH CONSTRAINTS

The power polynomials free of constraints applied in Savitzky-Golay filters not always ensure a sufficient quality of approximation. Quality of approximation and decomposition of runs can be formed by modifying the approximating functions by applying constraints onto values of left-hand and right-hand derivatives of the functions in the points (nodes) q_v (Fig.5).

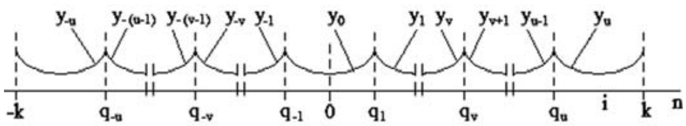

Fig. 5. *Schematic diagram of the central approximating object. **Notation** : y_v – approximating functions, {v = -u (1) u}; q_v – node coordinates, {v = - u (1) u}; i – approximating object axis, i = 0 – control point; n – axis of measurement series, n =1(1)N; k – width parameter of approximating object interval.*

It was assumed that approximating object is central one if its control point is located in the mid-point of the approximating object. Approximating object is symmetrical if the symmetry of nodes, constraints and kinds of functions (coefficients) regarding the mid-point of the object, takes place.

For the sake of easiness of formulating mathematical description of approximating object, the axis of arguments and that of approximating object was introduced where the control point coordinate is i = 0 for every successive **n**. Usually the control point is located in the mid - point of the approximation interval of the approximating object (Fig.5). If a node is placed in the control point then q_0 , but not y_0 , will appear in the object's model, that results from the assumed indexing principle.

Smoothing-out features of approximating object can be formed by setting-up its structure and values of its parameters including :

- type of approximating functions
- number of nodes and constraints
- kind of constraints: cut (spline), glued, riveted, broken ones
- either symmetry or asymmetry of function coefficients, location of control point, coordinates of nodes and their parameters, type of base functions.

The cut constraint takes place in a given node q_v of approximating object if at least one of the derivatives of approximating function is cut (unconstrained) in that node :

$$y^{(m)}_{v-1}(q_v) \not\forall_m y^{(m)}_{v}(q_v)\ ,\ y_{v-1}(q_v) = y_v(q_v) \tag{6}$$

where :

m – order of derivative
$\not\forall_m$ – symbol of cutting (non-constraining) of m-th derivative.

Such constraints are used to build splines. Obviously, appearance of even a single constraint of the kind in a given node produces an indeterminate break of function (depending on disturbances).

The glued constraint in a given node q_v takes place if the following relationships occur :

$$y_{v-1} \neq y_v\ ,\ y^{(m)}_{v-1}(q_v) = y^{(m)}_{v}(q_v) \\ y_{v-1}(q_v) = y_v(q_v) \tag{7}$$

As it results from that definition the functions to the right and to the left from the node q_v are of different types.

The broken constraint consists in setting the breaking coefficient $w^{(m)}_{q_v} \neq 1$ for a given m-order derivative in a given node q_v, that is equivalent to imposing a definite discontinuity of the derivative in the node in question. Values of approximating function in nodes are assumed continuous. By using the notation from Fig.5 the above given definition can be expressed as follows :

$$y^{(m)}_{q_v}(q_v) = w^{(m)}_{q_v} y^{(m)}_{q_v-1}(q_v) \\ y^{(0)}_{q_v}(q_v) = y^{(0)}_{q_v-1}(q_v)\ ,\ w^{(m)}_{q_v} \neq 1 \tag{8}$$

The broken constraints differ from the cut ones applied to spline functions by that they are assumed determined ones.

The spline constraints are free (undetermined), that results from cutting the selected derivatives. The simplest broken object is a broken line built of straight segments.

The riveted constraints of two sections of approximating object's function occurs when the overlapping of intervals of left and right approximating functions takes place, that can be expressed as follows :

$$r_v \neq 1_{v+1} \tag{9}$$

as well as when equality of the function or one of its derivatives occurs even in a single node.

In Fig.6 is shown an example of a simple riveted approximating object of three nodes in which values of the function are riveted.

The features of the above defined approximating objects are illustrated by a few examples of their application to smoothing-out the runs [1, 7].

Approximating object features can be also formed by inserting weights (weighting functions) into approximation equations. The weighting methods are used in statistical data analysis, especially in the case of smoothing-out small data sets. The weights constitute a kind of constraints imposed upon function values.

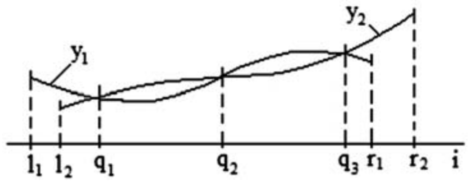

Fig. 6. *Schematic diagram of the approximating object riveted in three points : $y_1(q_1) = y_2(q_1)$, $y_1(q_2) = y_2(q_2)$, $y_1(q_3) = y_2(q_3)$; for the central object the following is valid: $r_2 = - l_1$, $r_1 = - l_2$, $q_3 = - q_1$, $q_2 = 0$.*

Staś [10], basing on a reference, gave an example of smoothing-out object which could be effective in the case of smoothing-out the indicator diagram. His formula for the smoothing-out object in question can be expressed – after formal transformation – as follows :

$$\hat{y}_i = \sum_{i=-k}^{k} w_i \tilde{y}_i \tag{10}$$

where the weights $\mathbf{w_i}$ are determined from the formula :

$$w_i = \left[\sum_{i=-k}^{k}\binom{2k}{i+k}\right]^{-1}\binom{2k}{i+k}\ ,\ \sum_{1=-k}^{k} w_i = 1 \tag{11}$$

where :

k – interval width parameter of approximating object in question.

As demonstrated, multiple approximation of the run **p** by using the object F0w with weights has not led to any better result of smoothing-out as compared with that obtained by means of the simple movable average (object F0) (Fig.7).

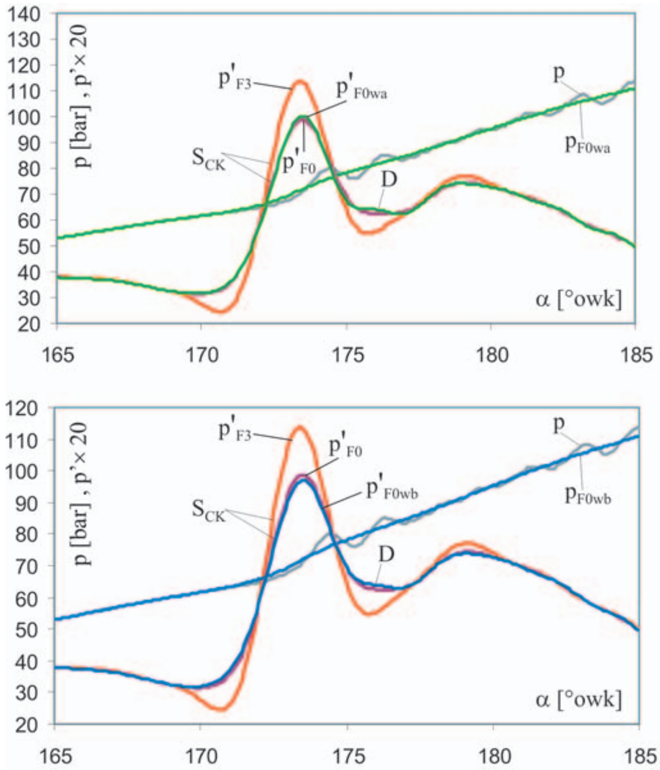

Fig. 7. *Comparison of smoothing-out quality of the run **p** by using the movable average (object F0) and that obtained by means of the movable weighted average (object F0w). Parameters of the smoothing-out objects: **F0**: k = 8, P = 4; **F0wa**: k = 8, P = 25; **F0wb**: k = 32, P = 7; p_{F0wa} , p'_{F0wa} – the smoothed-out run and its first derivative determined by means of the object F0wa, p_{F0wb} , p'_{F0wb} – the smoothed-out run and its first derivative determined by means of the object F0wb, D – deformation .*

As seen in Fig.7, in the case of application of the object F0wa, as many as P = 25 smoothing-out steps are necessary to obtain the result comparable with that achieved by using the object F0 (P = 4) which is the simple movable average. Additionally, the deformation D appeared on the derivative p'_{FOwa}. The increasing of k value up to k = 32 resulted in the decreasing number of smoothing-out steps P = 7, but it did not provide any practical benefits as compared with the results of application of the movable average. In both the cases the derivatives significantly differ from the reference run p'_{F3} obtained by using the object F3.

However the application of weighting functions changes smoothing-out features of approximating object and in certain cases their application may be justified.

DECOMPOSITION OF RUNS BY MEANS OF WAVELET FILTERS

In technical diagnostics are observed many attempts to apply wavelet analysis for separating – from measured runs – – the signals containing diagnostic information. The pressure run **p** was subjected to decomposition by using six known wavelet filters (offered in the Wavelet Explorer package in cooperation with Mathematica software) for various parameters of the filters [11].

In Fig.8 are shown the results obtained by using Daubechies and Shannon filters of the parameters given in their indices.

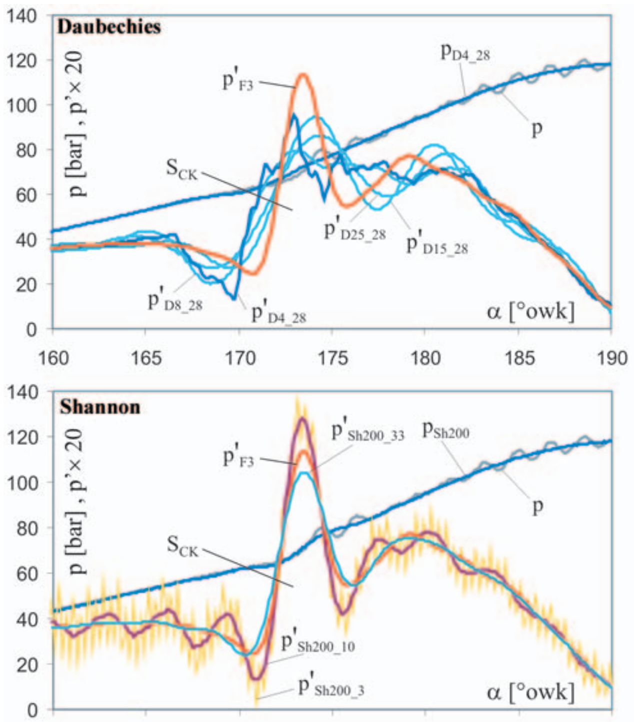

Fig. 8. *Comparison of the results of smoothing-out the indicator diagram **p** by means of wavelet filters of two kinds with those obtained by using the object F3. **Notation** : the indices of p and p': **D** – Daubechies filter, **Sh** - Shannon filter; numerical values of the indices, e.g. 4_28, stand for parameters of a given filter acc. Wavelet – Explorer description; for p'_{Sh200_3}, p'_{Sh200_10}, p'_{Sh200_33} the index values _3; _10; _33 stand for the values of the parameter k of the smoothing-out object (3rd order power polynomial) .*

As seen in Fig. 8 the first derivatives achieved from the runs smoothed-out by using the filters are impermissibly distorted as compared with the run p'_{F3} obtained by using the object F3. In the case of Shannon filter the additional smoothing-out by means of the movable approximation method made it possible to obtain the run p'_{Sh200_33} which is very similar to the run p'_{F3}. In the case of the remaining filters the additional smoothing-out can not provide any improvement because of subsequent loss of information. The first derivative deformations analogous to those in the case of Daubechies filter, were obtained by using also other wavelet filters, such as e.g. : Meyer's, Least Asymmetric, Spline and Coiflet filter [11]. It should be stressed that Shannon filter is deemed one of the worst. However in this case it was the only one which made it possible – after application of additional smoothing-out procedure – to obtain sufficiently correct results. The wavelet decomposition of runs provides also disturbance runs in the form of the so-called details. In Fig.9 are shown the high-frequency details Dp_{Sp4} , Dp_{Sp3} obtained for two first steps of decomposition by means of the filter Sp3_50 (Fig.8).

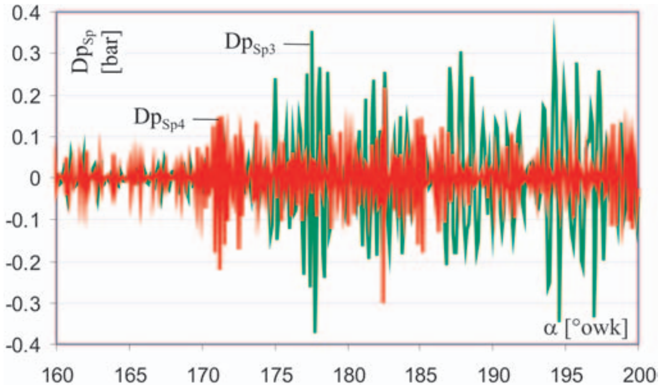

Fig. 9. *Runs of the high-frequency details (deviations) Dp_{Sp4} , Dp_{Sp3} separated in result of decomposition of the run **p** by using the filter Sp3_50 (Fig.8) .*

Comparing the runs Dp_{Sp4}, Dp_{Sp3} (Fig.9) with the runs Dp_{F01}, Dp_{F12} (Fig.3) one can postulate that they are similar (convergent) to each other. Degree of convergence of the runs can be assessed by performing direct comparison, correlation or coherence analysis.

In the case of low-frequency deviations (Fig.10) a noticeable convergence of the runs Dp_{Sp1} and Dp_{Sp2} with the runs Dp_{F23} (Fig.4) can be observed; however the level of their differences can not be considered negligible.

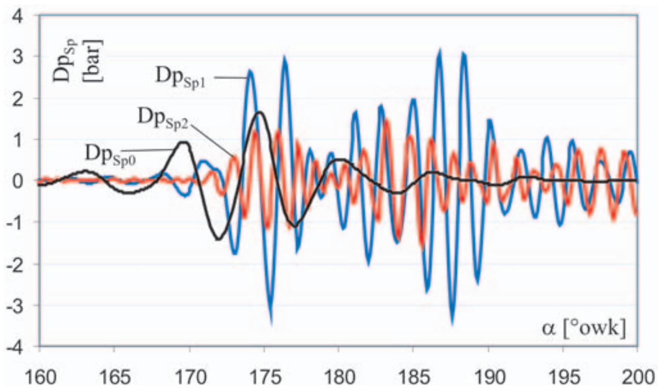

Fig.10. *Runs of the low-frequency details (deviations) Dp_{Sp0} , Dp_{Sp1} and Dp_{Sp2} separated in result of decomposition of the run **p** by using the filter Sp3_50 (Fig. 8) .*

Analyzing the runs Dp_{F23}-Dp_{F47} (Fig. 4) one can observed that in the applied display scale the waving on the runs within the coordinate interval up to the angle α = 170°owk, or even to 172°owk, are not visible. However in the case of the run Dp_{Sp0} (Fig. 10) a significant waving can be observed beginning already from the angle α = 160°owk. The run Dp_{Sp0} has not any equivalent among the runs presented in Fig. 4. Beginning from the angle α = 168°owk, a significant waving is also visible on the run Dp_{Sp1} (Fig. 10), which deforms the first derivative run p'_{Sp3_50} to an impermissible degree (Fig. 8).

Such phenomena were observed in analyzing a number of other runs including those much less disturbed, and in every case negative result was obtained of smoothing-out process for determining first derivative, except the case of the application of Shannon filter connected with final smoothing-out operation. The problems may serve as subjects of separate research.

CONCLUSIONS

- By applying the multiple movable approximation of runs by using objects of appropriately selected features to obtain a demanded degree of smoothing-out the run and to perform decomposition of distortions, is possible.
- To form features of approximating objects can be used : cut, glued, broken or riveted constraints as well as weights. The features can be formed by choosing : kind of base functions, width of object's interval, number and kind of constraints, number and location of nodes. Multiplicity of approximation repetitions (number of steps) influences smoothing-out results specially.
- The full-interval approximation of runs by using spline functions may lead to significant errors in the form of generation of waving which does not exist really.
- The decomposition (filtration) by means of wavelets may be also loaded by significant errors both as to the smoothed-out run and the obtained details (deviations). It does not contradict the usefulness of the method for e.g. image compression where the disturbance level involved by wavelet filters may be insignificant. Applying the method for filtration of diagnostic signals in engineering one should be careful in accepting the obtained results especially if their confirmation by any other method is not performed.

NOMENCLATURE

D – run distortion,
F3 – movable approximating object : 3[rd] order polynomial, k = 16, P = 5
i – axis of arguments of an approximating object
k – width parameter of approximation interval of central object
m – derivative order
n – numerical axis of measurement series, n = 1(1)N
P – number of steps (passages) of approximation
p – run of cylinder pressure (indicator diagram)
p' – first derivative of the pressure p
p'_{F3} – first derivative of the pressure p determined with the use of the object F3
q, q_v – node coordinates of the approximating object, {v = - u (1) u}
S_{CK} – kinetic combustion symptom
S_R – re-injection symptom
$\hat{y}$ – approximating function
$\tilde{y} = y$ – measurement series
y_v – approximating function, {v = -u (1) u}
$y_v^{(m)}$ – *m-th* derivative of the function y_v
α – crankshaft rotation angle
°owk – degree of crankshaft rotation angle

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Miscellanea

Days of Engineering

On 23-25 November 2006, 37[th] Days of Engineering was held on the occasion of 60[th] Anniversary of Technical University of Szczecin, the oldest technical university of West Pomerania, as well as of many scientific technical societies of the town, namely : that of electricians, geodesists, mechanical engineers and technicians, water engineers and technicians as well as the Federation of Scientific Technical Societies NOT (Naczelna Organizacja Techniczna).

The jubilee was celebrated under the slogan :

Youth and Engineering – a chance to developing the Town and Region,

which has had a very distinct meaning.

It was arranged by the following organizations :

- the Federation of Scientific Technical Societies NOT, Szczecin
- Szczecin Division of the Polish Society of Electricians
- Technical University of Szczecin
- The Society of Graduates from Technical University of Szczecin.