Measurements of Pressure Fields with Multi-Point Membrane Gauges at Electrohydraulic Forming

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Abstract

Success of electrohydraulic forming (EHF) process depends on coincidence of the needed pressure field with the field generated by discharge chamber at sequent stages of sheet blank deformation.

Impulse loading at high-voltage discharge has a very complicated character and involves many phenomena: direct shock waves, hydraulic flows, quasi-static pressure of gas bubble, reflected shock waves, cavitation, secondary shock waves, etc. Also internal shapes of a discharge chamber, design and location of electrodes have a great influence on pressure distribution along blank surface. Because of these features, the simulation of EHF processes is very complicated task to be solved for chambers equipped with single electrode pair. And difficulties are increased greatly for simulation of multi-electrode discharge blocks (MDB). First of all, reliable data on pressure distribution at various discharge conditions are necessary to reveal and describe influence of each factor of impulse loading.

Multi-point membrane pressure gauges (MPG) give an opportunity to obtain pressure maps with high resolution at relatively low cost. By design MPG typically consists of body plate with large number of small holes and sensitive element – metallic membrane. Deformation of membrane in each point (hole) can be measured and recalculated into pressure. Totality of many pressure points allows plotting a pressure map. MPGs are better suitable for measurement of shock-waves pressure. For this purpose the holes diameter and membrane thickness should be specified in such a manner that membrane is sensitive only to shock waves.

Combination of MPG measurements with piezoelectric sensors can give full information about pressure map changing in time. These data could be a good basis for simulation of impulse loading with approximation formulas and also could be used as a check data for the simulation programs based on theoretical relationships.

Initially the method based on MPG application was designed for investigations and improvements of discharge chambers with various forms of internal (reflecting) surfaces, electrodes position and their shapes, influence of design features on pressure distribution.

Vast experimental investigations were carried out with MPG application for typical single-electrode-pair discharge chambers (conical and parabolic) and multi-electrode discharge blocks.

Keywords

Impact Forming, Measurement, Distributed Pressure, Sheet metal, Membrane Pressure Gauge

1 Introduction

Simulation of processes of electrohydraulic impact forming (EHF) needs experimental determination of fields of impact loading along sheet blank surface with regard to its change in time.

Creation of models based only on theoretical description of loading impact often gives results inadequate to real loading conditions. In order to obtain more exact results the mathematical model should be corrected with the experimental data.

Application of piezo-electric sensors gives information about parameters of shock waves in time that is very essential for modeling the processes of impact loading and deformation of sheet blanks. But for obtaining the detailed loading map along large area the large quantity (several hundreds and even thousands) of piezo-electric sensors is needed. Complexity of organization of measurements with large quantity of sensors, high cost of piezo-electric sensors and measurement instruments result in impracticability of such experimental task.

Multi-point membrane pressure gauges (MPG) well suit to the task of measurement of pressure fields along large area. They are characterized by design simplicity and low cost. By design MPG typically consists of body plate with large number of holes and sensitive element – metallic membrane. However, by its nature, MPGs record integral action of all factors of impact loading generated by high-voltage discharge in a liquid: shock waves, hydraulic flows, quasi-static pressure of vapor bubble in closed discharge chambers. Action of pressure impact is recorded in the form of membrane deflection (residual plastic deformation) on places (points) of holes in a gauge body. Deformation of membrane on each point can be measured and recalculated into pressure. Totality of many points allows plotting a pressure map. Magnitude of membrane deflection is proportional to maximum (peak) value of a pressure impact, its duration and membrane parameters. That is, membrane gages give information about pressure impact combined in one parameter – membrane deflection.

Initially MPGs were applied for estimation of energy portions in blank deformation delivered by shock wave, hydraulic flow, quasi-static pressure, as well as for determination of maximum capabilities and pressure distribution for discharge chambers of various design.

This work has a purpose to develop method for making membrane-gauge tests and results processing that will allow describing a process of impact pressure loading with time increments.

Deformation of membrane under the action of all various energy-force factors of an underwater discharge has very complicated character. But shock waves have a leading role in deformation process. For the first approach the distribution of only shock waves pressure was specified for measurement. In the book [1] it is shown that, if time of membrane plastic deformation is much less than characteristic time θ of pressure impact, the membrane deflection will be proportional to the pressure amplitude. Time of plastic deformation τ_{pl} is determined from the famous R. Cole's formula

$$\tau_{pl} = \frac{\rho c (d/2)^2}{4\sigma s} , \qquad (1)$$

where ρ and c – density of transmitting medium and sound velocity in it, respectively; d and s diameter and thickness of membrane, respectively; σ – average value of strength and yield limits.

Thus, selecting proper values of membrane diameter and thickness one can "tune" membrane pressure gauge to a measurement of shock wave pressure.

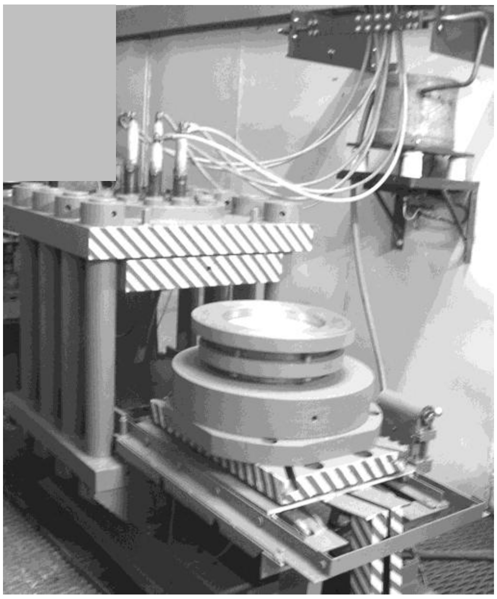

Figure 1: *General view of technological block of UEHSH-2 installation*

2 Analysis of previous investigations results

One of the first vast investigations of pressure fields with MPG application is submitted in the dissertation [2]. Impact loading was created by multi-electrode discharge block (MDB) of experimental electrohydraulic installation UEHSH-2 (Figure 1).

When making tests the loading was mainly performed at the following parameters: charge voltage V_0 = 25 kV, capacity of one discharge circuit C = 16.6 microfarad, distance between MDB and membrane gauge H = = (50–130) мм (Figure 2), axial position of electrodes h_e = 95 mm, spark gap l_e = 30 mm. Mechanical properties of metallic membranes are: steel 08kp – ultimate tensile strength σ_u = 379 MPa, yield limit σ_y = 234 MPa, percentage elongation δ = 18 %; aluminum alloy AK4-1 – σ_u = 325 MPa, $\sigma_{0.2}$ = 290 MPa, δ = 6 %. Thickness of steel mem-

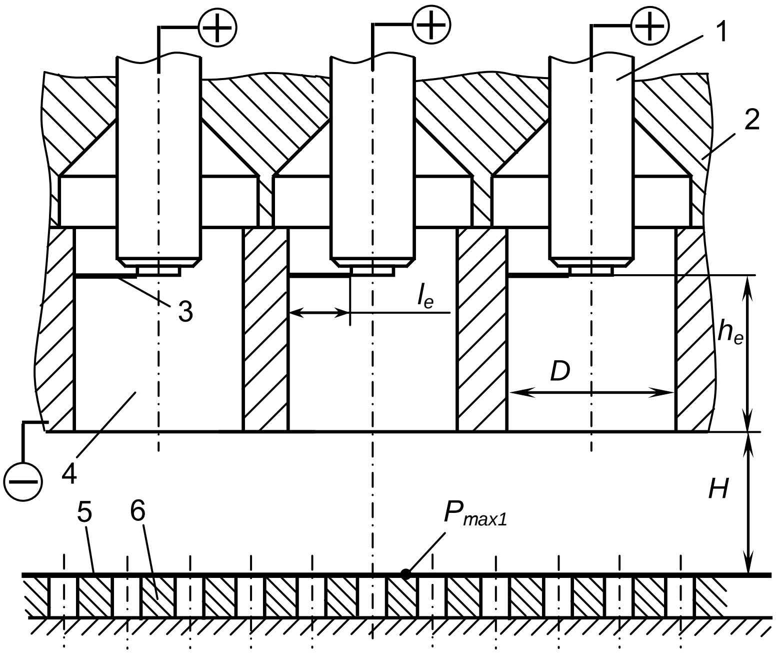

Figure 2: *Test diagram for MPG measurements of pressure fields [2]: 1 – insulated electrode; 2 – MDB body; 3 – electric discharge channel; 4 – guide hole in opposite electrode-plate; 5 – membrane; 6 – MPG plate; l_e – spark gap length; h_e – axial coordinate of electrode; D – guide hole diameter; H – distance between MDB and MPG; P_{max1} – maximum pressure generated by one electrode pair*

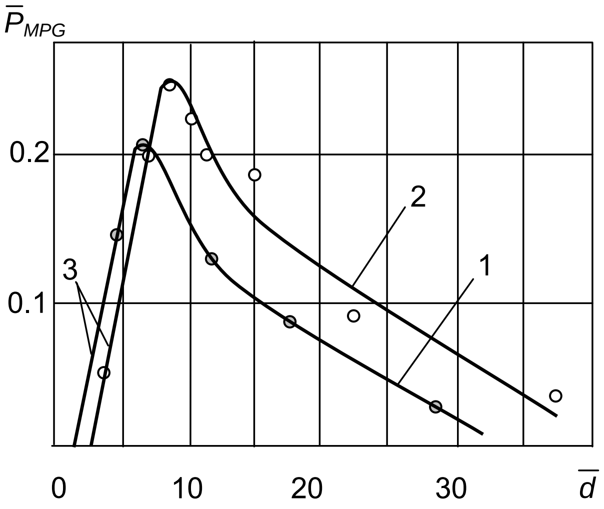

***Figure 3**: Relationship between normalized equivalent static pressure and relative diameter of MPG holes at constant discharge-circuit parameters [1]: 1 – membrane of steel 08kp, s = 0.8 mm; 2 – membrane of aluminum alloy AK4-1, s = 0.6 mm; 3 – straight segments of curves*

branes varied in the range of 0.6 to 0.8 mm, of the aluminum ones – 0.6 mm.

In the test diagram submitted in the Figure 2 the diameter of gauge holes was selected equal to 6 mm in order to register a pressure only from shock waves.

Investigations results [2, 3] showed that at some definite combination of geometric, mechanical and physical properties of membrane and parameters of pressure impact, membrane, as a sensitive element of gauge, registers only action of shock waves. Deformation of membrane occurs during characteristic time θ or less. Value of membrane deflection is linear proportional to peak value P_m of shock wave pressure in a definite range of ratios $\overline{d} = d/s$, where d is holes diameter, s – thickness of membrane (Figure 3). Approximately this range can be defined as $\overline{d} < (6\ldots8)$. Here “equivalent static pressure” is adopted as a parameter for estimation of impact loading. It is calculated from the known Laplace formula for spherical element with the measured deflection (residual deformation) of membrane. In Figure 3 pressure is submitted in normalized form $\overline{P}_{MPG} = P_{MPG}/P_m$, where P_m is maximum (peak) pressure of direct shock wave.

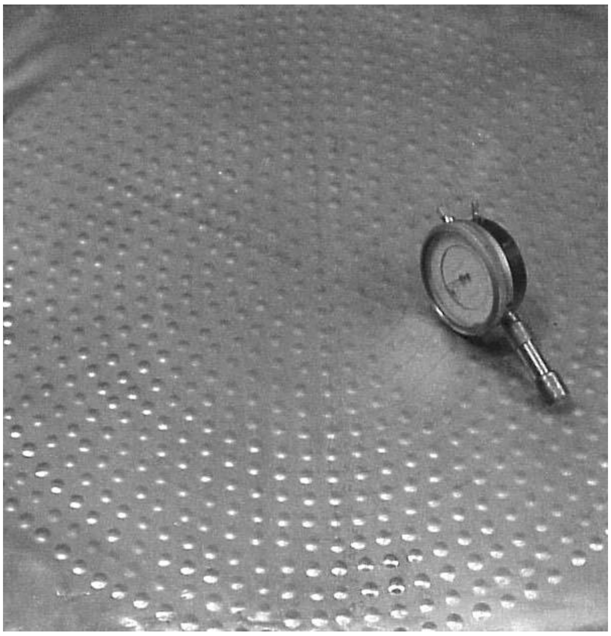

***Figure 4**: Membrane after impact loading and dial indicator for measurements of membrane deflections at the places of MPG holes*

Linear dependence between parameters $\overline{P}_{MPG}$ and $\overline{d}$ means that membrane deformation occurs during time of shock wave action. This proves correctness of the formula (1). With increase of parameter $\overline{d}$ value $\overline{P}_{MPG}$ reaches its maximum and begins to decrease. This proves that other factors of impact loading (hydraulic flows, cavitation, etc.) are involved in the process of deformation. It is worth to mention that dependence $h = f(\overline{d})$ has a similar form.

Typical metallic membrane after impact loading on the membrane gauge with 6-mm holes in the UEHSH-2 installation with 7 working electrodes is shown in Figure 4. Measurements of deflection (dimples height h) were performed with a dial indicator and special adaptor with accuracy of 0.01 mm.

Results of MPG measurements showed peculiarities of shock-wave pressure fields generated by discharge chambers of certain design (Figure 5). Such maps are very useful for analysis and improvement of discharge chamber design, electrodes positions in order to obtain pressure fields of desired distribution.

For example, one of peculiarities of loading with a single electrode located in the MDB hole was displacement of high-pressure area to the side opposite to position of discharge channel (see Figure 5). Probably this peculiarity could not be revealed only with a theoretical model.

Loading with several simultaneous discharges has a more complicated character because of non-linear effects of interaction of several shock waves propagating at different angles respect each other. On the surface of wall they generate zone of interactions with maximum pressure greatly exceeding simple sum of shock-wave pressures. Interaction of 2 shock waves is easier for analysis. In Figure 6 interaction zone is located be-

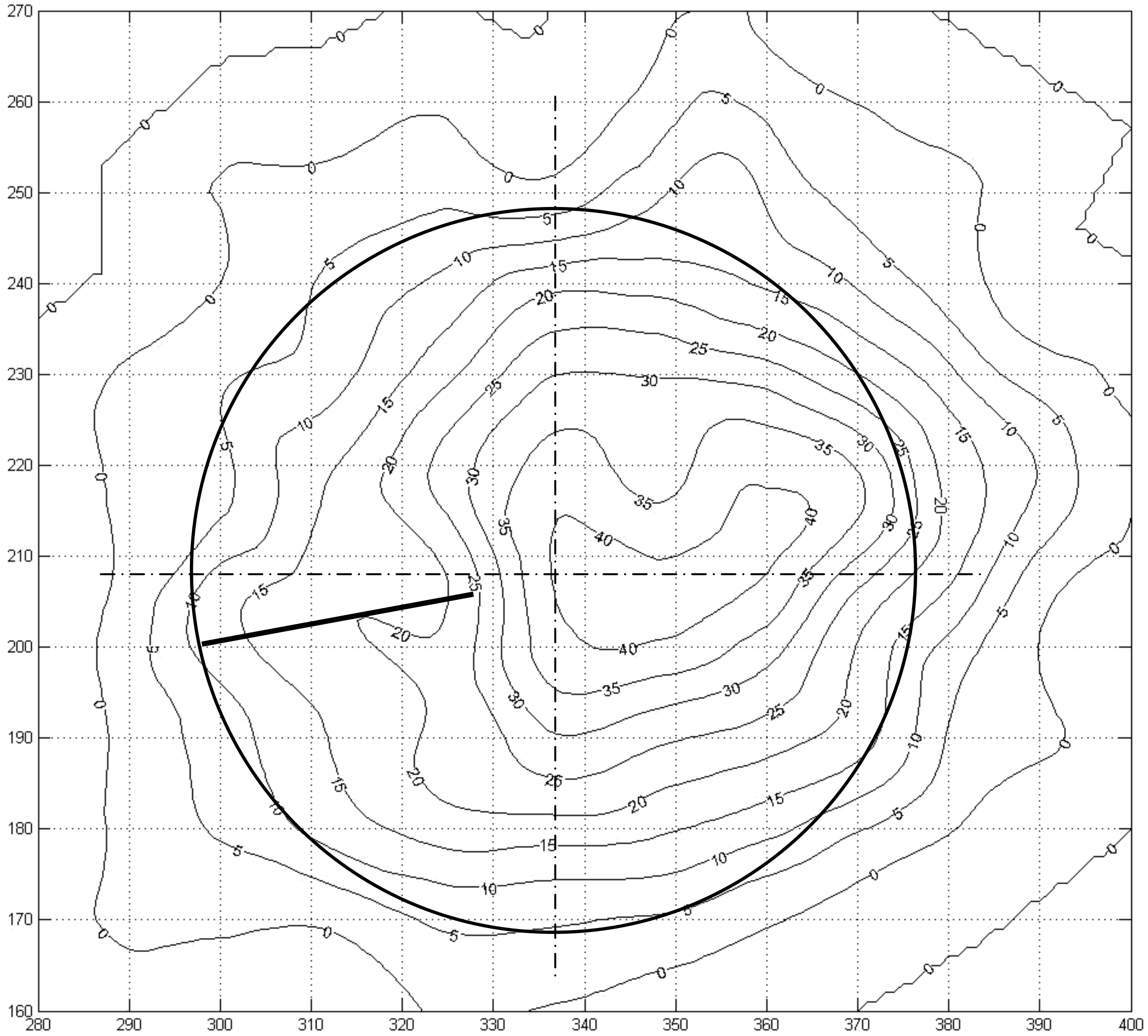

***Figure 5**: Map of shock-wave pressure field generated by discharge in one electrode pair of multi-electrode block (see Fig. 2): round circle shows contour of exit hole D; thick straight line shows discharge channel. Pressure is given in MPa, coordinates – in mm*

tween 2 circles (symbolizing 2 exit holes in MDB discharge plate) and determined by expanded isobar of 5 MPa with maximum pressure of 25 MPa and more in the center. In comparison with single-electrode loading (see Figure 5) total maximum pressure in the interaction zone increased approximately 25 times of sum of maximum pressures created by 2 shock waves.

Interaction of larger quantity of shock waves results in further strengthening of non-linear effects. Pressure maps generated by 3, 5 and 7 electrodes have more complicated character [4].

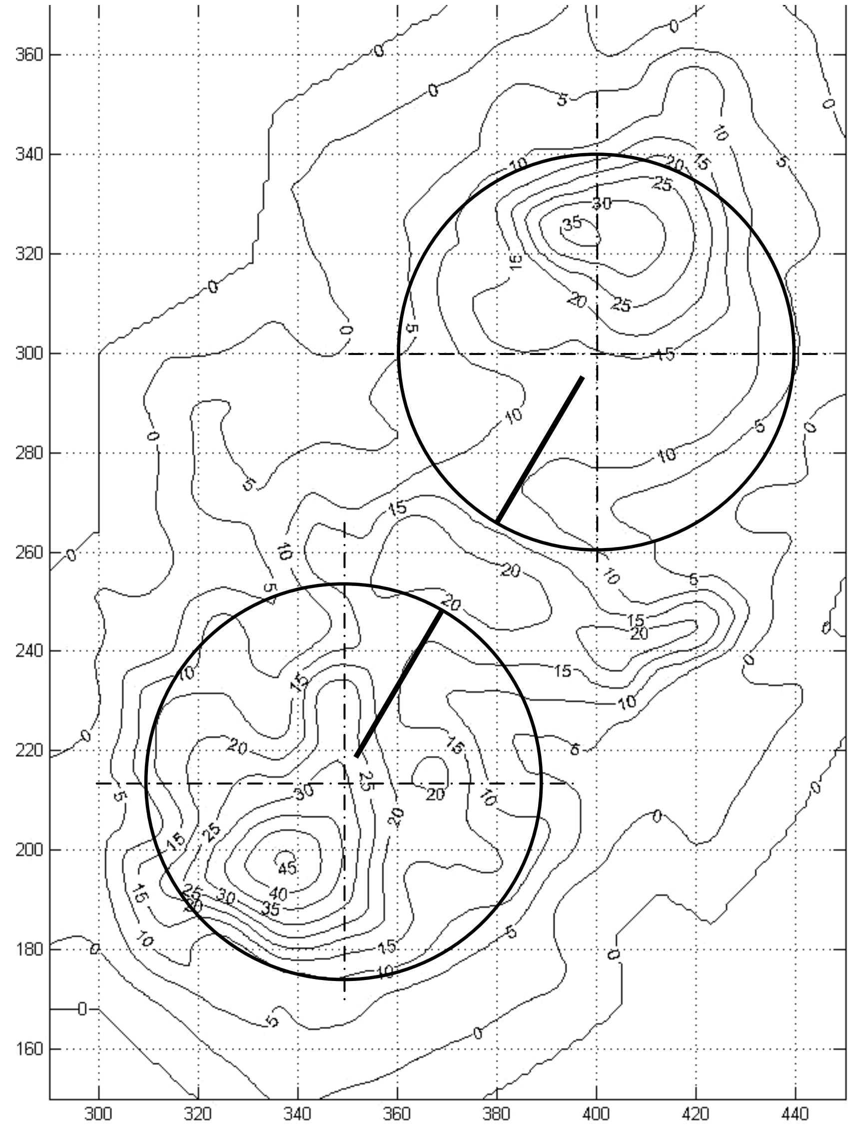

***Figure 6**: Map of shock-wave pressure field generated by discharges in two MDB electrode pairs (see Fig. 2): round circles show exit holes D; thick straight lines show discharge channels. Pressure is given in MPa, coordinates – in mm*

3 Method for tests carrying-out and results processing

Proposed method includes several stages.

The first stage has a purpose to find function for conversion of pressure values measured with a membrane gauge P_{MPG} into values of shock-wave peak pressure P_m. This is performed by several tests with various energies of discharges. Measurements are performed by single-point membrane gauge of apt hole diameter and membrane thickness (to register only shock wave, see Fig. 3) and piezo-electric sensor to register the P_m values at the same conditions. Thus, function $P_m = f(P_{MPG})$ will be obtained. It is assumed that this function will be linear. Also application of function $P_m = f(h)$ is possible, where h is deflection of membrane under the action of pressure impact. Hence, at this stage calibration of membrane gauge is performed.

The second stage is measurements of pressure fields with multi-point MPG under the discharge chamber to be investigated. Here the real pressure distributions are obtained in the form of data matrix (h_i; x_i; y_i), where (x_i; y_i) are coordinates of points (holes) of membrane-gauge plate. With aid of function $P_m = f(P_{MPG})$ (or $P_m = f(h)$) the data are converted into the matrix (P_{mi}; x_i; y_i). But this is a static distribution of peak values of shock-wave pressure.

At the third stage in order to obtain pressure parameter changing in time it is necessary to find characteristic time θ_i in the formula for each point i

$$P_i = P_{mi} \cdot e^{-\frac{\tau}{\theta_i}} \quad . \tag{2}$$

The θ_i values can be calculated from the known formulas [4, 5]

$$\theta = \tau_{0.1}/ln\,10\,; \quad \tau_{0.1} = 0.74\tau_1\bar{r}^{1/8}; \quad \bar{r} = r \cdot \left(\frac{\rho\, l_e}{V^2C^2L}\right)^{1/4}, \tag{3}$$

where τ_1 is a duration of the 1st half-period of discharge current; V, C, L – voltage, capacitance and inductance of discharge circuit respectively; ρ – density of transmitting medium (water).

Results of computations performed for the specified conditions showed the value θ_{com} = 30.3 microseconds, while experimental data gave the value θ_{exp} = 26 microseconds. Relative error of computations equals 16.5 % that is quite good for the first approach. Of course, application experimental θ_{exp} values obtained at the first stage will improve accuracy of the method.

At the fourth stage the moments $\Delta\tau_{\text{i}}$ when shock waves reach the wall (membrane) are determined from geometric formulas taking into account the design of considered discharge chamber or block. Here $\Delta\tau_{\text{i}}$ is a time delay when front of shock wave propagates from discharge channel to the point i on the membrane surface.

Performing all the works of specified stages one can restore the picture of loading that changes in time.

4 Conclusions

Peculiarities and advantages of measurements of pressure fields with multi-point membrane pressure gauges at impact forming have been analysed

The method for organisation of measurements with MPG and piezo-electric sensors, processing of measurements data has been proposed.

The results of MPG measurements and their processing could be a good basis for simulation of impulse loading with approximation formulas and also could be used as a check data for the simulation programs based on theoretical relationships.

Further improvement of the method based on MPG application should take into account other factors of impact loading (hydraulic flows, quasi-static pressure) and phenomenon of cavitation. For this purpose the application of MPG with larger holes is planned with respective correction of the data processing algorithms.

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