Supercomputer real-time experimental data processing: technology and applications*

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Abstract. The study is focused on the technology of remote real-time processing of intensive data streams from experimental stands using supercomputers. The structure of distributing data system, software for data processing, optimized PIV algorithm are presented. Using of real-time data processing makes possible realization of experiments with feedback when external forcing depends on internal characteristics of the system. Approbation of this technique is demonstrated on experimental study of intensive cyclonic vortex formation from localized heat source in a rotating layer of fluid. In this study the heating intensity depends on velocity of the flow. The characteristics of the flow obtained by supercomputer real-time processing of PIV images are used as input parameters for the heating system. The concept of using developed technology in the experimental stands of aircraft industry is also described.

Keywords: supercomputer, experimental data processing, PIV, SciMQ, laboratory analog of tropical cyclone, feedback

1 Introduction

At the present significant e-Science projects deal with the processing of large amounts of data obtained from experimental stands (for example, CERN LHC in high-energy physics). The growth in the amount of experimental data makes

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impossible the data processing using local computer power. Traditionally, grid computing is used to solve this problem, when the received data are distributed for processing and analysis in many computer centers. However, this scheme is not suitable for the cases when data processing should be performed directly during the experiment. It is necessary for on-line analyses of the results or controlled forcing. For example experimental study of formation of laboratory analog of tropical cyclone [1–4] with a controlled feedback between flow velocity and heat release. Realization of controlled feedback required solution of a number of technical problems such as data acquisition and storage, real-time data processing, integration of PIV (Particle Image Velocimetry) and heating control systems. The common way of application of PIV technique for velocity field reconstruction consist of acquisition of images of tracers and their postprocessing. The main problem toward realization of real-time PIV (RTPIV) measurements is a high computing cost of data postprocessing [5]. There are several ways for realization of RTPIV. Simplified PIV algorithms and small images allow to processed PIV images up to 15 Hz [6]. Another way is using FPGA (field programmable gate array) technology, the strong limitations of which is requirement of using specific hardware language for programming the PIV code. The detailed description of FPGA can found in [5, 7]. Growth of GPU computing power results in RTPIV based on implementation of GPU code for PIV processing [8]. Alternative efficient solution of the described problem is a main goal of the present study. The key idea of our approach is a transfer of resource-intensive data processing to the supercomputer. Integration of experimental measurement system and supercomputer is realized by using of data stream manager SciMQ [9] and supercomputer software for PIV processing.

2 Real-time supercomputer processing of experimental data

Remote data processing using external computing system requires organization of data transport network between measuring and computational systems. Another problem is efficient distribution of experimental data on computing nodes and return of processed data back to the main experimental computer [10, 11].The possibility of distributed processing imposes some restrictions on the structure of the data stream. The data stream from the measurement system must be discrete, that is, consist of independent blocks (messages). The processing of each message by application algorithms must be independent of other messages and the results of their processing. If the data stream from the measurement system meets these requirements, then it can be processed on remote supercomputers in real time by distributing stream messages to accessible computing nodes.

The presence of a discrete stream with independent processing of each message allows us to apply the concept of queues for organizing the processing of experimental data in real time on a supercomputer. The use of queues for data transmission makes possible the separation of the measuring and computing systems, renouncing the synchronization at the level of computational nodes, and isolation of distributing and collecting data from computational nodes in one subsystem – the data stream manager. The architecture of a system for processing experimental data in real time on a supercomputer is shown in Fig. 1.

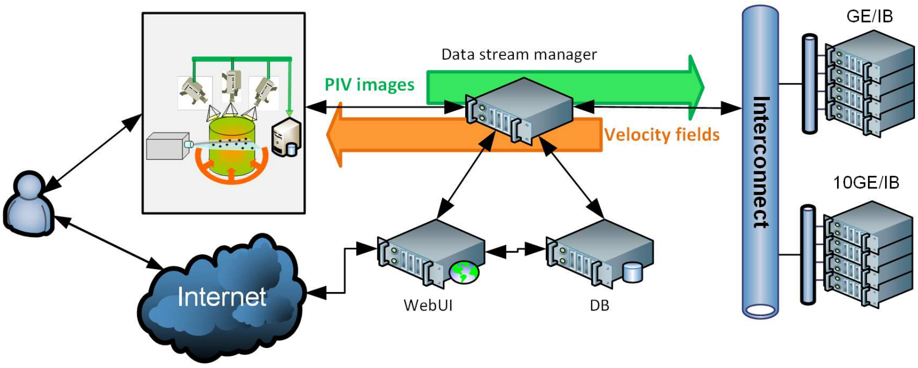


Fig. 1. The architecture of a system for processing experimental data on a supercomputer

The advantage of this application is parallel data transfer from the data stream manager to the supercomputer, which significantly increases the efficiency of data transmission in the case of using a remote long distance supercomputer [11].

Development of our own software stack for controlling of data streams was necessary because existing solutions do not satisfy high requirements for network capacity (for messages large than 10 MB), usability and efficiency for data transfer through extensive communication channels [10].

2.1 Software-hardware platform for processing experimental data

A supercomputer "Triton" with a peak performance of 23.1 TFlops, built on the basis of Intel Xeon E5450 processors (Harpertown, SSE 4.1) and Intel Xeon E5-2690v4 (Broadwell, AVX2) is used for experimental data processing. Computing nodes are combined with InfiniBand (Harpertown nodes – 20 Gbps DDR, Broadwell nodes – 56 Gbps FDR) and Ethernet (Harpertown nodes – 1 Gbps, Broadwell nodes – 10 Gbps) interconnects.

The SciMQ data stream manager [9, 11] is installed on the HP ProLiant DL360p Gen8 application server (2x Intel Xeon CPU E5-2660, 2.20 GHz, RAM 128 GB), which is connected to the network at a speed of 10 Gbps. SciMQ software consists of the following main components:

1. Data stream manager;
2. Database;

3. WebUI – Web interface.

SciMQ data stream manager is a highly performance queue server, developed by authors which is ready for efficient work with large messages up to tens of megabytes. This condition is necessary for PIV images transport. Manager is responsible for control of the sending messages in queues, intermediate storing, distribution among computational nodes of supercomputer or other external systems.

At the current stage, a 1 Gbps link is used between PIV system and the application server, and a 10 Gbps communication channel between the application server and the "Triton" supercomputer.

2.2 The architecture of a data processing application for a supercomputer

In the proposed architecture, the supercomputer runs software that receives new messages from the queue manager, processes them with application algorithms, and sends the processing results back to the queue manager.

To simplify the using of applied algorithms, a modular application that solves problems of receiving and sending messages, parsing the original messages, and formatting the processing results was implemented. The application supports the development of modules of applied algorithms that are implemented in the form of C++ classes using the specified interface.

Main application features:

- Organization of a network connection with the data stream manager with control over its operation and reconnection in the event of a disconnection.
- Receiving of new messages for processing, including prefetch mode, when the following message is downloaded in the background mode. The use of preload allows to increase the efficiency of the use of processor cores when the supercomputer is located far from the data stream manager.
- Sending the results of processing to the data stream manager. Both receiving and sending messages are executed along with processing in the dedicated thread.
- United management of configuration of the system and using algorithms through a single configuration file.
- Integration with the Intel Threading Building Blocks (Intel TBB) library, which allows data processing algorithms to use Intel TBB functions for parallel processing of one message.
- Integration with MPI, which allows to inform the data stream manager about the completion of processing only once (not from each compute node with the application running).
- The organization of storing and distributing by computing nodes of the history of processed data, which will be available for processing subsequent messages. It allows to implement adaptive algorithms that take into account the specifics of initial and earlier processed data.

Fig. 2 shows the block diagram of the data processing application for the supercomputer.

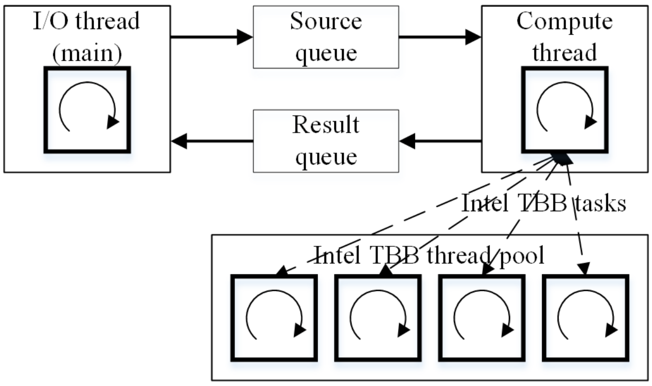


Fig. 2. The block diagram of the data processing application for the supercomputer.

The application works in several threads. The main thread is responsible for input/output (I/O) – receiving messages from the data stream manager and sending processing results. The second thread is computational – it starts the basic functions of applied algorithms. In addition, the Intel TBB library thread pool is used to speed up data processing in application algorithms. The interaction between the computational thread and the I/O thread is done by two internal queues, one of which transmits input data from the I/O thread to the computational thread, and the other transmits processed results from the computational thread to the I/O thread.

2.3 Module of PIV data processing

As a basic PIV algorithm we chose the one realized in PIVlab software [12] published by BSD license. Since there is no Matlab software installed on supercomputer "Triton" PIV algorithms from PIVlab initially realized in Matlab were rewritten in C++ and optimized by using Intel libraries (MKL and IPP). Some algorithms were optimized by manual vectorization using SSE and AVX instructions. The MKL library is used in Sequential mode, because MKL functions are called from parallelized code. For manually-optimized functions, when an application is started, an implementation using the processor-supported instruction set is selected.

The stages of operation of the algorithm are shown in Fig. 3.

The processing of each interrogation area is completely independent of the others. This allows parallel processing of one measurement by distributing interrogation areas across different cores of the compute node using the functions of the Intel TBB library.

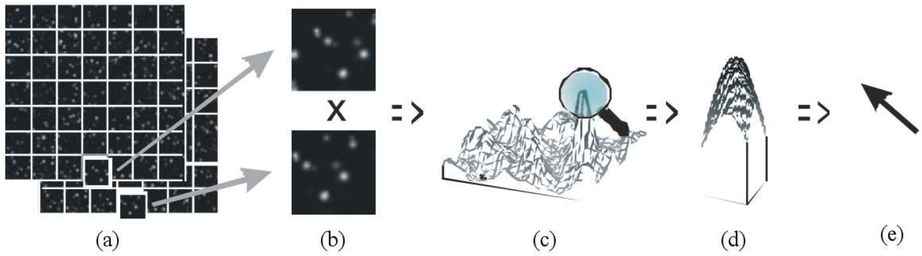


Fig. 3. The stages of operation of PIVlab software: a – formation of interrogation windows, b – cross-correlation, c – search for correlation maxima, d – determination of the coordinates of the maxima, e – calculation of the velocity vector.

Implementation of efficient paralleling of processing using all available cores of computational node was successful on all stages except initial unpacking compressed PNG (portable network graphics) images. At this stage only two data streams are used (because of the two frames in one measurement) excluding the interpolation algorithm which are called four times during data processing. The interpolation algorithm uses global mutex and only one thread, since the Intel MKL PARDISO solver used in it is not thread safe in Sequential mode.

3 Application of the developed system

Developed system is actively used in laboratory study of tropical cyclone formation. Specifically it is applied for modelling of complex process of latent heat release. Feedback between intensity of the flow and the amount of heat flux is realized.

It is also planned to use the developed system for recording and processing of fast processes with feedback during aircraft flights. The main problem is the processes of icing of structural aircraft elements.

3.1 Laboratory modelling of tropical cyclones with controlled forcing

Connection between hydrodynamic and thermodynamic processes is important factor in different natural and technological systems. For example velocity or flow topology variation can lead to increasing or decreasing of heat flux in processes of convective heat transfer, combustion or exothermic chemical reactions. Open problem is a link between wind velocity and latent heat release during formation of large-scale atmospheric vortices like tropical cyclones (hurricanes, typhoons). The problem of tropical cyclogenesis attracts great attention because of multiple human losses and vast economical damage. The main problem is long-term reliable forecast. The quality of prediction of tropical cyclone intensity and track of its motion strongly depends on the choice of mathematical models. Up to now capabilities of numerical modeling are restricted. Most of numerical simulations are carried out using spatial resolution of 2-3 km with parametrization of the subgrid processes. Some effects like the influence of secondary flows with characteristic scale of 1-3 km on heat and mass transfer are either parametrized or neglected. Another serious problem for numerical modeling is a large number of parameters (humidity, compressibility, physical properties of media and many others). Taking into account that the time of one full-scale 3D run is one week or more to study the role of all parameters is hardly possible.

Limited capabilities of direct numerical modeling of atmospheric flows increase interest to the laboratory modeling of geophysical processes. On the base of approach described in [1] and using of PIV (Particle Image Velocimetry) system it was shown [2–4] that the structure of laboratory convective vortex is similar to the structure of typical tropical cyclone. Supercomputer data processing can be used for modelling of latent heat release in the process of tropical cyclone formation. Realization of controlled feedback between velocity and heating required solution of a number of technical problems such as data acquisition and storing, real-time data processing, integration of PIV and heating control systems.

Experimental setup Experimental model is a cylindrical vessel of diameter $D = 300mm$, and height $H = 40mm$ (Fig. 4(a)). The sides and bottom were made of plexiglass with a thickness $3mm$ and $20mm$ respectively. There was no cover or additional heat insulation at the sidewalls. The heater is a brass cylindrical plate mounted flush with the bottom. The diameter of the plate d is $104mm$, and its thickness is $10mm$. The brass plate is heated by an electrical coil placed on the lower side of the disc. Massive heater provides uniform heating which is optimal for vortex excitation. Cylindrical vessel was placed on a rotating horizontal table (Fig. 4(b)). Silicon oil PMS-5 (5 cSt at $T = 25°$) is used as working fluid. In all experiments, the depth of the fluid layer h was 30 mm and the surface of the fluid was open. The room temperature was kept constant by air-conditioning system, and cooling of the fluid was provided mainly by the heat exchange with surrounding air on the free surface and some heat losses through sidewalls. Details of experimental setup, structure and characteristics of the laboratory analog of tropical cyclone can be found in [3, 4]. The images for PIV processing were obtained with a 2D particle image velocimetry (PIV) system Polis and the software package Actual Flow.

Experiment with a feedback requires real-time data processing. Standard kit of Actual Flow software does not have such option. Also we need to note that PIV technique is resource demanding and even for measurements at relatively low frequency (0.5 Hz) computing resources of personal computer are not sufficient for real-time velocity reconstruction. In order to solve this problem we use supercomputer for PIV images processing. The variation of number of computational nodes allows to achieve necessary rate of image processing.

Actual Flow is a commercial software which does not have documented API for interaction with external systems and realization of required series of mea-

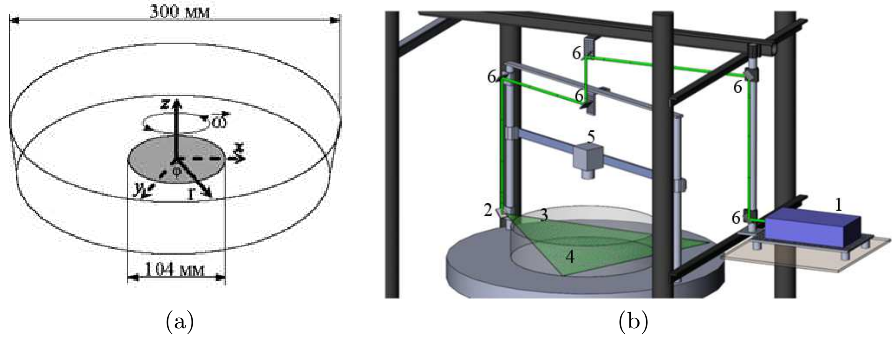


Fig. 4. Experimental model, dimensions and location of the coordinate system (a); experimental stand (b): 1 – dual pulsed laser for PIV, 2 – laser sheet system, 3 – laser sheet, 4 – tracers, 5 – CCD camera, 6 – mirrors.

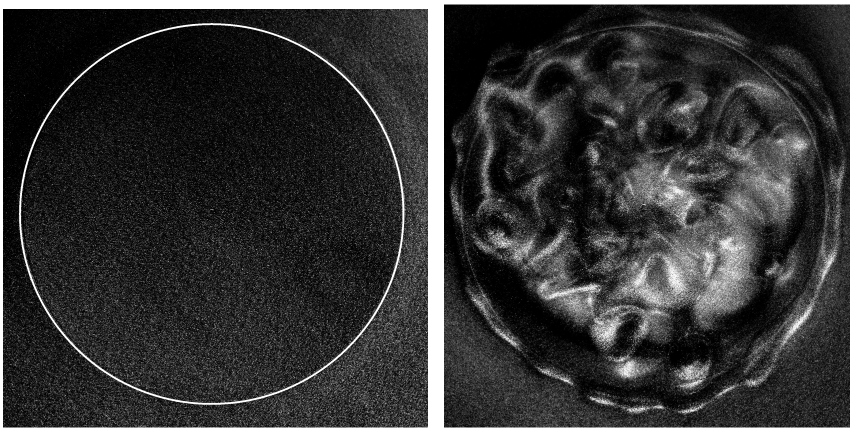
surements. For solution of this problem following procedure was used. During experiment Actual Flow saves for each measurement three files: two images and file with metadata in xml format. Developed data loader using WinAPI analyses catalog of Actual Flow data. For each new xml file availability of images is checked. When all three files are available they are packed and transferred to the data stream manager for sending to supercomputer for processing.

Test experiments The developed system for realization of experiments with feedback was checked on test experiments. The test experiment was done as follows.The experimental model was placed on a rotating stand. The solid-state rotation was achieved. It takes about 2 hours (for a period of rotation $T = 77\ s$). After that the measurement process was started using the PIV system “Polis”.

Simultaneously with a measurement process, for the organization of the initial radial flow, a constant power heating (about 30 % of the maximum) was switched on for 30 seconds. After initiation of radial motion the heating was switched to a feedback mode in which the heating power was proportional to the average radial motion velocity in the heating region. The area of measurements and the complex structure of forming convective flows after the switching on the heating is illustrated in Fig. 5.

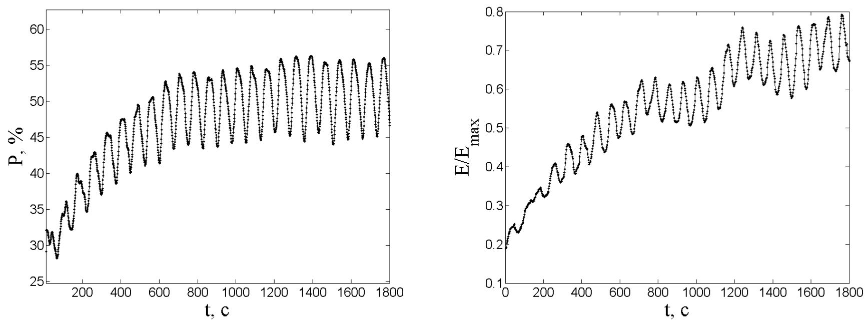
Fig. 6 shows the time dependences of the heating power (proportional to the mean radial velocity) and the kinetic energy of the cyclonic motion. It is clearly seen that for a given relationship between the power and the mean velocity of the radial flow, the transition to the quasi-stationary state occurs fairly quickly (in the time of 5-6 revolutions of the model). The characteristic oscillations of the mean velocity and kinetic energy are a feature of the convective vortex flows in the system under consideration.

Fig. 7 shows vector fields for the early and late stages of the vortex development. Test experiments showed the efficiency of the complex integration of measurement system, supercomputer and heating system. The next step will be



(a) (b)

Fig. 5. a – field of measurements, thick white line shows the heating area of diameter D = 104 mm; b – formation of convective structures after switching on the heating, vizualization by aluminum powder.



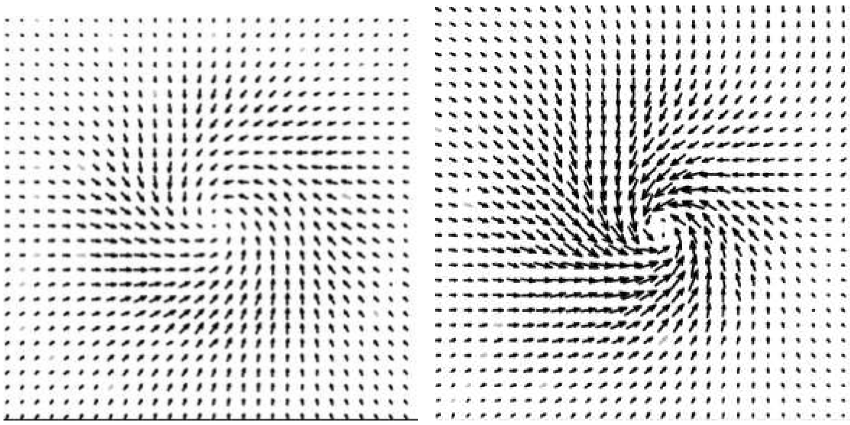
(a) (b)

Fig. 6. a – temporal variation of the heating power (percentage of the maximum value); b – temporal variation of the kinetic energy of azimuthal flow in the heating area.

a detailed study of the effect of functional dependencies between the heating intensity and the flow structure.

3.2 Application of recording and processing techniques of fast processes for icing research of structural aircraft elements

For another applied problem – modelling of icing processes it is also necessary to use real-time processing of PIV data. The formation of ice on the structural elements of aircraft in flight can lead to a significant deterioration of the aerodynamic characteristics and controllability of the aircraft, the failure of control



(a) (b)

Fig. 7. Vector velocity fileds, left – t=100 s, right – t=1500 s.

systems, as well as to the destruction of engine components, which is an actual problem of safety of flights. According to accident statistics ("Army AircraftIcing" data, 2002), between 1985 and 1999, 255 cases of aircraft icing occurred, of which 12% with victims, and total losses amounted to 28 million $.

According to the data of "Aircraft Owners and Pilot Association" (2007) – 202 cases of aircraft icing occurred between 1998 and 2007, of which 21% with victims. The urgency of the problem does not decrease at the present time. A recent example is the crash of the AN-148 aircraft due to icing on February 11, 2018. The complexity and, in particular, the interdisciplinary nature of the physical and mathematical modeling of gas-hydrodynamic processes and icing in flight conditions does not allow reliable prediction of possible dangerous and unacceptable operating modes of aircraft.

Investigation of icing processes is planned to be carried out in a small-size climatic wind tunnel (SSCWT) of a closed type (compressor power 0.3 MW) at the Perm National Research Polytechnic University (PNRPU) [13, 14]. SSCWT of a closed type will provide the possibility of carrying out physical experiments with the reproduction of flight icing conditions at subsonic Mach numbers and negative temperatures of breaking. A distinctive feature of this stand will be high energy efficiency, due to the closed isolated wind tunnel and the relatively small size of the working part. The closed working part of SSCWT will ensure a high degree of uniformity of the watered airflow and the possibility of a detailed study of the physical processes during icing in flight.

For the real-time measurements in fast processes it is planned to use phase doppler anemometry (PDA) (Fig. 8) and high-speed cameras or time-resolved PIV systems.

It is planned that experimental data will be transferred to the high-performance computer complex PNRPU [15] for processing – calculation of gas-

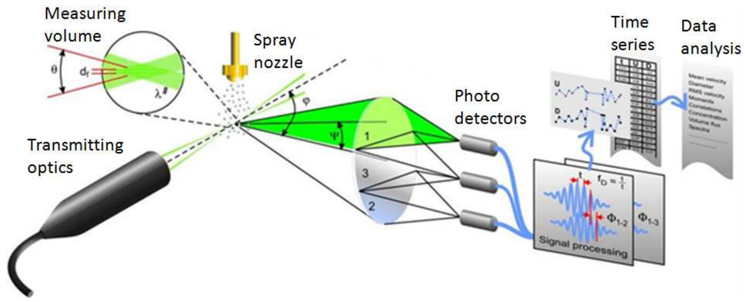


Fig. 8. Optical scheme for analysis of particle dynamics (Particle Dynamics Analysis).

dynamic flow parameters: velocity fields, temperatures and distributions of droplets, qualitative and quantitative parameters of icing. All data must be recorded simultaneously in several sections of SSCWT. Control parameters of experiments will be also recorded.

At the same time, physical experiments are planned to be conducted on reduced models. These results will be used for verification of numerical simulations. After that numerical simulations of full-size models will be carried out. For the verification, it is necessary to specify in detail the fields of distribution of gas-dynamic parameters, obtained from the results of the physical experiment, as boundary conditions for carrying out a numerical simulation.

The results of processing of the initial data obtained in real time are planned to be used to refine the course of the experiments, as well as for the parallel execution of the full-scale and computational experiment, where the results of the full-scale experiment are used in the computational experiment.

4 Conclusion

Developed system for real-time experimental data processing is described. The key feature of this system is using supercomputer for computationally intensive processing. The possibility of the transfer of complex calculations from the main experimental computer to the external computing system (supercomputer) is demonstrated.The description of the modular application for writing algorithms for the supercomputer processing is given.The algorithm for processing of PIV measurements using supercomputer is described.The developed system for realization of studies with feedback was checked on test experiments that showed the efficiency of the complex integration of measurement system, supercomputer and heating system. The next step will be a detailed study of the effect of functional dependencies between the heating intensity and the flow structure. The system is ready to use high-speed cameras for obtaining PIV images. Development of adaptive PIV algorithms, taking into account the dynamics of the the investigated flow is planned. Supercomputer processing can be used for the studying of icing of aircraft elements in a wind tunnel.

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