Designing Custom-made Power PC for High-tech Scientific Experimentation

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***Abstract*— A critical assessment is performed on the results of developing a custom-made laboratory dedicated PC with enhanced efficiency and extended functional capabilities (*Power PC*) aiming at to develop a high-precision scientific experimentation platform with considerable calculation power. Main goal of the research reported in this article concerns the development of a functionally fitted computerized test platform for supporting hi-tech experimental investigations on theoretically derived system phenomena regarded to a particular class of vaguely examined control systems: V-interconnected MIMO plants. By ensuring easy technical modifiability, the constructed experimental test bench is able to reproduce various hydraulic schemes with reverse cross interactions. This feature may guarantee large options for changing the intrinsic plant properties and causing *fundamental shifts* in plant behaviour. The process experimentation and computerized investigations on the physical rig are planned to be performed via the custom-assembled *Power PC* provided with improved performance. Hardware resource evaluation on the necessary characteristics/properties of the *Power PC* and subsequent vigorous *Benchmark* testing to produce relevant results from the computer examinations are performed and critically analysed in the light of the technical goals and computational efficiency achieved. The available multi-threading CPU topology is concerned at main importance to the computational abilities of the tested PC. The hardware platform of the data acquisition system enclosed, the whole set of special algorithmization functions and process GUI are grounded on the implementation of embedded *DS1104* development controller set (*dSPACE GmbH*) for *Rapid Control Prototyping* (*RCP*). The application software for ensuring most of the theoretical tasks is developed via the *Matlab-Simulink* Software Suite from *Mathworks Inc*.**

Keywords*— Hydraulic plants; MIMO systems; V-interconnections; Research test bench; Real-time PC hardware; Embedded DSP, Development controller

I. Introduction

This article describes the initial stage of a theoretical research, devoted to developing an experimental test framework for control system investigations on hydraulic processes. It is the start of a research scientific project on MIMO control systems having V-type cross-interconnections in plant structure. The hydraulic process itself is selected presumably for its clear physical interpretation of the V-interactions in the MIMO framework.

The initial task of this development includes design and assembling of a small-scale multi-body hydraulic plant (Fig. 1) consisting of two or three intercoupled water tanks and furnished with excess of measuring devices. By introducing suitable constructive and functional flexibilities in the experimental rig, fundamental shifts of system behaviour via structural and operational modifications are aimed to be achieved.

The scientific goals of this research concern examining definite basic system properties of MIMO interconnected plants with cross V-interactions due to varying constructive and operational conditions. By the help of the test rig, experimental investigations on the theoretically derived system phenomena (e.g. fundamental property shifts) and feature changes in characteristics of the hydraulic plants possessing V-type interconnectivity [4] are planned to be accomplished aiming at to improve and extend the available results.

For the particular research goals, a precise real-time data acquisition system to the running hydraulic processes that is based on the *DS1104* DSP development controller is also devised. It is housed in a dedicated desktop PC having improved functionality and regarded as reinforced type *Power PC* [10]. In this research article, the intrinsic hardware specifications, necessary properties and test results from trial runs of the implemented *Power PC* are closely exhibited and discussed in detail. Afterwards, the resulted performance and attained calculation efficiency are analysed and evaluated.

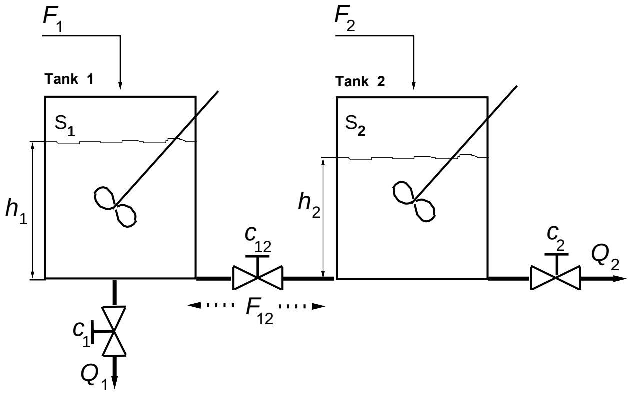

Fig. 1. *General scheme of coupled two-tank hydraulic unit.*

The task needs for analysing and predicting unknown process properties and performances evidently imposes derivation and use of rigorous models having both physical and abstract mathematical substance. By coupling the test models with the digital development system, one will ensure experimental research platform for powerful scientific investigations. Furthermore, the implemented technical facility must guarantee utilities and options for inquiring the examined system behaviours by obtaining precise process observations via digital data acquisition from considerably fast process phenomena. *On-line* functionality for comparing simulated model results with live process data and consecutive invention of control algorithms to an arbitrary sophistication level is also available. Both classical theoretic control methods and abstract intelligent approaches are included as options for generating process control algorithms over the full range of examined phenomena.

A. *Applied and theoretical developments*

Early research works concerning system theoretical properties of the special class MIMO plants with V-cross interconnections were first reported in [2]. To validate these results and eventually further deepen the fundamental knowledge by discovering some reasoning relations about all known theoretical issues, high-fidelity live experiments on a physical model rig are necessary to be initially performed. The examination trials encompass series of laboratory tests, aiming at to analyse some theoretical properties on a multi-body hydraulic plant (Fig. 1) from a control point of view [5].

The research methodology, envisaged to be implemented in the investigations, may be generalized with several sequential steps:

- Constructing hi-tech hydraulic test platform;

- Purposeful experimentations via the physical test rig;

- Building mathematical models with improved fidelity;

- Analytical and simulated model investigations;

- Deriving and specifying system properties and features regarding the MIMO V-plants interconnectivity;

- Obtain efficient hybrid control algorithms with special properties.

The proposed research sequence combines system-theoretic backgrounds with novel analytical results and vigorous mathematical modelling on the hydraulic phenomena aiming at explanation the intrinsic process nature of the unknown properties.

Preceding the model investigations, technical development and constructing a *test unit* composed of several interconnected vessels, guaranteeing flexible background for experimentation on hydraulic effects with *reverse cross interactions* under varying operational modes is to be achieved. The laboratory rig is provided with precise measuring equipment, control armature, and suitable technical resources to ease the structural modifications and operating changeability of the hydraulic plant for getting possible the observation of functional shifts in fundamental control properties. Furthermore, the constructed test bench will ensure a framework for experimental investigations on the V-interconnection influences via variability analysis.

The research experimentations via the pilot rig and all data obtained about the phenomena will serve for evolving precise mathematical models of the process behaviour, as well for specifying novel theoretical results via improvements in description and comparative analysis using live measurements from the physical plant. These models will be further implemented for developing argued hypotheses about the unknown phenomena, as they are recognized from the systematized process data. For deriving new efficient control algorithms, able to cope with both the observed effects and the non-explained phenomena, model heterogeneity and hybrid control approaches are envisaged.

Simulation modelling as main research technique in the present development, will be applied both for derivation of results and for check of physical models. The refinement and improvement of the models will take place in the DSP development environment of *DS1104* (*dSPACE GmbH*) via implementing *Rapid Control Prototyping* (*RCP*) technique and real-time simulation procedures [10] under *MATLAB* (*Mathworks Inc.*) control software. On the stage of inventing suitable control algorithms, simulation modeling will consolidate different theoretical concepts and approaches for creating relevant hybrid control algorithms, that are built up by principally heterogeneous mathematical components and functional properties.

By implementing the experimental rig, the following theoretical tasks to the project development are set:

- Examining and establishing the intrinsic nature of V-cross connections phenomena in MIMO systems on the pilot hydraulic plant.

- Deriving quantitative relations and mathematical models for characterizing the examined hydraulic system.
- Combined model/experimentation check-up of preformulated theoretical results concerning shifts in fundamental properties of V-interconnected MIMO systems.
- Generalization of the experimental results for V-interconnectivity using live data from the test rig.
- Developing precise workable mathematical models of the experimental V-interconnected hydraulic plant and performing validation test about model reliability in a large operating area.
- Inventing and proposing new schemes, principles and approaches for control of V-interconnected MIMO plants under possible fundamental property shifts.

B. Experimental and research stages

On the initial project stage, constructive development of a pilot physical plant model as a multi-body hydraulic unit with full-scale technical options for changing properties is provided. The test-bench measuring system includes on-line process data acquisition and digital data processing by implementing specialized software for analysis and examinations. All investigations are performed on the hydraulic test rig (Fig. 1) in series of physical experiments under varying operating conditions.

In theoretical and didactic references, coupled hydraulic tanks implemented as laboratory-scale pilot rigs for analytical examples or experimental testbench demonstrations are favorite choice of an illustrative plant in many investigation studies and educational tools. Diverse connection schemes, different number of tanks and spatially distributed vessels are often observed in the multiformity of scientific and technical notes on the topic.

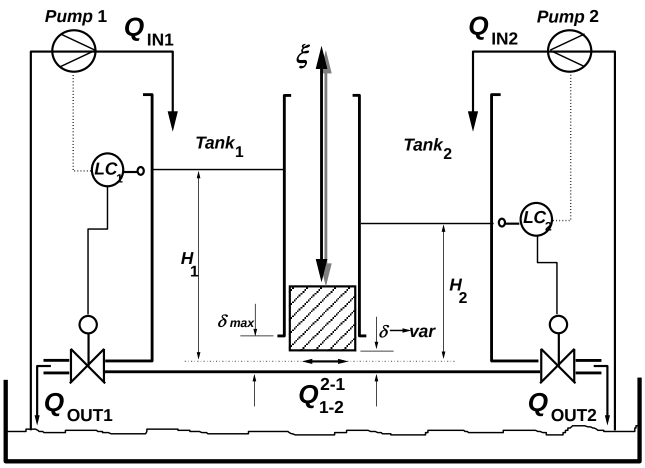

Fig. 2. *Two hydraulic tanks coupled by movable plate.*

Various technical schemes of multivessel hydraulic plants with interactions have been demonstrated in numerous scientific and didactic references up to this time. A comprehensive examination shows that the general distinction consists in the interconnection mechanisms [7, 8, 18] between vessels.

One constructive solution for introducing vigorous interconnections between tanks in a hydraulic multi-body unit consists of a shared movable partition plate, that slips tightly up and down (Fig. 2) between the adjacent chambers of the vessels [8], so ensuring alternate cross-sectional area of the passage entry and a range of flow rates. Technically said, this construction is a very original one and it can pass large throughputs of liquid flow interchange between the vessels, though with smooth characteristics, but it doesn't allow for easy and precise measurement of the flow transfers between the vessels.

The standard technical solutions for coupling between hydraulic vessels in a multi-body plant (Fig. 1) utilize plain piping connections [6, 7, 12, 18], thus ensuring hard hydrostatic interactions. In such manifold systems, the measurements of flow rate are easy technical task and different sensor types are applicable. Here, the simplest variant uses constant-sized plumbing connections without any technical facilities for reducing the pipe flow [18]. Evidently, such compound scheme ensures very limited parameter variations. The latter would possibly be caused only by the varying load changes to the plant (e.g. the input flows). So, under these circumstances, the system properties are almost hardly assigned by the preset constructive characteristics. Options for "fundamental system shifts" are slightly possible and very difficult to be achieved.

A more versatile technical solution regarding the fundamental hydraulic variations that is able easily to cause system property shifts, demands optional changes to the interconnection flows between tanks. Such type of flexible construction is explored, for instance, in [6, 7]. In tandem with admissible load changes, the static flexibility of the hydraulic multi-body plant increases drastically and system property shifts easily arouse.

Other forms of interconnections between hydraulic vessels also do exist. They differ from the previous cases generally by the spatial arrangement between tanks [12, 17], the existence of mixed hydrostatic and/or forced inter-tank flows between vessels [11, 17], etc. These constructions, however, don't perform clear system-oriented representation of V-interconnections. So, by these reasons they are omitted of consideration.

At the second stage of the research project, a set of hybrid analytical/experimental models with improved sophistication and fidelity of the hydraulic processes should be obtained. Validation and verification checks of the invented models will be performed by utilizing real-time data from the process test bench via *RCP* and *HIL* (*Hardware in the Loop*) simulation techniques performed on the development controller *DS1104* from the *dSPACE GmbH* series.

At the final research stage, inventing, devising and direct implementation of promising control approaches, as well as user-defined *Ad hoc* algorithms with hybrid structures are planned to be performed. The latter group encompasses modern solutions in design of MIMO control systems with powerful non-classical approaches for model descript-tion, which as a result would achieve improved control efficiency (e.g. large-range robustness, arbitrary high performance, relative unification of results and application independence), that is guaranteed via intelligent approaches for description and control design in various forms. The implemented technical solution at this final stage is regarded to as *HIL in the closed loop* experimentation for fast prototyping of control systems. It is also based on the special embedded options of the *DS1104* controller unit.

At all research stages, the functional run of the development hardware is ensured by the software support of *Matlab-Simulink* (*Rel.* 2018) selection of packs, from *The Mathworks* Co. All calculation issues are organized by implementing the custom-assembled *Power PC*.

C. Research equipment

The research test bed, intended to be used for project experimentation, is grounded on a flowing-type multibody hydraulic rig, composed of interconnected water tanks having independent input flows and effluents, and equipped by sufficient number of measuring and control devices to obtain precise parameter values. Relevant process configuration and extra facilities for functional and constructive variability are also provided.

For fulfillment the project goals, a flexible digital development system, based on the *DS1104* DSP controller from *dSPACE GmbH* for both measurement and control functions is provided to supply precise process data. The system contains real-time options for extended functionality during execution of standard and user-defined control tasks in the *MATLAB-Simulink* software environment. In tandem with the *ACE1104PCIE Research Kit* software pack, the system ensures also an extended set of application software (algorithms for data processing, analysis and visualization, GUI utilities, etc.) for encompassing large scope of scientific and research tasks.

The specialized instrumentation set for continuous measurement of functional variables from the hydraulic process (liquid levels, flow rates to and from the component tanks, reversible cross-flow rates, pressure) is characterizing by high precision and fidelity. The controlled devices and fluid-related armature are mounted in-situ and distant human-operated interface via the digital system is provided.

The auxiliary set of technical instrumentation to the experimental rig encompasses vessels, water pumps (for both control and circulation), electrical control valves, stop armature, cross sectional limiters, electrical supply modules and compound fittings that finalize the list of the equipment.

II. *POWER PC* TECHNICAL SPECIFICATIONS

For successful operation of the experimental test bench along with the digital research system, a powerful personal computer (*Power PC*) with improved characteristics (computing speed, memory volumes, available interfaces, card slot selection, cooling potential, etc.) should be provided. Evaluation of the necessary computer resources and functionalities, however, could be devised only after clearing the required options and capabilities that an experiment-dedicated *Power PC* should possess. As a consequence, the technical PC specifications could then be substantially evaluated.

A. Critical Review on the available PC market

According to the often contradictory and multidirectional targets, consisting in general of pursuing acceptable compromise between “price-calculation efficiency” vs. “high-tech quality & operational reliability”, the available on market ready-to-use PC machines[1] should be appreciated after thorough assessment as a rather unsatisfactory choice. No matter if the issues of examination are arbitrary trade companies or specified market prices quoted, the available whole-at-one PC products demonstrate some evident shortcomings: weaker calculation power provided, somewhat lower level of technical innovativeness incorporated and slightly outdated conceptual solutions at the main building elements in comparison to the hardware components, proposed on the actual hi-tech computer market. So, an inference is immediately imposing, that a needy client, who must follow very demanding requirements, would obtain a computing device with high-level characteristics only if he assembles it by using selected components with satisfactory specifications.

B. Planning system functionality of the Power PC

The first significant consideration, necessary to conform about a control-dedicated PC architecture concerns the necessity of several differing by their physical entity memory storage devices. Choosing a fast SSD memory unit is a valuable solution, of course, but the available capacity and reliability of hard disk storage devices (HDD) have yet unbeaten indicators. One must not also forget the need of mobile data storage units like the CD/DVD optical drive and the mass storages on flash memory. Ensuring efficient memory facilities for processing and storing large-scale bulk volumes of fast-varying On-line data is a substantial, though not crucial property. Nevertheless, this problem concerns directly the available SSD characteristics.

For scientific computational tasks, however, the general calculation speed and flexibility have ever predominant importance. These features are mainly bound to the CPU specifications regarding its nominal working frequency, cash memory available and the option for providing steadily *overclocking* operations.

[1] The computer market in Bulgaria at present time

The notion of speed is regarded also on the required SSD properties, formulated as the *necessary run-time for a call-up*. Similarly, the RAM memory chips installed demonstrate their speed abilities via the necessary *Call time* and *Reply time* for contacting to/from the main memory.

Surprisingly, the *communication exchange speed* between the data storage unit and the processor may aggravate considerably the overall system performance of seemingly exceptional and powerful computer configurations, due to its strong influence on the system bus characteristics. For this reason, similar hardware-dependent shortcomings must be eliminated either by using sufficiently fast SSD storage device for dealing with time-critical operations and calculations, and/or by implementing suitable motherboard architecture with superior data-exchange speed features throughout the system bus. Evidently, having both simultaneously is the best solution. As a consequence, the applied hardware and software organization principles appear to be very critical to overall computer performance and general behaviour.

Due to the specified application requirements imposed, the visualization facilities of the computer configuration should belong to one of high-class devices. The overall performance of the video-card depends strongly on the embedded processor's speed, available video memory, the word length of communication data bus, pixel resolution, efficient cooling facilities, etc.

The option to adopt embedded add-ups in the form of autonomous third-party digital systems stays mandatory for enlarging the standard PC configuration with both additional devices and special functional options. In this light, the availability of suitable interface for the *DS1104* development DSP controller is indispensable feature.

The ability for safely undergo massive sudden increases in power consumption and afterwards, efficiently taking away the excessive thermal radiation from the interior computer housing to the environment outside is deadly important for hybrid digital computing devices with lot of processors available. So, possible cooling extension options and versatile monitoring facilities are useful to be "at hand".

The analysis of necessary properties and available ready-make machines on the computers market forces the project staff to take the substantiated general decision for assembling a unique custom-made *Power PC* machine with improved operational characteristics of the selected components.

C. Technical requirements and necessary functional characteristics to the Power PC

Most severe regulations are imposed by the embedded development controller of *dSPACE* [14] as a hardware add-up to the *Power PC*. The requirements consist of two main demand groups:

- Necessary properties of the technical framework to mounting the process controller;

- Software compatibility, calculation abilities and miscellaneous supporting functions.

1) Hardware requirements

A x64-based personal computer as host PC or *Embedded PC* 3rd generation with Intel® Core TM i7-3517UE is necessary as Host Processor. All *dSPACE* software products require at least an *Intel Core 2 Duo* processor at 2 *GHz* (or equivalent). *Intel Core i7* or equivalent is recommended for desktop PCs.

All *dSPACE* software products require at least 8 *GB* RAM (recommended 16 *GB* RAM or more).

About the necessary disk space for a complete installation from the DVD set, up to 22 *GB* free hard disk space on the program partition (plus up to 10 *GB* at the system partition for runtime software like the Microsoft.NET Framework) are to be ensured. Additional disk space is necessary for the third-party software (***The MathWorks*** packs, etc.). At least one DVD drive is required for the initial *dSPACE* software installation.

The hardware mounting of *DS1104* card must precede without fail the installation of all necessary application software (the *dSPACE* software suite and third-party add-ons (*MATLAB-Simulink* package)).

Hardware connectivity to basic *dSPACE* Software Applications

ConfigurationDesk Utility (Configuration Version)

For communication with *RapidPro* hardware: USB port Ver. 1.1 (complying with USB 2.0).

TargetLink Test Suite

Processor-in-the-loop (*PIL*) simulation: serial port (*RS232*) or free *USB* port (depending on board type).

Necessary 9600 *bps* to connect *dSPACE* Simulator's *Failure Insertion Unit* (*FIU*) of the *PHS* bus-based *HIL* systems.

Requirements for the Graphics Adapter & Display

- Standard graphics adapter to work with the *dSPACE* products: min resolution of 1024x768 *pixel*.

For the *ConfigurationDesk* (Implementation version): Standard resolution of 1280x800 *pixel*.

- Special *Windows-display-property* settings for *ContolDesk*, *MotionDesk*, *ModelDesk*, *Model Interface Package* for *Simulink* and *RTI blocksets*.
For *Windows 10*: The *Windows* display scaling level ("Custom sizing options") set at 100 % (default setting). Other settings are not supported.

2) Software system requirements

Third-party software: *MATLAB®* needs an *OpenGL*-compliant graphics adapter (16, 24, or 32-*bit*), or Standard graphics adapter with 1024x768 *pixel* resolution (minimum)

For 3-D Graphics: Graphics card supporting at least *Microsoft DirectX 9*.

License Handling: A free USB port available.

Special Interface Slots: One slot *PCIe* Type.

Operating System type on Host PC: Only 64-*bit* operating systems are admissible.

- *Windows 7* (64-*bit* version) with Service Pack 1, *Professional*. *Ultimate*, and *Enterprise* also supported.

- *Windows 10 Professional*: Appropriate OS version.

III. RESEARCH PROBLEM STATEMENT

Here the theoretical backgrounds inspiring the investigations on MIMO V-plants are briefly discussed. The initial analytical results revealed unknown novelties about system behaviour of a class of MIMO processes. Afterwards, the abstract theoretical finds were broadened to necessity of real process experimentation, and then the technical need of high-performance computational facility with extended features emerged.

A. Theoretical grounds on V-interacted systems

The investigations on multivariable interconnected systems and the proper methods for their control have been started long ago [1, 3, 13, 15], but new discoveries and engineering results are still emerging [2, 4, 17]. The reason of this ceaseless interest lays in the strong importance and vast outspreading of the MIMO phenomenon, yet existing theoretical gaps in the area and the needs for improved modern solutions to industry. Under systematic investigation on control plant properties both in process technology and in technical industry, one can discover that the interconnected multivariable nature is spread around practically everywhere. Due to the stringent technical requirements to process control in view of this overwhelming MIMO phenomenon, systematic counteraction via novel theories and applied methods have been already created, but others are still under development and invention even nowadays as, for instance, new model representations and hybrid theoretical solutions.

1) Intelligible statement to MIMO canonical forms

Early investigations on interconnected MIMO systems have been limited only to analysis of their structural properties. *Mesarović* [19] introduces the notion of *canonical structures* in MIMO system theory, confining to only two basic mechanisms of intercon-necttion: the one of *P*- or the other with *V*-type interac-tions [1, 3, 6, 13, 15, 20]. Newer investigations [4] show, however, that various structural mixes are also theoretically feasible and do really exist in practice. In the establishing monographs on the topic, however, only fragmented inclines about optional MIMO-structural mixes are discussed, though not supported with theoretical backgrounds and live examples.

In [20], the input-output properties of (2x2) P-interconnected systems are predominantly discussed and only partial results about the systems possessing V-structure are shown. The issues about V-canonical structures are only confined to demonstrate the transformation into P-form feasible, and this way formal P-V equivalence is inferred and even adopted. However, these results are not supported by strict analysis and in-debt examinations. Going this way, new investigations [4] have approved, that principal distinctions between the properties of basic MIMO structures do exist. So, it becomes unreliable to treat just formally both MIMO system behaviours via a uniform theoretic structural representation and neglect the existed natural multiformity.

2) MIMO interconnected V-canonical plants

The interconnected MIMO plants, possessing V-canonical interaction structure (Fig. 3, 4), are characterizing by cross dynamic channels in a direction, reverse to one of the causal input-output relationships [13]:

$$y_i(s)=G_{ii}(s)\left[u_i(s)+\sum_{\substack{j=1\\ j\neq i}}^{n}G_{ij}(s)y_j(s)\right],\quad i=1,2,\ldots,n \qquad (1)$$

By representing model (1) in a vector-matrix form, one obtains (2) after implementing $\mathbf{G_d}(s)=diag[G_{ii}(s)]$:

$$\mathbf{F}(s)\mathbf{y}(s)=\mathbf{u}(s)\Leftrightarrow\mathbf{y}(s)=\mathbf{W}(s)\mathbf{u}(s),$$
$$\mathbf{W}(s)=\mathbf{F}^{-1}(s)=\left[\mathbf{I}-\mathbf{G_d}(s)\mathbf{G_k}(s)\right]^{-1}\mathbf{G_d}(s) \qquad (2)$$

Here,

$$\mathbf{G_k}(s)=\begin{bmatrix}0 & G_{12}(s) & \cdots & G_{1n}(s)\\ G_{21}(s) & 0 & \cdots & G_{2n}(s)\\ . & . & \cdots & .\\ G_{n1}(s) & G_{n2}(s) & \cdots & 0\end{bmatrix}$$

$$\mathbf{F}(s)=\begin{bmatrix}\frac{1}{G_{11}(s)} & -G_{12}(s) & \cdots & -G_{1n}(s)\\ -G_{21}(s) & \frac{1}{G_{22}(s)} & \cdots & -G_{2n}(s)\\ . & . & \cdots & .\\ -G_{n1}(s) & -G_{n2}(s) & \cdots & \frac{1}{G_{nn}(s)}\end{bmatrix} \qquad (3)$$

The mathematical assumption for a V-model to be transformed into P-form is specified as $\det\left[\mathbf{I}-\mathbf{G_d}(s)\mathbf{G_k}(s)\right]\neq 0$, and matrix $\mathbf{F}(s)$ be square.

The matrix transfer function $\mathbf{F}_{2x2}(s)$ of a general (2x2) V-interconnected plant follows directly from (3) after substituting n=2. Its inverse matrix $\mathbf{W}^{V}_{2x2}(s)=[\mathbf{F}_{2x2}(s)]^{-1}$ takes important role to the investigations on V-systems. One can take it according to (2) after respective transformation in an input-output P-form [4]:

$$\mathbf{W}^{\mathrm{V}}_{\mathbf{2x2}}(s)=\frac{1}{\Delta_V(s)}\begin{bmatrix} G_{11}(s) & G_{11}G_{12}G_{22}(s) \\ G_{11}G_{21}G_{22}(s) & G_{22}(s)\end{bmatrix}= \\ =\frac{1}{1-\chi_V(s)}\left[\mathbf{I}+\mathbf{G_d}(s)\mathbf{G_k}(s)\right]\mathbf{G_d}(s) \qquad (4)$$

where

$$\Delta_V(s)=1-\chi_V(s),\ \chi_V(s)=G_{11}(s)G_{22}(s)G_{12}(s)G_{21}(s) \quad (5)$$

The term $\chi_V(s)$ is denoted as the *Dynamic Interaction Coefficient* of a TITO V-canonical system and serves as particular measure for the strength of the cross interactions between channels. It shows the main difference between the V- and P-interconnected TITO structures, that is evident by comparison to the respective interaction coefficient $\chi_P(s)$ of a TITO P-structures: $\chi_P(s)=G_{12}(s)G_{21}(s)[G_{11}(s)G_{22}(s)]^{-1}$.

If a general TITO V-plant is transformed into P-form via the matrix $\mathbf{W}^{\mathbf{V}}_{\mathbf{2x2}}(s)$ according to (4), it could be represented by the equivalent block diagram shown on Fig. 4, where the following system of equations is valid for the plant outputs:

$$y_i(s)=\frac{G_{ii}(s)}{1-\chi_V(s)}u_i(s)+\frac{G_{ii}(s)G_{ij}(s)G_{jj}(s)}{1-\chi_V(s)}u_j(s),\ i\neq j=1,2 \qquad (6)$$

Supposing self-control to all dynamic channels, the asymptotic properties ($t\to\infty$) of the process outputs (6) under effects of $u_1=u_2=1(t)$ or $u_1=1(t)$, $u_2=0$, are obtained as follows, though always $y_1(\infty)\neq y_2(\infty)$:

$$y_i(\infty)=k_{ii}\left.\frac{1+k_{ij}k_{jj}}{1-\chi_V(0)}\right|_{u_i=1(t)},\ i\neq j=1,2 \qquad (7)$$

or $y_1(\infty)=\left.\dfrac{k_{11}}{1-\chi_V(0)}\right|_{\substack{u_1=1(t)\\u_2=0}},\ y_2(\infty)=\left.\dfrac{k_{11}k_{21}k_{22}}{1-\chi_V(0)}\right|_{\substack{u_1=1(t)\\u_2=0}}$

Here, by $\chi_V(0)=k_{11}k_{12}k_{21}k_{22}$, the *Static Interaction Co-efficient* of a TITO V-interconnected plant is denoted.

By applying (7) when $\chi_V^*(0)=k_{11}^*k_{12}^*k_{21}^*k_{22}^*\equiv 1$ is reached to get the theoretical limit values of the outputs, a curious special property of TITO V-interconnected plants is inferred [4], taking effect for arbitrary combinations of feasible gain values k^*_{ij} in the component plant models $G_{ij}(s)$. Evidently, if $\chi_V(0)\geq 1$, unconstrained velocity increase of the TITO V-plant outputs is observing, no matter if all dynamic channels $G_{ij}(s)$ reach separately self-control. At that, if $\chi^*_V(0)=1$, then the plant will demonstrate unlimited behaviour of a system having a pole at $s=0$, which output increases infinitely with constant velocity, i.e. astatic properties observed. And if $\chi_V(0)>1$, following the *Small Gain Theorem*, the plant transients will rise unsteady. This theoretical phenomenon shows the existence of an intrinsic special feature in V-interconnected plants about the possibility to behave with permanent (and probably abrupt) shifting their fundamental stability properties, depending solely by the particular combinations between the current constructive plant parameters and the changeable load factors of the process itself. This special parametric property of the V-interconnected plants stipulates for the anticipating odd appearances of structural instability, at that to all system outputs simultaneously [4].

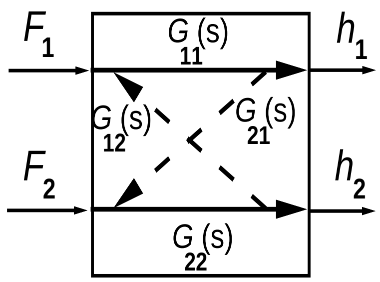

Fig. 3. *Structural I-O diagram of TITO V-plant (tank levels h_i are the outputs).*

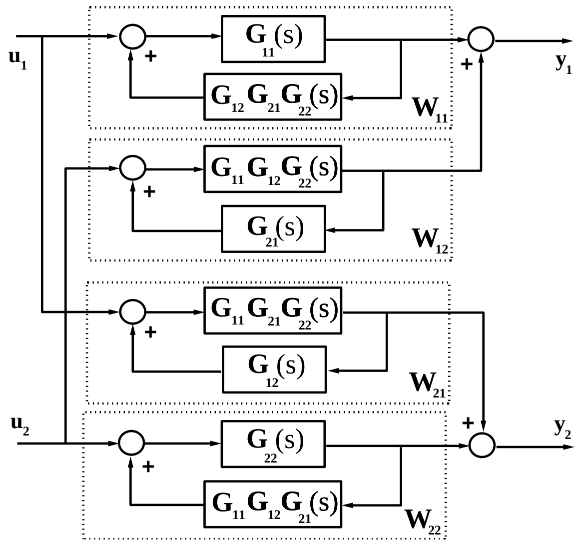

Fig. 4. *(2x2) V-plant representation via P-matrix* $\mathbf{W}^{\mathbf{V}}_{\mathbf{2x2}}(s)$.

Qualitative suggestions about possible hidden instability in MIMO systems with reversed cross interconnections are yet reported [1], but they are not referred explicitly to intrinsic V-structure of the process. Instead, MIMO V-canonical model representation is considered just as a formal option contrasting to the more convenient alternative P-form. Similar hints are also reported in [9] by utilizing the notion of "*internal loop*", for all that considering it able to call forth system instability if realized in a positive feedback form, but this assumption is also not precise. Vice-versa the previous references, yet *Krasovskii* [3] claims a qualitative suggestion, that if a single negative feedback in the MIMO system do exists (i.e. V-type cross element from y_i to u_j with negative gain) then the interconnected V-system will always preserve stability. Evidently, this condition follows directly by (5)÷(7), but it is not also a unique one. A stronger generalization holds after combining the existing facts by developed new results in the following theorem [4]:

Theorem 1. Given a general (2x2) V-interconnected system (plant), consisting of dynamic elements, that are represented by strictly proper transfer functions. The necessary and sufficient condition for the open-loop MIMO V-system (plant) be generally stable under $u_i=1(t)$ is if any of the following two pre-requisites holds:

(i) $|\chi_V(0)| < 1$, or (ii) $\text{sign}\{\chi_V(0)\} = -1$, if $|\chi_V(0)|>1$.

If one applies the math definition for obtaining the characteristic polynomial of a general MIMO system in matrix transfer function form [13] to the P-matrix $\mathbf{W}^V(s)$ of a (2x2) V-interconnected MIMO plant (4), then the polynomial $H^V_{2x2}(s)$ directly follows and afterwards, the characteristic equation $H^V_{2x2}(s)=0$ can be obtained:

$$H^V_{2x2}(s) = Den\{\det[\mathbf{W}^V_{2x2}(s)]\} = 1-\chi_V(s) \Rightarrow \Rightarrow H^V_{2x2}(s) = 1-\prod_{\substack{i=1\\j=1}}^{2} G_{ij}(s) = 0 \quad (8)$$

By assuming self-control to all dynamic channels, the $H^V_{2x2}(s)$ could be written in an explicit form:

$$H^V_{2x2}(s) = 1-\prod_{\substack{i=1\\j=1}}^{2} N_{ij}(s)\left[\prod_{\substack{i=1\\j=1}}^{2} D_{ij}(s)\right]^{-1}$$

and afterwards

$$H^V_{2x2}(s) = \prod_{\substack{i=1\\j=1}}^{2} D_{ij}(s) - \prod_{\substack{j=1\\j=1}}^{2} N_{ij}(s) = 0 \quad (9)$$

By comparing (9) to the characteristic equation of a general (2x2) *P*-interconnected plant, obtained via

$$H^P_{2x2}(s) = \prod_{i,j=1}^{2} N_{ii}(s)\prod_{i,j=1}^{2} D_{ij}(s) - \prod_{i,j=1}^{2} N_{ij}(s)\prod_{i,j=1}^{2} D_{ii}(s) = 0$$

followed from $H^P_{2x2}(s)=1-\chi_P(s)$, a substantial distinction is immediately observing due to the different expressions for $\chi_P(s)$ and $\chi_V(s)$, regardless the similar general forms of both characteristic polynomials. Something more, (9) shows, that the theoretical backgrounds about MIMO P-systems are no longer valid for the case of V-interconnectivity.

For a V-interconnected plant possessing strict properness to all dynamic channels, following from (9), the characteristic equation will get a particular form:

$$H^V_{2x2}(s) = \prod_{\substack{i=1\\j=1}}^{n} (T_{ij}s+1) - \prod_{\substack{i=1\\j=1}}^{n} k_{ij} = 0, \quad (10)$$

whence the important issue follows, that the poles of a V-plant are distinguishing principally from those ones of a MIMO plant composed by the same transfer functions and having P-interconnected internal structure. Moreover, the V-plant poles don't coincide under general circumstances with no one of the separate poles (possibly stable) from the component transfer functions $G_{ij}(s)$, $i,j=1,\dots,n$. Furthermore, for V-interconnected MIMO plants, stability can't be guaranteed only by the separate poles of the component transfer elements $G_{ij}(s)$, due to the non-trivial inclusion of the numerator polynomials $\prod_{i,j=1}^{2} N_{ij}(s)$ in $H^V_{2x2}(s)$, leading to deviations from the (supposing steady) local specifications in $\prod_{i,j=1}^{2} D_{ij}(s)$ of the resulting V-system poles.

In the special case, when $\chi_V{}^*(0)=1$ it follows, that both V-system outputs will demonstrate purely astatic properties and even small deviations in plant gains k_{ij} will be able to produce instability at $\chi_V(0)>1$ to all system outputs y_i. That's why, the notion of *Critical Interaction Gain* $\chi_V{}^*(0)$ is introduced [4] to measure quantitatively the vicinity of a MIMO V-system to the state of singularity at $\chi^*_V(0)=1$. It is evident, that $\chi_V(0)$ index depends solely on the V-plant static properties through all dynamic channels and is formally specified by the numerator polynomials of $G_{ij}(s)$ at $s=0$.

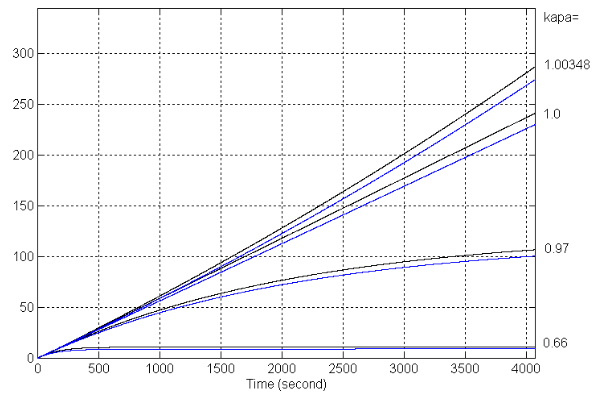

Fig. 5. *Time responses of a TITO V-interconnected plant for varying values of $\chi_V(0)$.*

As an illustrative example, let suppose that a TITO V-plant (Fig. 3) with strictly proper components $G_{ij}(s)$ that are giving result for $\chi_V(0)=0.97$, is described via (10) by the following characteristic polynomial:

$$H^V_{2x2}(s) = (6.5s+1)(5.0s+1)(7.5s+1)(8.0s+1) - -(1.5)(0.7)(0.44)(2.1) \quad (11)$$

By examining the output transients of the V-plant on Fig. 5, one might consider the very sluggish time behaviour (~$5\text{x}10^3$ *sec* comparing to ~150 *sec* for the separate channel responses) performed from the outputs and the large final values ($y_1(\infty)=124.3$, $y_2(\infty)=116.9$), comparing to k_{ij}~1.5 to 2.1. These properties are somewhat expectable, however. They evidently follow directly from the system poles disposal at (-0.305; -0.152±j0.1465; -0.0011), with one lying almost at the origin. This fact conforms to MIMO V-stability measure, calculated at $\chi_V(0)=0.97$, that is too near the critical value of $\chi^*_V(0)=1$. In case just a single plant gain slightly decreases, e.g. $k_{21}=0.44$ to $k_{21}=0.3$, then the *Static Interaction Coefficient* becomes $\chi_V(0)=0.66$ and all system responses improve their time performance significantly with admissible amplitudes, e.g. $t_\infty=400$ *sec*, $y_1(\infty)=7.597$ and $y_2(\infty)=3.695$ (Fig. 5). For the critical value of $\chi_V{}^*(0)=1.0$, obtained if $k_{21}=0.4536$, pure astatic responses for both y_i are resulting. Finally, when $\chi_V(0)>1.0$ (e.g. $\chi_V(0)=1.00348$ at $k_{21}=0.456$), unstable time transients are obtained expectedly (the uppermost couple of graphics).

B. Physical model of the experimental hydraulic rig

The present investigations on V-interconnected plants are conducting on a pilot hydraulic multi-body rig, Fig. 1, aiming at to obtain live observations on the explored phenomena about the scientific hypotheses approved. *Johansson* [17], shows experimental results on investigations of a complicated four-tank hydraulic bench with particular circulation of flows between the vessels. The dynamic model developed to the tested hydraulic plant contains a real multivariable system zero, that reverses its sign for changing to *non-minimum phase behaviour*. The shift is done according to some constructive parameters and operating conditions. An issue is drawn that the observed shift in plant properties is caused by arising of structural variations. In the reference cited, also a reasonable physical interpretation of the phenomenon is proposed, but the possibility for emerging other fundamental system behaviours under the influence of cross interactions is merely suggested.

Various functional schemes for coupling between two hydraulic tanks are known [5, 6, 7]. In [6], a simplified double-tank unit with single inlet/outlet and bottom interflow F_{12} is examined (Fig. 1, Q_1=0, F_2=0). The same construction is also implemented with double filling/emptying facilities, that refers better to our research goals regarding plant V-interconnectivity [4]. For this latter scheme, however, contradictory dynamic behaviors of the formally identical hydraulic TITO plants are derived independently according to [5] and [7]. Interconnected TITO models with cross V-interactions in both references are proposed, though having similar general terms. Due to [7], the plant sub-models and all outputs y_i behave intrinsic self-control. On the contrary, however, the liquid level dynamics in [5] are modelled as *Type 1* (astatic) dynamic system. This theoretical paradox is easy to be explained by the specific plant characteristics of the effluent flows in [7], bearing dependent-by-the-level flow responses with self-control. As for [5], it is assumed, that the effluent flows from both tanks are (almost) constant in time, thus giving by some reasons level-independent flow rates $Q_i=const_i$, though $u_i=F_i-Q_i$.

The mathematical model [7] regarding time deviations at the liquid levels h_1, h_2, in both vessels (Fig. 1) under changes of the input-output flows F_i, Q_i, and available mutual cross interactions (bi-directional flow F_{12}, due to hydrostatic differences between the tank levels) is representing in general form by the following non-linear system of differential equations:

$$\left|\begin{array}{ll}\rho S_1 \dfrac{dh_1}{dt} = F_1 - Q_1(h_1) - F_{12}(h_1,h_2), & F_{12} = c_{12}(h_1 - h_2) \\ \rho S_2 \dfrac{dh_2}{dt} = F_2 - Q_2(h_2) + F_{12}(h_1,h_2), & Q_i = a\sqrt{2gh_i}\end{array}\right. \qquad (12)$$

Here, S_i are the cross-section areas of both tanks, and ρ, a, g, c_{12} are known hydraulic parameters.

After linearizing Q_i=f(h_i) in the vicinity of the operation point (h_{i0}, $Q_{i0}=F_{i0}$, i=1,2), a linear process model in small quantities is easy to obtain, and further – the differential input/output model ($u_i \equiv \Delta F_i$, $y_i \equiv \Delta h_i$):

$$\left|\begin{array}{l}\rho S_1 \dfrac{d\Delta h_1}{dt} = \Delta F_1 - \dfrac{Q_{10}}{2h_{10}}\Delta h_1 - c_{12}(\Delta h_1 - \Delta h_2) \\ \rho S_2 \dfrac{d\Delta h_2}{dt} = \Delta F_2 - \dfrac{Q_{20}}{2h_{20}}\Delta h_2 + c_{12}(\Delta h_1 - \Delta h_2)\end{array}\right. \cong$$

$$\cong \left|\begin{array}{l}\rho S_1 \dfrac{dy_1}{dt} + \left(\dfrac{Q_{10}}{2h_{10}} + c_{12}\right)y_1 - c_{12}y_2 = u_1(t) \\ \rho S_2 \dfrac{dy_2}{dt} + \left(\dfrac{Q_{20}}{2h_{20}} + c_{12}\right)y_2 - c_{12}y_1 = u_2(t)\end{array}\right. \qquad (13)$$

After applying *Laplace*-transform to (13) and composing separate transfer functions, the physical TITO model of the coupled two hydraulic vessels is represented as a [2x2] V-interconnected plant in the general form (1)÷(3):

$$\left\|\begin{array}{l}(a_{11}s + a_{12})y_1(s) + a_{21}y_2(s) = u_1(s) \\ b_{21}y_1(s) + (b_{22}s + b_{12})y_2(s) = u_2(s)\end{array}\right. \Rightarrow$$

$$\Rightarrow \underbrace{\begin{vmatrix}\dfrac{1}{G_{11}(s)} & -G_{12}(s) \\ -G_{21}(s) & \dfrac{1}{G_{22}(s)}\end{vmatrix}}_{\mathbf{F}(s)} \underbrace{\begin{vmatrix}y_1(s) \\ y_2(s)\end{vmatrix}}_{\mathbf{y}(s)} = \underbrace{\begin{vmatrix}u_1(s) \\ u_2(s)\end{vmatrix}}_{\mathbf{u}(s)}, \qquad (14)$$

This model undoubtedly shows the internal nature of the interactions in the hydraulic vessels. Here, $G_{ii}(s)=k_{ii}/(T_{ii}s+1)$, $\mathbf{k}_{ii}=\{1/a_{12},\ 1/b_{12}\}$, $\mathbf{T}_{ii}=\{a_{11}/a_{12},\ b_{22}/b_{12}\}$, i=1, 2. The cross connections $\mathbf{G}_{ij}=\{a_{21},\ b_{21}\}\equiv\{c_{12},\ c_{12}\}$ appear as static terms at this model. The model coefficients k_{ii}, T_{ii} depend explicitly by the process parameters via the following relations:

$$k_{ii} = \left(\frac{Q_{i0}}{2h_{i0}} + c_{12}\right)^{-1},\ T_{ii} = \rho S_i k_{ii} = \rho S_i \left(\frac{Q_{i0}}{2h_{i0}} + c_{12}\right)^{-1},$$
$$k_{ij} = c_{12},\quad i, j = 1,2 \qquad (15)$$

The model (12)÷(15) is illustrated at the block-diagram on Fig. 3, where the reverse cross effects h_i-F_j of the V-interconnective terms are denoted as G_{12} and G_{21}. From the parametric relations (15), one could derive an important issue about the strong influence of constructive parameters (throughput coefficient c_{12}) and operation factors (h_{i0}, $Q_{i0}=F_{i0}$, i=1,2) on the gains k_{ij}, and consequently, via the interaction factor $\chi_V(0)$ to fundamental properties of the V-TITO hydraulic plant. It is also evident by (13), that under level-invariant outflows each system output h_i will depend only by ΔF_i

and will possess no self-control. For this reason, quantitative evaluation of the phenomenon is relevant to be done. It sets a non-trivial task, especially under changeable constructive characteristics and shifted operating conditions. The problem contains both theoretical obscurity and technical challenges regarding hardly measurable fine processes, often neglected in gross engineering considerations. So, as a consequence of the fundamental dynamic variability established, special functional improvements are to be done at a new stage of sophistication for operating in large process ranges. Appropriate control algorithms should also be subject to invention for this research task.

Some hints about adopting incorrect interaction model structure regarding MIMO systems

- Complex industrial systems are often modeled at the early identification stages on the “do-it-by-elements” principle, because it is reasonable to compose much easier a granular MIMO-matrix functional model, instead of inventing a sophisticated general MIMO description no matter if it is in *LDU* system form, or equivalently, in a sophisticated state space representation. As a consequence, by this structural approach a large number of SISO sub-models are easily derived in a sequential manner. Often, they are integrated in inappropriate for the particular MIMO system P-structures and the envisaged by the model plant properties might be principally wrong.

- It is also well known, that the mathematical descriptions of MIMO plants in non-parametric forms (frequency function models or impulse response models) allow only P-canonical MIMO representations due to the cause-effect requirements. This constraint, however, could automatically infer to principal errors of third kind. That’s why, for MIMO systems of V-canonical or mixed structures only parametric model descriptions are admissible.

C. *Hypotheses and generalizations*

After the theoretical issues exposed, relevant suggestions on the examined phenomena are done:

(i) Inherent physical nature of the interconnectivity in multivariable industrial processes and technical plants with interactions always do exists [2]. This intrinsic plant property non-ambiguously fixes an invariant structural type of interconnectivity and mere neglecting the peculiarity and non-equivalent treatment of the phenomena is strongly unacceptable as leading to errors of third type in the respective model representations.

(ii) The V-type MIMO interconnections give rise to ability for changes in the fundamental plant properties [4, 6] during large variations in operational conditions or constructive modifications.

(iii) An attempt has been made for substantiating observed strange process behaviours, reported in the process control references [1], but non-satisfactorily yet explained by the applied theory. These sudden phenomena produce seemingly causeless instability falls of industrial processes having normally stable behaviour. Known analytical models of the hydraulic plants considered behave by substance as macro-descriptions with lot assumptions and simplifications [5], done mainly for engineering convenience. But some faster mid-frequency processes with insignificant weight and short-time duration are practically not considered by these models. That’s why, for revealing the intrinsic process specifics, adding these features to improve model relevancy is also necessary, aiming at to obtain high-quality simulation results.

By the illustrative simulating examples shown, some general concluding guidelines for the project investigations might be immediately drawn:

(iv) In theoretical aspect, it is fully unjustifiable the intrinsic structure of MIMO systems to be neglected with regard to all sorts of control problems, including the identification tasks, only on the name of theoretical convenience. So, the ungrounded conceptual exchange of the particular-type canonical structure to another more suitable one is strongly non-admissible.

(v) Real possibility for changes in the fundamental process properties (stability, self-control, non-minimum phase shifts) of MIMO V-interconnected plants is proven to exist as a result of arbitrary small variations in system parameters (process gains) around lot operation points due to hardly predictable constructive moves and/or operating alterations.

(vi) Strong necessity exists for much more in-depth theoretical analysis and new results about the properties of MIMO V-interconnectivity as in theoretical and qualitative aspects, so to the quantitative measures, aiming at covering the whole multiformity of this phenomenon in technical and industrial areas.

(vii) In many applied problems, the emergence of abnormal conditions resulting to shifted fundamental plant properties are directly dependent on the constructive features, operating conditions and/or other phenomena. This fact imposes necessity of deep theoretical investigations for inventing universal measures, indices, criteria and factors with theoretical background, suitable enough to be applied in practical and industrial control problems for the considered class of plants.

IV. BENCHMARK PRODUCTIVITY ASSESSMENT

In digital computing, a benchmarking procedure consists of running a specialized computer program, a set of dedicated programs, or executing a group of low-level system operations in order to assess the relative performance of the computational object. It is conducted by running a number of standard tests and trials for it. Computer benchmarking could regard to overall and/or component hardware, and system software in general.

The *Benchmark values* serve as useful merits for quick assessment of the hardware performance. However, computers may be destined to different goals and being intended to various applications, though working with different software. While attempts have been made by the developers to compose a universal benchmark code that encompasses the whole real-life multiformity used in the real applications, it turned out to be impossible for any benchmark software suite to predict exactly all the particular individual's usage patterns. The reason is that computers are applied now for both gaming and web services, but also for office and calculation tasks. So, very strict common sense has to be inferred when interpreting some benchmark test results. For example, the *3DMark* value isn't particularly relevant for assessing an office station.

When applying *Memory Benchmarks* there are many factors to consider: the system setups a memory is running under or the switched by the user overclocking option. So, memory tests must be organized as being less dependent from the CPU, nevertheless they are strongly influenced by the system processor.

It is proven by many testing trials and confirmed from thousands of benchmarks collected, that memory performance is highly dependent on CPU properties. Consequently, less powerful CPUs may not be able to utilize the full capabilities of the memory modules. Therefore, such results appear to be a sub-set of all test data, taken from the configurations with newer faster CPUs. By this reason, systems with slow CPUs have been excluded from some benchmark tests.

There are also cases where high-performance memory often hasn't been configured to run at its maximum speed. While the memory set might support higher-speed *XMP* profiles, these might not automatically be selected in BIOS, thus leaving the machine running at a slightly slower speed than the RAM could support. These conditions can also skew the averaged data presented in the tests.

In general, the bigger the index number, the faster the PC system. The overall system ratings, however, are not an average or a plain sum of the sub-scores. The whole index is limited by the weakest component(s) in the PC. So, even for a system with extremely fast CPU, but furnished with an average-grade memory and HDD, the overall score would still only be disappointed. For some combinations of hardware characteristics and intended PC implementations, another bottlenecking component may then emerge. Evidently, real-time application systems furnished with SSDs, will not suffer by the poor HDD performance, at the expense of RAM's reply time and motherboard internal bus speeds.

A selection of benchmark procedures is reviewed here and the particular indexes and system ratings regarding the examined *PowerPC* machine are shown below. The tests are exemplified by pure procedure output data.

*A. **UserBenchMark** Test Suite*

UserBenchMark utility [21] is referring to the group of bench-marking software for general tests and comparisons between similar machines. It is a free-access product and can be easily downloaded and run to derive common inferences about the realistic performance and productivity of a computer configuration.

The CPU tests include integer and floating-point arithmetic and string manipulation. The CPU benchmark trial determines the current base clock speed, then independently carries out tests for floating point, integer and mixed performance at core depths ranging from 1 to 32 levels.

GPU tests include six 3D-game simulations. Drive tests include read/write operations, sustained write and mixed I/O. RAM tests include single and multicore bandwidth specifications and memory latency test.

The overall procedure helps to identify the strongest and weakest components in a PC, compare the trial PC components to those from current market leaders and other users with the same hardware. The latter consists in comparing 100 PCs with the similar components regarding manufacturer and technical specifications. The issued statistical percentiles for the tested machine serve as ranking scores about the performance result of each individual component and the overall PC in an averaged sense.

UserBenchmark estimates of the *PowerPC*

UserBenchmarks overall PC estimate:
Game PC 83 %, Desktop 167 %, Work Station 132 %.

CPU: Intel Core i7-8700K - 106.5%

GPU: Nvidia GTX 1060-3GB - 68.8%

SSD: Samsung 970 Pro NVMe PCIe M.2 512GB - 396%

HDD: WDC WD4003FFBX-68MU3N0 4TB - 22.2%

RAM: Kingston HyperX DDR4 3600 2x8GB - 107%

MBD: Asrock Z370 Taichi

Generally said, the overall *Power PC* performance results (67^{th} percentile) are somewhat up the golden mean. It falls out definitely from the group of the Gamer's machines. But the desktop and workstation characteristics are much better than 100% and this clearly indicates, that the main dedication of the system for scientific tasks is fulfilled. The weakest components are the video card (69%) and especially the HDD by its poor mark of 22.2%. The latter device has probably no technical shortcomings and the reason consists in its intended purpose. The important devices for a real-time experimentation system (CPU, RAM, SSD), however, demonstrate good behaviour and excellent performance. The motherboard (MBD) itself has no clear estimation mark by this test. This fact evidently implies, that the suite is particularly targeted.

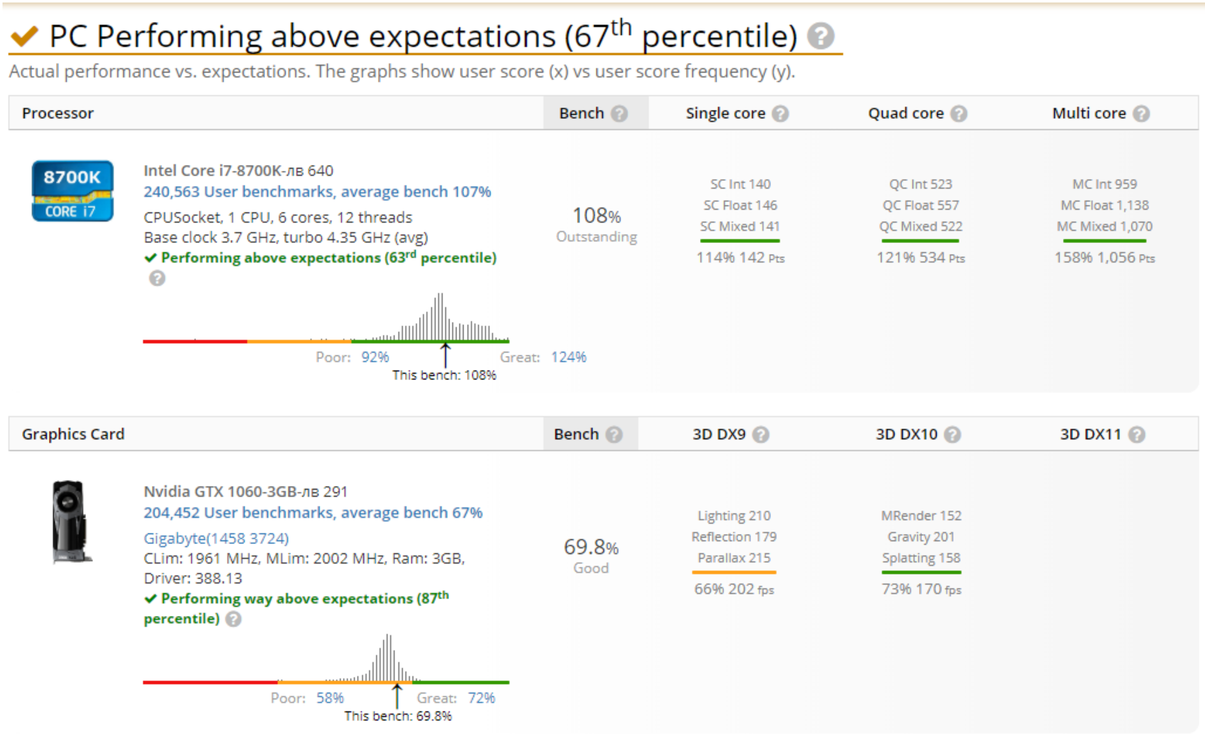

Fig. 6. *UserBenchmarks test results regarding CPU and GPU devices.*

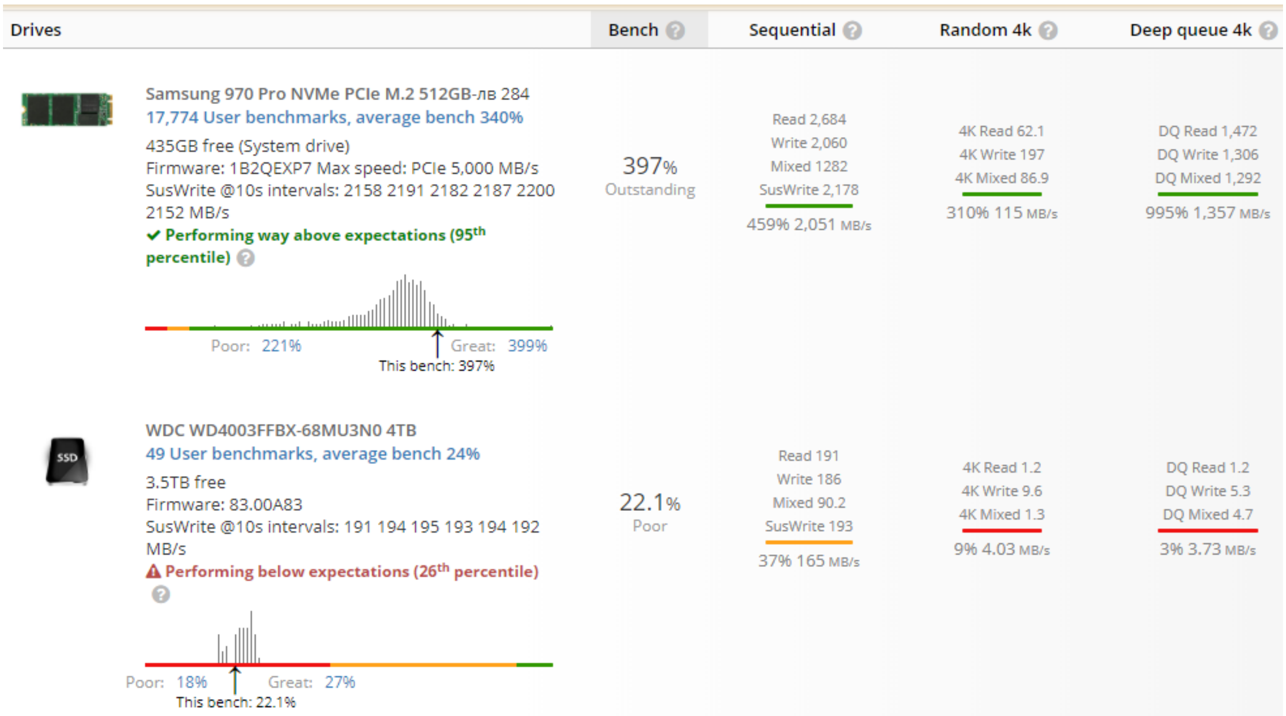

Fig. 7. *UserBenchmarks test results about SSD and HDD units.*

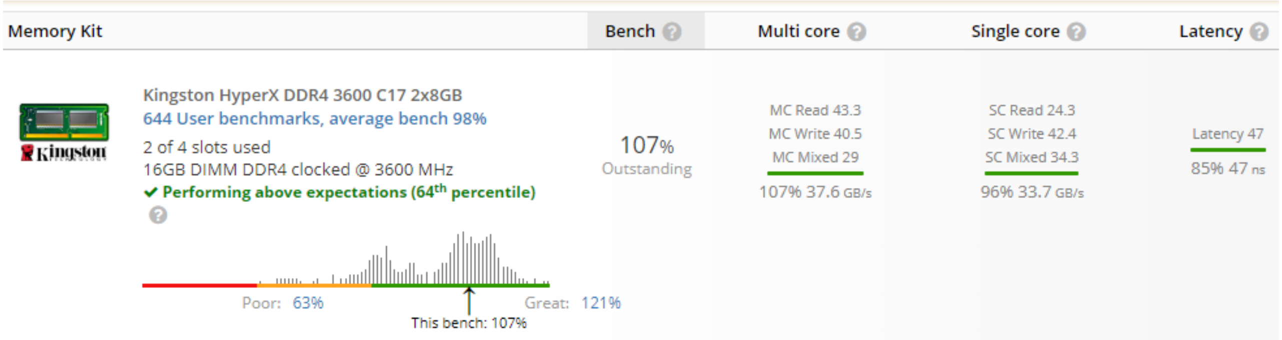

Fig. 8. *UserBenchmarks test results for the RAM memory.*

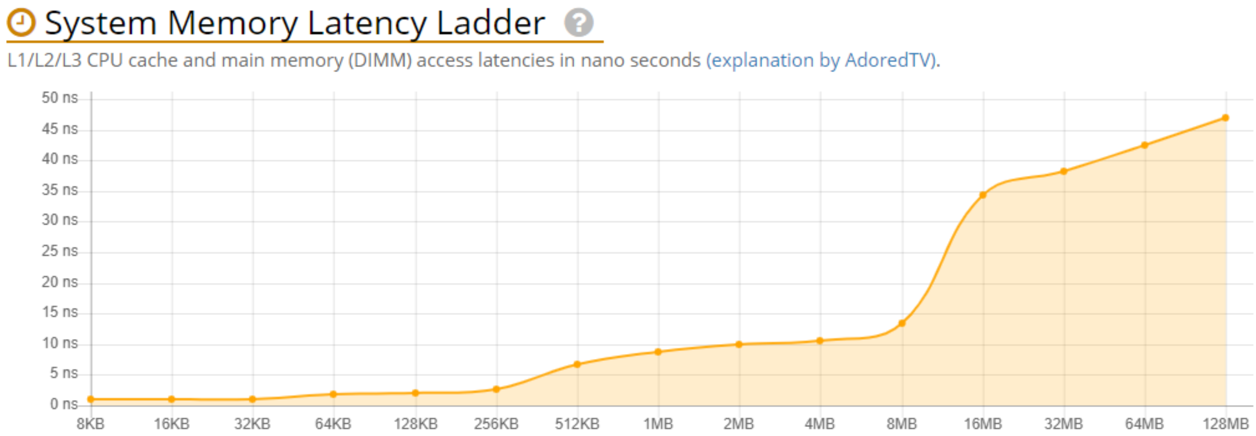

Fig. 9. *Memory latency test. Given: 46 nsec. Top result from UserBenchmark database: 16 nsec.*

B. PC Performance Check via Windows10 tools

Older versions of the *Windows* operating system (*Win Vista* and *Win 7*) provide a ready-make performance index, denoted as *SystemScore*. It could be found in the *System properties* section and gives a general estimate about the power of the particular PC hardware. The test is based on separate assessment of the computer's graphics, hard disks, CPU, memory and other devices to give an integrated score fixed between 0.0 and 10.0. Hardly any computer may get the maximum score of 10.0, but this result indicates how one could increase it by adding or installing more powerful hardware components. Practically, an older PC version could achieve better score after upgrading the motherboard and the CPU to result in a more powerful configuration. This experience index score is removed from *Windows 10*, however. But an embedded command-line tool that analyzes the PC's hardware is still included in the recent builds of *Windows 10*. It is called ***WinSAT*** [22] and one can obtain the system score by issuing the command *<winsat formal>* from the administrator (power user) menu. Here are the test results issued to the *PowerPC*.

Formal.Assessment (Initial).WinSAT.xml

</SystemEnvironment>
<WinSPR>
<SystemScore>**8.9**</SystemScore>
<MemoryScore>9.2</MemoryScore>
<CpuScore>9.2</CpuScore>
<CPUSubAggScore>8.5</CPUSubAggScore>
<VideoEncodeScore>9.9</VideoEncodeScore>
<GraphicsScore>8.9</GraphicsScore>
<Dx9SubScore>9.9</Dx9SubScore>
<Dx10SubScore>9.9</Dx10SubScore>
<GamingScore>9.9</GamingScore>
<DiskScore>9.25</DiskScore>

Again, an acceptable (but not exceptional) general score (<SystemScore>**8.9**) about the machine is obtained, in contradiction, however, to demonstrated almost peak individual results from the key hardware components.

*C. **PassMark** Performance Test*

This test [23] allows to perform objectively a benchmark trial at selected PC by implementing variety of different speed tests and compare the obtained results to those from other computers.

The *PassMark PerformanceTest* consists of 32 standard benchmark routines across five test suites to examine various performance aspects. There are procedures for testing the CPU, Disk, Memory, 3D- and 2D-graphics. For each suite a separate "*Mark*" value is produced, e.g. the *CPUmark* value is a measure of the CPU's performance. All five *marks* are then combined into a single overall score by calculating the *PassMark* rating, that is a measure of the entire system's performance.

The test results ("The Baselines") used for comparison in the *System Benchmark Tests* are gathered from users' submissions to the *PassMark* web site, as well as from internal testing. At the time, above 20000 are the high *CPUMark* data results collected, while 8000 of them are more typical for newish machines.

The standard *PassMark* test suite contains the following procedures:

- **CPU tests.** Mathematical operations, compression, encryption, physics.
- **2D graphics tests**. Vectors, bitmaps, fonts, text, and GUI elements.
- **3D graphics tests**. *DirectX-9* to *DirectX-12* in 4K resolution. *DirectCompute* & *OpenCL*.
- **Disk tests**. Reading, writing and seeking within disk files plus IOPS
- **Memory tests**. Memory access speeds and latency time.

A list of all *CPUMark* values collected can be found on the **CPUBenchMark.net** web site.

The "*PassMark* Rating" itself is combination of the CPU, 2D, 3D, Memory and Disk Ratings, in sense "the bigger the number, the faster (better) the computer (component) is". The exact calculation formula is as follows:

$$\left[\frac{(k_1 CPU)^{-1}+(k_2 D_2)^{-1}+(k_3 D_3)^{-1}+(k_4 Mem)^{-1}+(k_5 Disk)^{-1}}{5}\right]^{-1}$$

where k_1=0.396566187; k_2=3.178718116; k_3=2.52519587; k_4=1.757085479; k_5=1.668158805;

The formula contains higher weights to the CPU and disk tests and lower contribution by 2D and memory tests. This is inferred because both the CPU and disk performance are generally more important to the common user perception for computer fastness. The score is also calculated in such a way that a single extremely high-rating value cannot significantly improve the final score. Conversely, a single low-scored item can drag the overall *PassMark* rating down significantly by this formula. Furthermore, all components in a computer system must perform well in order the final rating to be high.

The CD/DVD test has no longer any contribution to overall ratings as it was in the previous 8^{th} version.

Direct2D, *DirectX 10*, *DirectX 11*, *DirectX 12* and *DirectCompute* tests may be omitted to perform on systems where these features are unsupported. However, a penalty is provided for them being missing.

Overall PC System *PassMark* rating: 1^{st} - 11724.2; 12^{th} - 9956; 20^{th} - 9810.9; … ***Power PC*: 7727.8.**

A. *Calculation power. **y-cruncher** computational test program for multi-digit calculation of π* [24]

The ***y-cruncher*** program Ver. **0.7.7 Build 9499** (Rel. March 10, 2019), is a multi-threaded version for calculation of π and other mathematical constants. It is purposed especially for ***Windows*** applications. The computation mode utilizes RAM memory only.

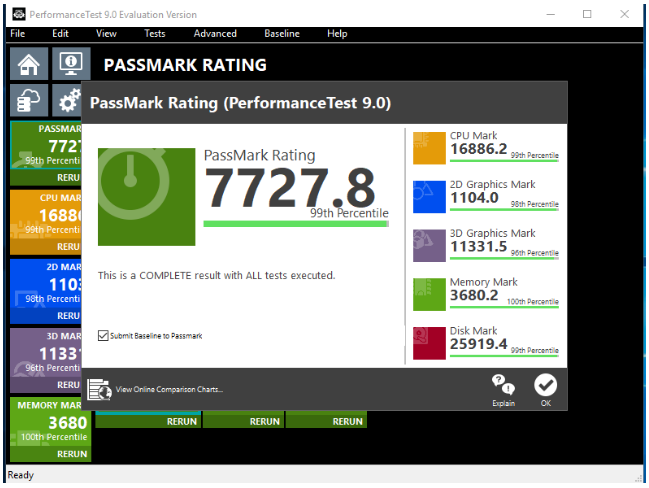

Fig. 10. *Final PassMark test screen.*

The essential result in this benchmark trial consists in evaluating how fast a machine can compute π to arbitrary large number of digits and compare the elapsed time of calculation to a set of available test data. ***y-cruncher*** is a specialized program that can compute π and other constants to practically unlimited number of digits (trillions, Nx10^{12}), if respective machine resources are available. It is the first of its kind due to the multi-threading and scalability features concerning multi-core systems. Since its launch in 2009, it has become a common benchmarking and stress-testing application for gamers and hardware examiners and has been used to achieve several world records for calculating the longest series of digits to π ever computed. A novel feature at this last release is the option for evaluating arbitrary user-defined formulas.

The final list of program functions integrated in *Ver. 0.7.7* is as follows:

= **Basic Arithmetic:** addition, subtraction, multiplication, division, integer power;

= **Elementary Functions:** square root, arithmetic-geometric mean (*AGM*), logarithms, *ArcCoth*() of integer;
= **Special Functions:** *ArcSinlemn*() of rational argument, hypergeometric series of rational functions;

= **Constants:** *Golden Ratio*, *e*, π, *Zeta*(3), *Catalan*'s Constant, Lemniscate, *Euler-Mascheroni* constant.

The only new algorithmic improvement since the original announcement is the extension of logarithm to allow any real input as opposed to just small integers. All operations are fully parallelized, they run in quasi-linear time and load linearly the memory. There is also support for swap mode and checkpoint restart. Thus, anything that can be represented (or sufficiently approximated) by a reasonably small combination of these operations (subject to restrictions) can be feasibly computed to billions or even trillions of digits without being limited by physical memory. This is well beyond the capability of most computer algebra systems. So, this test suite serves as a useful tool for researchers in developing algorithms for high-precision computing of various constants and functions.

The main advantages of ***y-cruncher*** are as follows:

- **Computation of π and other constants** to arbitrary large number of digits. All times in seconds. All calculations are done entirely in RAM memory. The timings include whole time needed to convert the digits to decimal representation, but exclude the time needed to write out the digits to disk.

- **Two separate algorithms** (for computation and verification) are available to most constants.

- **Multi-Threaded computing capability.** Multi-threading can be used to fully utilize modern multi-core processors without significantly increasing memory usage.

- **Vectorized calculations.** Able to fully utilize the SIMD capabilities for most processors (SSE, AVX, AVX512, etc.).

- **Swap Space management** for large computations that require more memory than there is available. The swap mode, however, is probably one of the most complicated features in ***y-cruncher***. So, the advice is not to use SSDs if one cares about their long lifespan. Because ***y-cruncher*** can and will probably destroy SSDs, if one sustains in test running long enough.

- **Multi-Hard Drive.** Multiple hard drives can be used for faster disk swapping.

- **Semi-Fault Tolerant computing.** Able to detect and correct for minor errors that may be caused by hardware instability or software bugs.

- **Comparison Chart:** (Last update: Febr. 2nd, 2019).

The computational restrictions regarding the maximum number of decimal digits for π calculation and the available RAM memory are shown in Table I. By bold typeset the admissible test calculations via the examined here *PowerPC* machine are denoted. During the tests, the available *PowerPC* RAM Memory resulted to 13.4 *GB,* ensuring π-calculation to a maximum limit of $2.5x10^9$ decimal digits.

TABLE I. MAXIMUM POSSIBLE *NO*. OF CALCULATED DECIMAL DIGITS OF π VS. RAM MEMORY REQUIRED

Experiment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Number of digits $x10^9$	**0.025**	**0.05**	**0.1**	**0.25**	**0.5**	**1.0**	**2.5**	5.0	10.0	25.0	50.0	100	250	500	1000	2500
Memory *GB*	**0.222**	**0.34**	**0.593**	**1.33**	**2.56**	**5.03**	**11.9**	23.6	47.2	120	240	480	1130	2260	4720	11500

TABLE II. SINGLE-THREAD CALCULATION OF π BY THE *POWERPC*

Nu. Decimal digits of π $x10^6$	25	50	100	250	500	1000	2500
Necessary Memory, *MB*	222	340	593	1330	2560	5030	11900
Used Memory, *MB*	126	246	498	1240	2470	4940	11800
CPU Utilization, %	99.34	99.28	99.52	99.58	99.67	99.57	99.69
Multi-core Efficiency, %	8.28	8.27	8.29	8.30	8.31	8.30	8.31
π-Calculation Time, *sec*	4.113	9.554	21.611	62.349	142.104	314.417	896.994

TABLE III. MULTI-THREAD CALCULATION OF π BY THE *POWERPC*

Nu. Decimal digits of π $x10^6$	25	50	100	250	500	1000	2500
Necessary Memory, *MB*	222	340	593	1330	2560	5030	11900
Used Memory, *MB*	254	452	672	1290	2530	5060	11800
CPU Utilization, % Kernel Overhead, %	1091.85 -	1099.41 7.09	1109.2 5.89	1106.20 2.05	1111.51 1.33	1126.60 0.74	1146.37 0.67
Multi-core Efficiency, % Kernel Overhead, %	90.99 0.51	91.62 0.59	92.43 0.49	92.18 0.17	92.63 0.11	93.88 0.06	95.53 0.06
π Calculation Time, *sec*	0.927	2.013	4.373	11.969	26.117	56.864	159.714

TABLE IV. GENERAL π CALCULATION BENCHMARKS. OVERALL CPU RANKING VS. *POWERPC* PERFORMANCE

π No. of digits x10^6	Ranked Processor vs. *Power PC*	General Ranking No.	π Calculation time	Processor frequency *GHz*	Architec-ture	OS	DDR4 Memory *GB*	***y-cruncher*** Program version
25	Intel Xeon E5-2683 v3 V. 0.6.9	14	0.907	**2.0**	x64 AVX2	Win10	128	v.0.6.9
	PowerPC	15	0.927	**3.7**/4.7	*Coffee Lake*	Win10	16	v.0.7.7
50	AMD *Threadripper* 1950X	17	1.997	**4.0**	x64 ADX	"	64	v.0.7.3
	PowerPC	18	2.013	**3.7**/4.7	*Coffee Lake*		16	v.0.7.7
100	Intel Core i7 8700K	20	4.352	**5.0**	14-BDW	"	16	v.0.7.6
	PowerPC	21	4.373	**3.7**/4.7	*Coffee Lake*		16	v.0.7.7
250	Intel Core i7 8700K	19	11.925	**5.0**	14-BDW	"	16	v.0.7.6
	PowerPC	20	11.969	**3.7**/4.7	*Coffee Lake*		16	v.0.7.7
500	Intel Core i7 5960X	21	26.060	**4.0**	13-HSW	"	128	v.0.7.2
	PowerPC	22	26.117	**3.7**/4.7	*Coffee Lake*		16	v.0.7.7
1000	Intel Core i7 8700K	21	56.387	**4.9**	14-BDW	"	16	v.0.7.6
	PowerPC	22	56.864	3.7/4.7	*Coffee Lake*		16	v.0.7.7
2500	Intel Core i7 8700K	20	157.515	**4.9**	14-BDW	"	16	v.0.7.6
	PowerPC	21	159.714	**3.7**/4.7	*Coffee Lake*		16	v.0.7.7

All test trials were conducted under the following conditions: Processor's working frequency 3.7 *GHz,* overclocking capabilities not used. These are regarded to both operation modes of running the processor *Intel Core i7 8700K*: Single-thread calculations and Multi-Threading (Table II and Table III).

Finally, a comparison between the ***y-cruncher*** benchmarks and the *PowerPC* achievements is made to evaluate the test results to ones in the general data ranking. The confrontations are shown in Table IV.

Series of conclusions have to be drawn as a consequence of the test results already exposed. By comparing the data that can be found in the benchmark reference cited one may consider, that the necessary elapsed time for the *PowerPC* processor to fulfill the *π test* calculations up to 2.5x10^9 decimal digits is strictly identical to the results kept from previous trials with the same *Intel Core i7 8700K* processor, even though our results are slightly better, which could be explained by the improved RAM and system bus characteristics.

Another important issue concerns the enormous advantage given by the multithreading feature to complicated and bulky computational processes. It is evident by Table II and Table III, that under single-thread calculations the CPU loading reaches 99.7%, the multi-core efficiency is slightly above 8% compared to 1150% CPU utilization and multi-core use above 95% in multi-thread run. Also, the temporal achievements are differing in four to six times. This fact imposes the general conclusion, that multithreading capability is of vital importance to the effectiveness of applications with heavy calculation load. The same important conclusion is made, although in a particular way, by a PC hardware analyst, exploring what possible profits the increased thread capability delivers if applied to variety of gaming PCs [16]. So, by his opinion at examining the popular concurrent game *Civilization VI*, considerable performance boost via multithreading processor might be obtained. This is explaining by the game peculiarity to utilize continuously as much CPU resources, as are available at the moment. Concerning the majority of other entertainment games, however, their performance is evidently more reliant on the pixel-pushing abilities of the graphics card and multithreading perfection bears weak visible acceleration.

If one focuses at the comparisons shown in Table IV, important conclusions could be made about the inference of some hardware indicators on the PC performance. By taking both the 25 and 50.10^6 trial cases one may consider, that the enormous RAM volume (128 and 64 *GB* respectively) evidently compensates for the weaker properties of CPU. Similarly, overclocking implementation and huge RAM (128 *GB*) available helps to a vintage-version CPU (5.10^8 trial case) to equalize the score, thus fixing the guidelines about future performance improvements at the *PowerPC* machine.

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