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Reconstruction of Turbomachines on the Basis of the Flow Structure Visual Diagnostics

Vasyl Arsiri
Oleg Kravchenko
Odessa National Polytechnic University
Odessa, Ukraine
vasily.arsiry@gmail.com
sir.Kravchenko777@gmail.com

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The indicator of the quality of modern turbomachines is only the coefficient of efficiency, which characterizes the ratio of the useful work of compressors or fans to the energy expended on the drive. For the analysis of the quality of the motion, processes in flow parts, the values of resistances are used which are difficult to be considered as an indicator of the efficiency of dynamic processes. The report presents the results of visual diagnostics of the structure of flows during the movement in the elements of turbomachines, as well as options for improving the geometry of the flow parts - in the inlet pipes, impellers.

For the analysis of the efficiency of the motion of liquids and gases in flowing parts, a calculated index is proposed - the coefficient of hydraulic efficiency of dynamic processes. The joint use of two indicators - the efficiency of transformation of different types of energy (efficiency of turbomachines) and the efficiency of dynamic processes in flowing parts allows us to develop and to analyze the results of reconstruction of turbomachines. Reconstruction of turbomachines with the purpose of improving the geometry of the flow parts provides an increase in productivity of turbines, compressors, fans and pumps, while reducing the specific energy consumption for the processes of compression and transport of liquids and gases. Optimization of turbomachines flow parts based of flow structure visual diagnostics allows to reduce noise and vibration, as well as to solve other problems.

Keywords: turbomachines, efficiency, resistance, flow structure, visualization.

1. Introduction

The Turbomachines are connected with the movement of liquids or gases. The main problem of hydrodynamics is the substantial energy losses in order to overcome hydraulic resistance. Modern equipment, operation of which is linked to movement of liquids and gases (pumps, turbines, pipelines, turns etc.) has a low efficiency

due to substantial energy losses in order to overcome hydraulic resistance. Except for substantial energy losses the resistances cause pulsations and, as a consequence, a reduction in the range of capacity regulation of the equipment. Except for substantial energy losses, during movement of liquids and gases, resistance causes noise, vibration and other negative phenomena too. The aforementioned disadvantages are explained by imperfect (sometimes even primitive) geometry of flow passages, which are often made, based on simplicity of technologies.
The reason of these problems is the optical transparency of liquids and gases (water, air, oil and gas), so their flow structure is unavailable for studying. So far, mechanics of liquids has no any laws describing organization of hydrodynamic structure and applicable to design optimal flow passages. Turbulence is considered to be a complex movement of dissipative media and is associated with chaos [1]. Hydraulic reference books, which are used to design equipment, have unjustifiably accustomed technologically-simple flow passages for pipes, turns, valves, etc and their great hydraulic resistance. Modern ideas about the movement of liquids and gases are based on the concept of turbulence [2]. The equations describing the turbulent flow, expect the averaged parameters of velocity and pressure only. The visual diagnostic of flows has a special role in identifying and analysing the parameters of the equipment. The task of visual researches is to expose the picture of flow structure. The results of visual researches of flow structure, effluent in the flooded space most known from literature are presented on a Figure 1 [3].

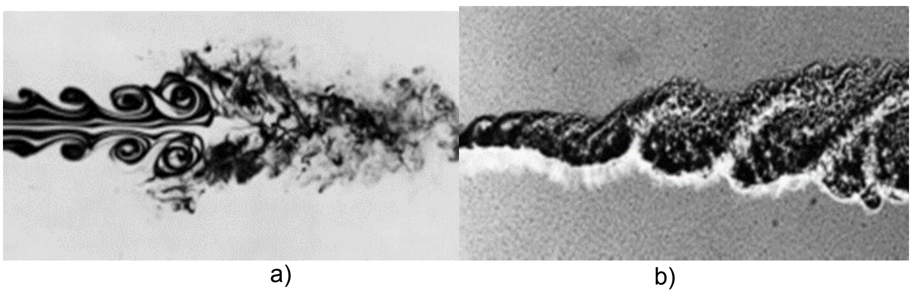
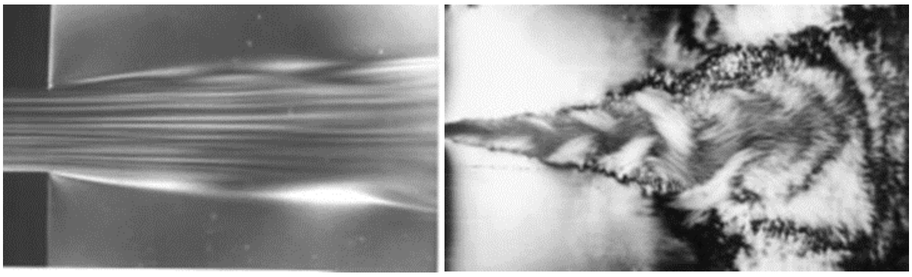


Figure 1 Flow visualization, effluent in the flooded space: a) the smoke visualization, b) the spark method

On the Figure 1a the laminar motion is presented, where steam-lines character of transversal structures' is visible. On the Figure 1b the turbulent flow is presented, where large-scale areas in a longitudinal section are visible. The Fig. 1b of turbulent flow, got by Roshko in 1976, allowed to change the picture about turbulence as chaotic motion on the determined chaos [3]. Already there are models, describing possibility of flow structure's origin in a boundary layer: by Taylor and by Kolmogorov. However presented sizes (dimension) of nascent flow structures are as dimensionless parameters, and they are accounted coming from the sizes (dimension) of boundary layer, the value of which is hard to measure. Existent turbulence models and the models, which are presented on the Fig. 1 do not give much information about the flow structure and are not suitable for the decision of technical tasks.

2. The method of flow structure visual diagnostics

The report presents method of *flow structure visual diagnostics* (*FSVD*). This method allows us to get information about the flow structure, suitable for the decision of the applied tasks. The high informing of FSVD is related to that use of optically active liquid (OAL - oxide vanadium V_2O_5) in the polarized light changes on optical density values (intensive white or grey) in every point of the flow depending on hydrodynamic tensions (gradients of speed or pressure). The special physical models with characteristic sections of flow passages are made for visual researches, in which OAL moves with given parameters by the Reynold's number. The process of motion is registered as a picture and analyzed. Light areas are characterized by the positive gradients of speed, dark areas are negative gradients of speed. Thus, images are characterized by the field of instantaneous values of speed. On a Figure 2 the results of visual diagnostics of flow structure in the flooded space executed by FSVD are presented [4].



a) b)

Figure 2 Visual diagnostics of flow structure: a) the laminar mode, b) the turbulent mode

Visual researches in physical models have proved experimentally that *the motion of liquids and gases has a steady structure*. The laminar mode is characterized by the regular distributing of structure in a cross section (Figure 2a). Structure along a flow (or flow-lines) have an identical absorbency, consequently they have a permanent size of speed. However in the cross-section of stream layers have a harmonic change an absorbency, consequently, a change of size speed across a stream has a wave character. The turbulent mode is characterized by discrete (coherent) optically homogeneous structures and vertical areas in the longitudinal section of stream (Figure 2b). The steady character of *flow structures (FS)* allow to develop and conduct the row of hydraulic experiments.

3. The FS-technology for design of flow passages

Methods of application the *FSVD* are shown on the example of designing an optimal flow passage of flow turn by 90°. The Figure 3 shows the flow structure in a device, which is referred to as “bend” and “lateral” – a turn with equal internal and external corners or radiuses of rounding. To characterize the optimal movement of liquids or gases, let us introduce a term called “hydraulic or dynamic efficiency of flow passage” η_D applicable to hydraulic or aerodynamic equipment. For this purpose, we use known meaning of consumption coefficient μ, which can be calculated based on a meaning of resistance ζ:

$$\eta_D = \frac{1}{\sqrt{1+\varsigma}} = Q_a/Q_t$$

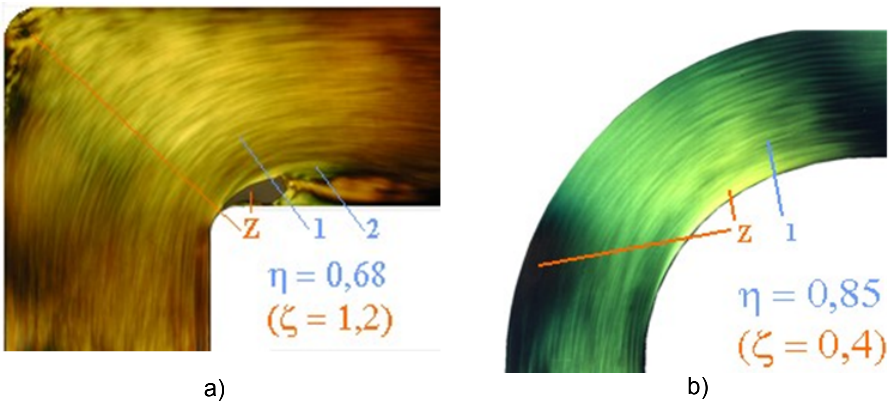


Figure 3 Flow structure in flow turn by 90°: a) “bend” $\eta_D = 0,68$, b) “lateral” $\eta_D = 0,85$

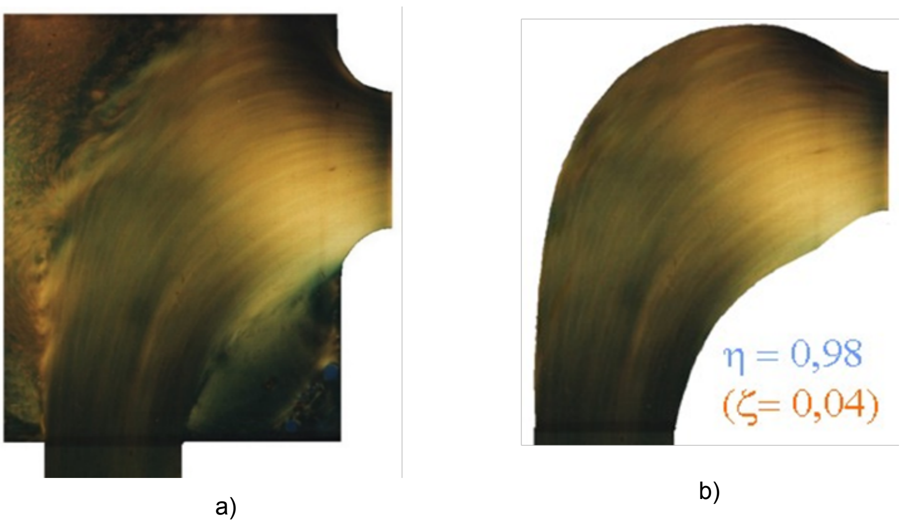


Figure 4 Designing of optimal turn by 90°: a) “black box”, b) “FS-turn” $\eta_D = 0,98$

Thus, movement efficiency of liquids and gases in flow passages η can be characterised by relation of actual consumption Q_a to teoretical consumption Q_t. If the meaning of hydraulic resistance $\zeta = 1{,}2$, then movement efficiency η of liquids or gases in the "bend" amounts to $\eta_D = 0{,}68$. The illustrations demonstrate reasons for such a poor efficiency. The dissipated areas, in which the flow comes off the walls Z, are the ones, where energy losses are maximum. The chaotically located transverse structures, presented as the current lines 1, and longitudinal flow structures, presented as homogeneous optical areas 2, do not contribute to an organized movement in the flow passage of the turn.

The FSVD method enables to improve significantly the efficiency of movement in the turn [4, 5, 6]. For this purpose, the flow structure of an optically - active liquid is examined in a specially designed model of a so-called "black box" (Figure 4a).
The flow passage of the "black box" provides for given inlet and outlet dimensions of the channel, taking into consideration radius of the flow turn in flooded space. Specially increased dimensions of flow passage in the "black box", between the first and last section, enable to turn the flow of liquid in the most optimal way. The obtained image of flow structure in the "black box" gives information to solve the problem of determining optimal limits and geometry of the flow turn (Figure 4b).
In flow passage of the turn by 90°, which is designed using knowledge of flow structure in transverse and longitudinal sections, the transport efficiency of liquids and gases is increased up to $\eta_{\ D} = 0{,}98$.

4. Gas turbine modernisation results

Among the examples of applying the FST-technology in order to raise productivity and efficiency of the energy equipment, there is reconstruction of the Westinghouse 25MW gas turbine at the Bruch power plant (Colorado, the USA) in 1997. The Bruch power plant is located at the height of 2500 meters; therefore, due to lack of oxygen in the air, its gas turbine plant Westinghouse 25MW could not secure an estimated power output. With help of FSVD, structure of gas flow in "the compressor inlet duct" was diagnosed [7, 8, 9]. A Figure 5a it illustrates the flow structure in flow passage of "the compressor inlet duct".
Apparently, reconstructions of the Westinghouse gas turbine within shortly and at minimum expense enabled to reduce pressure losses in "the compressor inlet duct" by 59%, whereas consumption of air for the turbine was increased by more than 19%. Testing of the turbo-plant prior to reconstruction and after the modernization was implemented by a specialized company Ratheon engineer @ constructors.
Analysis of the obtained results has shown that reduction in losses at "inlet" and "outlet" elements of the gas turbine, using the FSVD-method leads to good perspectives. Without changing flow passages of complicated elements in compressor and turbine, but merely changing geometry of "inlet" and "outlet" elements (reducing losses in the above elements), there is a possibility to have a substantial increase by 15% and more in productivity of gas turbines, improve their energy, cost and other characteristics.

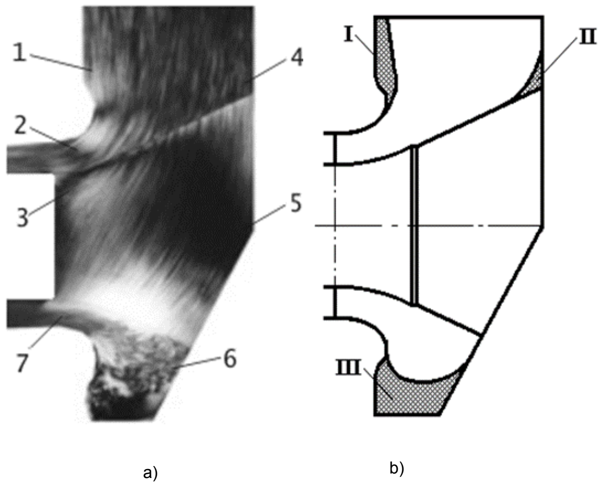


Figure 5 Reconstruction of the Westinghouse gas turbine compressor inlet duct: a) Flow structure at the flow passage of the Westinghouse gas turbine, b) Flow passage of the gas turbine with inserts-curves upon reconstruction

5. Improving centrifugal compressor for the purpose of noise reduction

The next example of implementation of the FSVD is the project of the centrifugal compressor (blower) DA-210 that has been realized in Poland in H. Cegielski-Poznan Company in 2002, for purpose of reduction of noise at its work. Blowers HCP company has good overall characteristics thanks to high impeller speeds [10, 11]. Because of the high speeds in the DA-210 flowing part elements it is generated noise, which considerably higher than the permissible level of 80 dB in the areas of flow comes off the walls. So it was necessary to close the blower by special devices to ensure the normal noise level.

It was managed DA-210 compressor flowing part visual diagnostics, namely several elements, of to identify areas, where the noise is generating. Based on the results of flow structure visual diagnostics were designed and made two changes: the dissipative areas removing in the sewer inlet part (1 change); replacement of sewer dissipative areas by special insert-curves (2 change).

Removing of areas of flow comes off the walls and the alignment of velocity distribution in the flowing parts was the main intention of the project. DA-210 testing results before and after reconstruction on the HCP stand showed a noise reduction during compressor working from 96 to 82 *dB*. It should be noted that the noise source more then 80dB after modernization was electric motor, not the compressor. An additional and important outcome of the reconstruction was to improve energy performance. The efficiency of the compressor has been increased by more than 3%. The test results showed that the characteristics of the forms of pressure (Figure 7 a) and power characteristics (Figure 7 b) changed after each change in the geometry of flow parts.

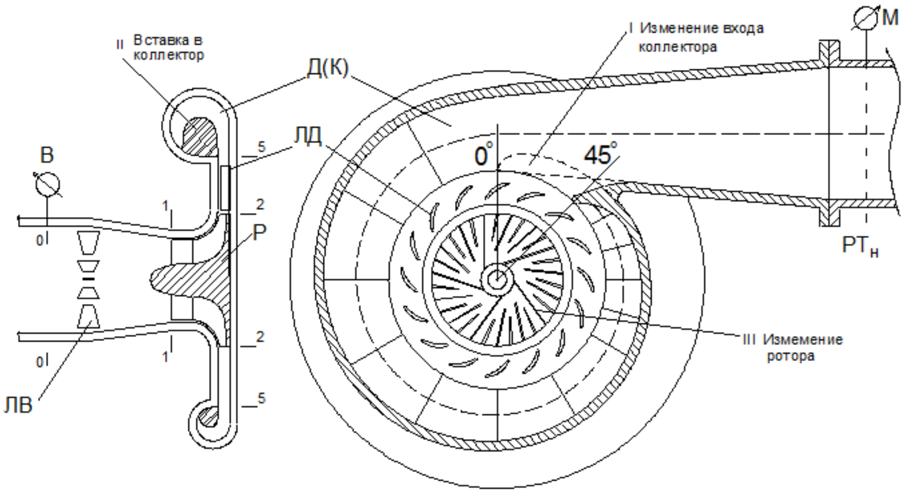
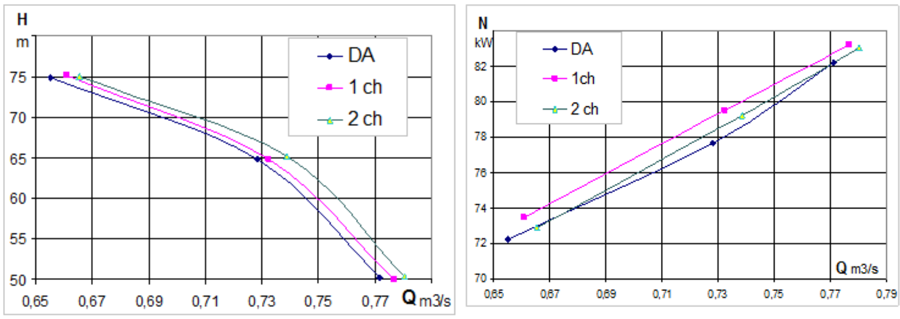


Figure 6 Drawing for reconstruction of blower DA-210



a) b)

Figure 7 Results of blower modernization DA-210: a) the pressure characteristics P = f (Q), b) the power cost characteristics N_{el} = f (Q)

Each stage of improving of the flow parts provided the decrease of resistance and making the pressure characteristic $P = f(Q)$ more flat or more horizontal. Form of power cost characteristics $N_{el} = f(Q)$ of the electric motor change from the concave (prior to reconstruction) to convex (upon the second flow part changes).

6. The system analysis of efficiency

The report shows the possibility of improving the flow of liquids or gases using the visual method of flows structures diagnostic. The method of physical modeling using an optically-active liquid allows us to reveal unknown information about the organization of flows in the form of transverse structures, longitudinal coherent structures and also well-known vortex dispersive zones, which are only a consequence of longitudinal flow structures. The geometry healing of flow parts with the purpose of improving the flow structure provides reduction of resistance 5 times or more. A high degree of hydraulic flows organization can be the basis for creating a new paradigm of "flow structure", which is useful to use in the design of equipment and hydraulic systems. However, the dynamic processes in the flow parts are characterized only by the resistance value. Other measures of efficiency are not used when designing. The experience of positive results of reducing resistance during the implementation of reconstruction projects, when the system's productivity increases with simultaneous reduction of the initial pressure leads to a decrease of efficiency pumps, fans, compressors. That is, the efficiency coefficient of the main equipment of the system and the resistance of the flow ranges characterize differently the efficiency indicators of the energy processes.

Energy processes can be divided into two fundamentally different types. First of all, these transformations are the "transformation" of different types of energy in the main equipment of power systems (boilers, turbines, pumps, fans). Secondly, these are dynamic processes "momentum", which characterize the movement of different media: water, air, steam ... and even electricity. Calculation of the efficiency of superchargers is based on the fact that a unified unit of measurement [Watt] has been developed to represent the power N as the intensity of the work A/t [Jps] for different types of energy.

Unification of the unit of measurement of power N allows analyzing the efficiency or efficiency $\boldsymbol{\eta}$ of transforming different types of energy in the main equipment. When designing, it is mistakenly to consider that the efficiency index of only the main equipment is sufficient to optimize the parameters. So the efficiency of the fans has a value of $\boldsymbol{\eta}\ _{fan} N_{aerod}/N_{el} = 0.85$. However, the efficiency of the fan characterizes the efficiency of conversion of electrical energy into aerodynamic only in the fan itself, and not in the aerodynamic system as a whole.

Therefore, based solely on optimizing the efficiency of the superchargers, attempts to reduce the specific energy costs in hydraulic systems have no prospects. It should be noted that the calculation of the power factor is also unified - for different types of energy: hydraulic, mechanical, electric, the power is calculated as the product of two components $N = P \times D$: potential P and dynamic component D. In order to drastically reduce the specific hydrodynamic energy losses by improving the flow structure, it is proposed a new method for analyzing the efficiency of dynamic processes. The coefficient of hydrodynamic efficiency μ can characterize the quality of realization of dynamic processes as the ratio of the dynamic component to the initial potential $\eta_D = D\ /\ P = 1/R$, or as an inverse resistance value. This indicator does not exceed $\eta_D = 0.2$ in the modern hydrodynamic systems.

Therefore, if the efficiency of energy transformation in the supercharger is $\eta_{fan} = 0.85$, and the total coefficient of hydrodynamic efficiency $\eta_D = 0.2$, then the system efficiency index has a significant reserve of increase.

$Eff_{sist} = \eta\ _{fan} \times \eta\ _{D}\ =\ 0.85\ \times\ 0.2 = 0.21$

Energy E – Work A $[J]$ – Power $N = A$ / t $[W] = [Jps]$	
Transfer of energy	Dynamic processes
Power $N = P \times D$ $[W]$	$D \to P$
$N_{el} = U \times I$ $[W]$	$I = U / R = \eta_D U$ $\eta_D = 1/ R = I / U$
$N_{hy} = Hg \times \rho Q$ $[W]$	$QV = \eta_D 2gHS = 2gHS/ (1+R)$ $\eta_D = 1/ (1+R) = QV / 2gHS = 0{,}2$
$\eta_{fan} = N_{hy}/N_{el} = 0{,}85$	

We propose an additional stage of hydraulic systems designing – improving the flow parts with implementation of the system-effectiveness analysis. The geometry of the channels or flow parts must form a flow structure that will ensure the high quality of the processes; reduction of energy losses more than 2 times; increase in the range of regulation; eliminate the causes of noise, vibration, ...

7. Conclusions

The work of the modern power equipment has a number of significant problems. Most of these problems are directly or indirectly related to the complex and sometimes primitive geometry of flow parts. The main reason of these problems is the optical transparency of liquids and gases, so their flow structure is unavailable for studying. Therefore, the modern equipment has a low efficiency due to substantial energy losses in order to overcome hydraulic resistance.

The innovated method of flow structure visual diagnostics (FSVD) can detect previously unknown information about the laws of motion of liquids and gases. The "flow structure" new model replaces the old "turbulence" model, where the "averaged parameters" chaos was an obstacle in energy saving problems solving. For the implementation of projects improving the equipment is necessary to develop new efficiency indicators of equipment and systems that should stimulate cost-effectiveness of the equipment and processes.

Using the flow structure organization laws while improving the flowing parts allows us to develop new or improve existing equipment with the opportunity to achieve a new level of energy, dimensional, acoustic, vibration, ejection and other characteristics. The proposed technology based at flow structure visual diagnostics gives the opportunity to develop of new energy equipment with high efficiency and It helps to solve complex problems of energy saving.

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