UNIVERSITY OF CRAIOVA
FACULTY OF MECHANICS

RESEARCH ON CONTROLLING MECHANISMS OF HYDRAULIC TURBINES

- SUMMARY OF THE PhD THESIS -

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- 2010 -

The necessity of high performance hydraulic machinery design and manufacture for the rehabilitation of existing hydropower units, adapted to each hydroelectric scheme facilities, required: CAD modeling use for the assemblies and parts of hydraulic machines; shape modeling and optimizing for the bladed component parts of hydraulic machines; finite element analysis of hydrodynamic flow and hydraulic route optimization in order to improve the constructive solutions by studying the stress field.

This doctoral thesis joins this line, as it is shown in the description below.

Objectives:

1. Kinematic modeling by methods based on a matrix formalism easily to implement on computers, with multiple opportunities to consider the geometric features of the cinematic elements.

2. Dynamic modeling of the wicket gate mechanism by considering it in an integrated system: mathematical models - experiment - numerical processing.

3. Complex geometric modeling of the wicket gate mechanism of the FVM 61.5-234 type Francis turbine, from CHE Tismana Subteran, using computer aided design environment, fully parameterized on 2D and 3D systems.

4. Virtual prototyping of the wicket gate mechanism with numerical simulations and graphics.

5. Development of an optimization algorithm in dynamic regime for mobile mechanical systems.

6. Diagnosis and experimental identification of dynamic parameters of the wicket gate mechanism of the FVM 61.5-234 type Francis turbine with vertical shaft, from CHE Tismana Subteran, for three operating modes: barring, operation at normal parameters and locking.

The current state of research and the importance justification of the theme are presented in **Chapter 1**.

The current state of research is structured using references and following these major segments:

- Dynamic modeling of mechanical systems;
- Achievements, theoretical and experimental research in hydraulic turbines domain;
- Modeling of mobile mechanical systems using finite element method;
- Methods for mechanical systems optimization;
- Overview of the Francis hydraulic turbine wicket gate mechanism.

Chapter 2 deals with the dynamic analysis of the wicket gate mechanism. It is a laborious chapter where the dynamic problems are studied and analyzed in an integrated system of the following type: mathematical model - experiment - processing and numerical simulation.

This chapter includes:

- A general method for kinematic modeling of the mobile mechanical systems based on a flexible matrix formalism, easy to implement in numerical computation programs (Maple in this case), with possibility of relatively simplistic considering of the kinematic elements geometry by introducing conversion matrices;

- Kinematic modeling of the wicket gate mechanism from the Francis turbine; The wicket gate mechanism is composed of the following main parts:
  - a guiding system with 16 blades rotating around their own axes, providing the fluid access to the turbine runner on the open position;
  - The mechanism for motion transmission which consists of an adjustment ring, a left-right screwed fork, having the possibility of its length modification, and a lever joining the control blade sub-assembly;
  - Two linear servo-engines with 300 mm maximum stroke for controlling the wicket gate closing or opening by the adjustment ring.

The parameterized system for geometric models conception, strictly respecting the boundary conditions for elements and sub-assemblies, has created optimum conditions for dynamic modeling of the mechanism, considering rigid or flexible links, and for optimizing the whole system in dynamic regime.

Geometric modeling of the wicket gate of the Francis hydraulic turbine, FVM 61.5 – 234 type, from the hydroelectric unit HPP Tismana Subteran, is shown in Fig. 1 and Fig. 2

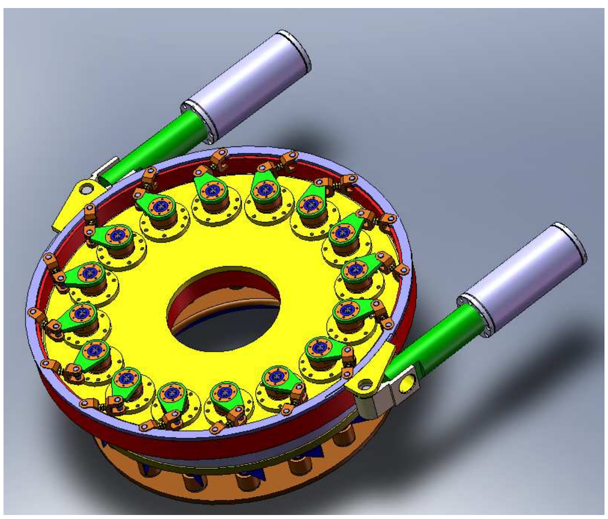

Fig.1 3D Model of the ticket gate of the Francis Turbine, FVM 61,5-234 type

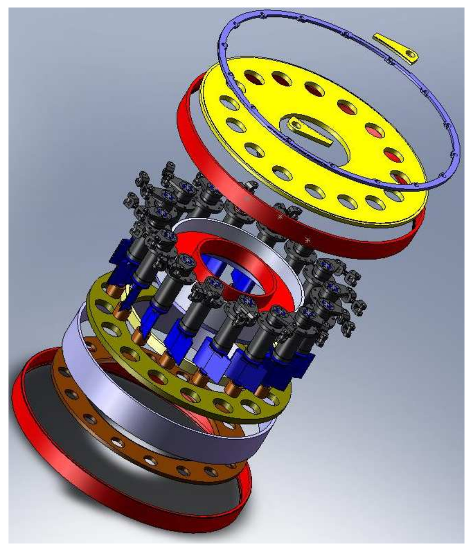

Fig. 2 Exploded view of the wicket gate mechanism

- Inverse dynamic analysis includes:

- The motion equations are considered in Newton-Euler formalism, assuming rigid links;

- The mathematical models are developed in order to identify the forces variation laws in dynamic regime, when there are considered the following reference systems:
  - a global reference system T_0 (X_0, Y_0, Z_0);
  - mobile reference systems $T_i'(x_i', y_i', z_i')$, $T_j'(x_j', y_j', z_j')$, joining the links *i* and *j*, $i = \overline{1,7}$;
  - reference systems $T_i^{K''}\left(x_i^{K''}, y_i^{K''}, z_i^{K''}\right)$ and $T_j^{K''}\left(x_j^{K''}, y_j^{K''}, z_j^{K''}\right)$ centered in the *K* pair and joining the links *i* and *j*.

Constraint forces may be expressed in relation to each of these reference systems, taking into account the coordinates transformation matrices.

The inverse dynamic analysis is accomplished by following the next steps:

- The equations system defining the mechanism kinematic configuration is determined;
- There are identified the structural elements used by the motion equations in Newton-Euler formalism: generalized coordinates vector $\vec{q}$, mass matrix defining inertial properties of the mechanical system, the Jacobian J_q corresponding to the generalized coordinates q and generalized active forces matrix Q^a;
- Calculation of Lagrange multipliers;
- The time variation laws determination in dynamic regime for the constraint forces acting in the kinematic pairs.

Input dynamic data have been identified experimentally for digital processing (the piston stroke and the resistance force on the blade).

It was developed a numerical processing program of mathematical models, which defines the time variation laws of constraint forces acting in the kinematic pairs.

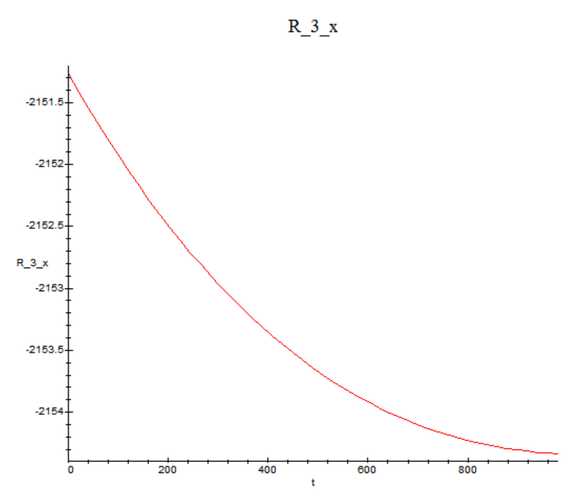

Fig. 3 Variation law of the constraint force, R_{3x}

Fig. 4 3D Model of the wicket gate mechanism, imported in ADAMS, C pair, 3D simulation.

- The wicket gate mechanism modeling and simulation using ADAMS programming environment.

The following steps were accomplished:

- The database were transferred from SolidWorks in ADAMS program, considering the links as parts defined by mass and inertial properties; this database correctly imported in ADAMS was the virtual model governing the process of virtual prototyping.
- The kinematic model of the imported virtual assembly was built by defining the links and the pairs, by applying the constraints and considering the mathematical expression of the generalized coordinate time variation law, established by experiment (piston stroke or the angle of the time variation of adjusting ring position);
- The dynamic model was built by considering the defining elements of the driving pair for a

dynamic analysis, i.e. damping coefficient, stiffness and actuation element (force or moment), when the external acting forces were known (in this case, the resistance force on the blade, experimentally determined).
- Model testing in a first phase of simulation, animation and numerical results visualization;
- Validation of the model built in ADAMS by reporting experimentally measured data (resistance force, the piston stroke variation law, driving force acting the piston or the moment acting in the central pair H of the adjusting ring) and comparing them with the theoretical results;
- Model parameterization by defining the design variables needed after the mechanism optimization process.
- The 3D simulation of the wicket gate mechanism operation in kinematic and dynamic conditions.

At the end of Chapter 2, the time variation laws of positions, velocities and linear or angular accelerations for links or some characteristic points, considered as focal points in the wicket gate performance or operation, are presented.

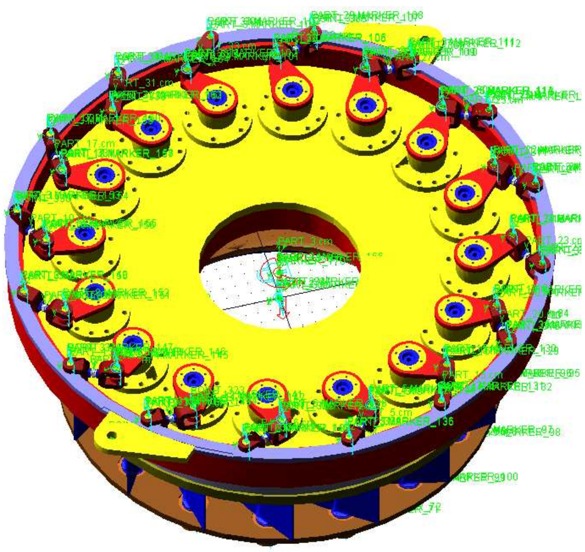

Fig. 5 The 3D mechanism model, identifying the kinematic pairs and links.

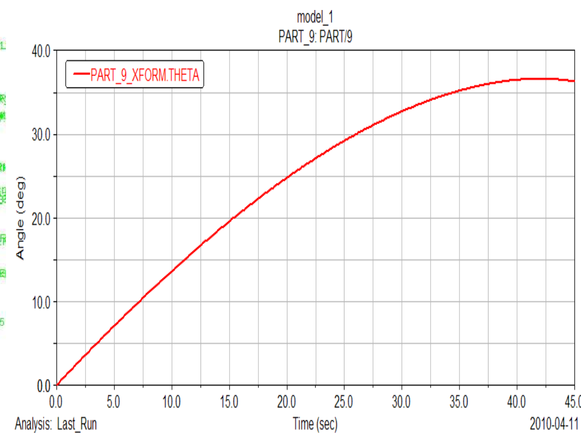

Fig. 6 The time variation law of the link 5 (part 9) angular position

Chapter 3 presents the wicket gate mechanism modeling using finite element method and it is structured in three parts:
- The dynamic model developing for a finite element analysis considering the most general case;
- Dynamic analysis of wicket gate blade using the finite element method;
- Dynamic analysis of the entire mechanism considering the links as deformable.

For the blade dynamic analyze using the finite element method, the blade is loaded with the time variable resistance force F_r generated by the fluid flow on the blade active surface, during the blade closing or opening.

This force is experimentally determined and it represents the time distributed load applied on the final driven element of the wicket gate mechanism.

The time variation laws for stresses, strains and displacements are identified. Now the blades optimization process may be developed, the objective function being the blade form or gauge (volume, weight) and the restriction being defined by a maximum value of stresses, strains and displacements.

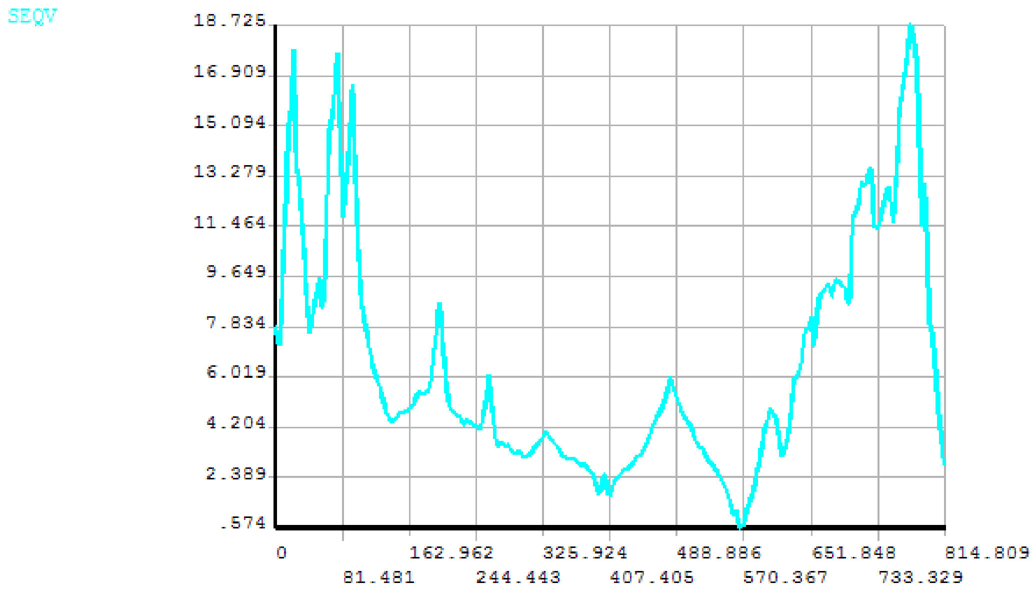

Fig. 7 Von Mises equivalent stresses distribution in the stress concentration zone

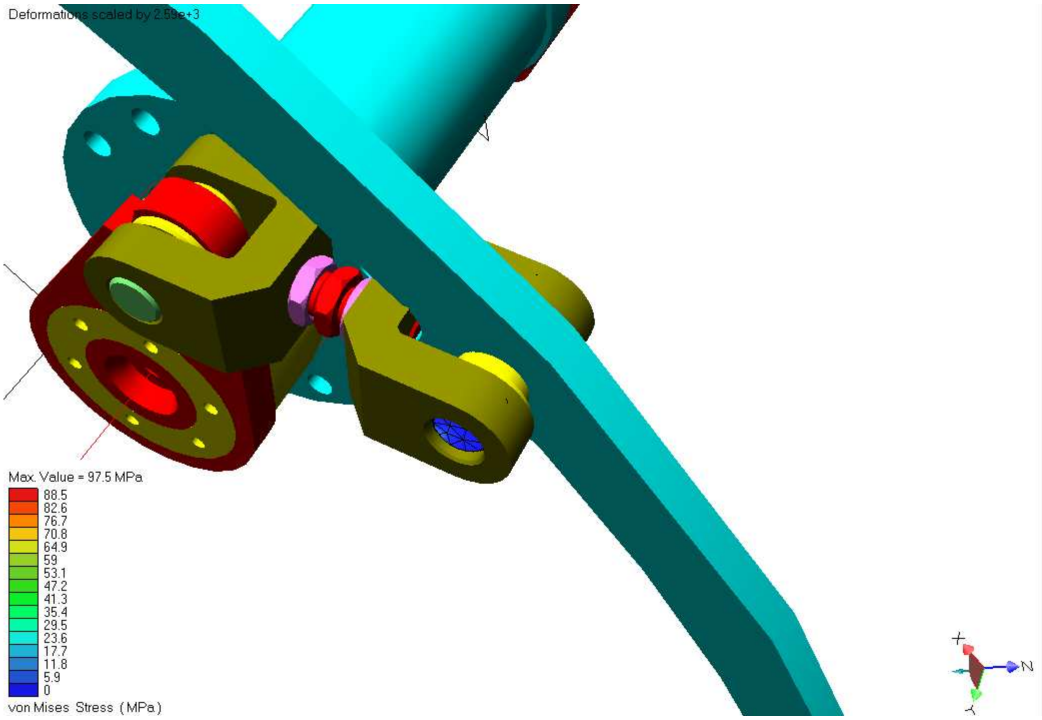

Fig. 8 Von Mises equivalent stresses distribution for the shear pin

Parametric geometric modeling of each mechanism component using the above procedure allows the development of the geometric, kinematic or dynamic optimization process, in terms of maxim accuracy.

For the elastic-dynamic analysis of the wicket gate mechanism it is used the finite element modeling.

It is examined each link considered as a sub-assembly with elastic-kinematic properties, in dynamic regime.

The finite element analysis of the mechanism reveals that the maximum stress value is registered for the shear pin, which serves as overload protection.

The wicket gate mechanism optimization done by means of ADAMS program is presented in **Chapter 4**.

The wicket gate mechanism optimization in ADAMS programming environment consists of the following steps: model parameterization; design variables setting out; objective function defining in order to be optimized; design studies for identifying the main design variables with significant influence on the objective functions; the mechanical system optimization taking into account the main design variables.

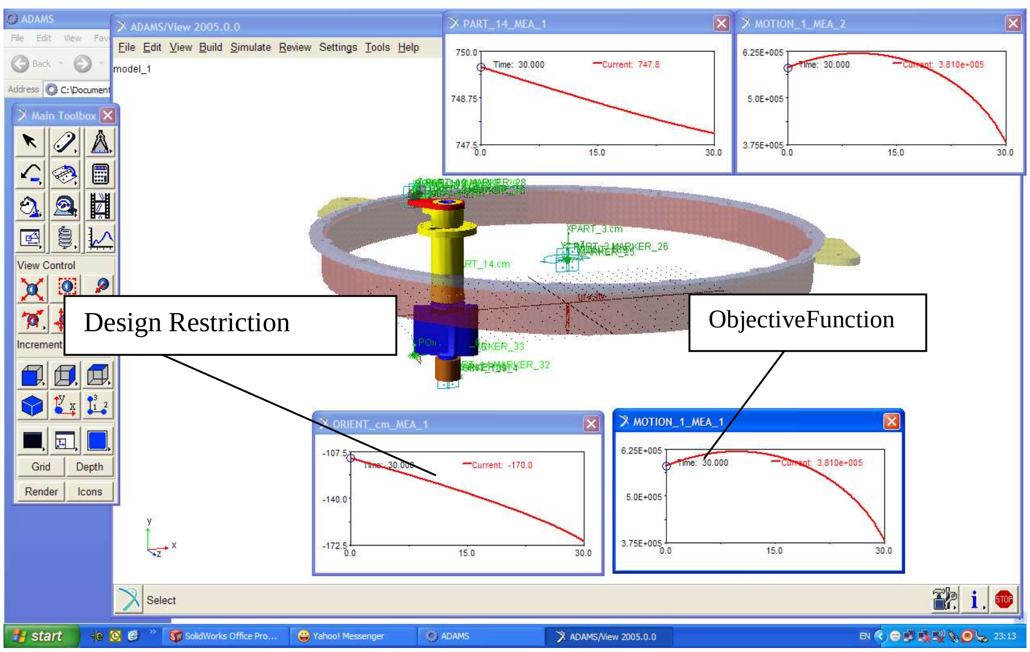

Fig. 9 The time variation laws for the optimization process parameters

In the first part of this chapter each step involved in mechanical system optimization is very accurately described.

For the mechanism dynamic response optimization it is important the moment acting in H, the central kinematic pair. Optimal dynamic response has to strictly respect the purpose for which the wicket gate mechanism was designed, respectively the closing or opening angle of the blade.

The objective function consists of this moment minimization.

The variation law of the resistance force acting on the blade was determined experimentally.

The time variation law of the blade closing or opening angle, governing the proper functioning of the wicket gate mechanism, is considered as a design restriction.

The time variation diagrams and the final diagram of the objective function, when the main design variables change, are determined over three iterations.

Analyzing these diagrams, it was established that DV_2 variable has a significant influence on the objective function, during the study design. This is an important observation which leads to the changing of the mechanism connecting rod length. Organologically, the connecting rod 4 is a modular system precisely designed to allow this change of length.

The final time development of the objective function is searched through this process, when the main design variables change keeping the blade angle within the limits imposed by the mechanism functional role.

Chapter 5 deals with experimental analysis of the wicket gate mechanism and of other important components of Francis turbine.

Fig. 10 Measuring scheme of the actuator piston linear stroke

1.1.1 Instrumentation and sensors used:
- Acquisition system Spider 8, 12 bit resolution;
- Signal conditioning NEXUS 2692-A-0I4, linearity 0.01%;
- Bruel & Kjaer accelerometers type 4391 (3 pcs.), linearity 2%;
- Race linear inductive transducer WA300, linearity 2%;
- Revolution potentiometric transducer type T127PA, 5 kΩ, 2% linearity;
- H4450-23 force transducer, linearity 3%;
- IBM ThinkPad R51 notebook.

1.1.2 Recorded parameters:
- F_tr (N) - the tensile force acting on H4450-23 wicket gate fork;

• Rot_Pal (deg) – control blade angle of rotation;
• Crs_Lin (mm) - piston linear stroke;
• AccO_Pal (m/s2) - acceleration in the horizontal direction of the control blade upper bearing;
• AccV_Pal (m/s2) - acceleration in the vertical direction of the control blade upper bearing;
• AccO_Lag (m/s2) - acceleration in the horizontal direction of the turbine upper bearing.

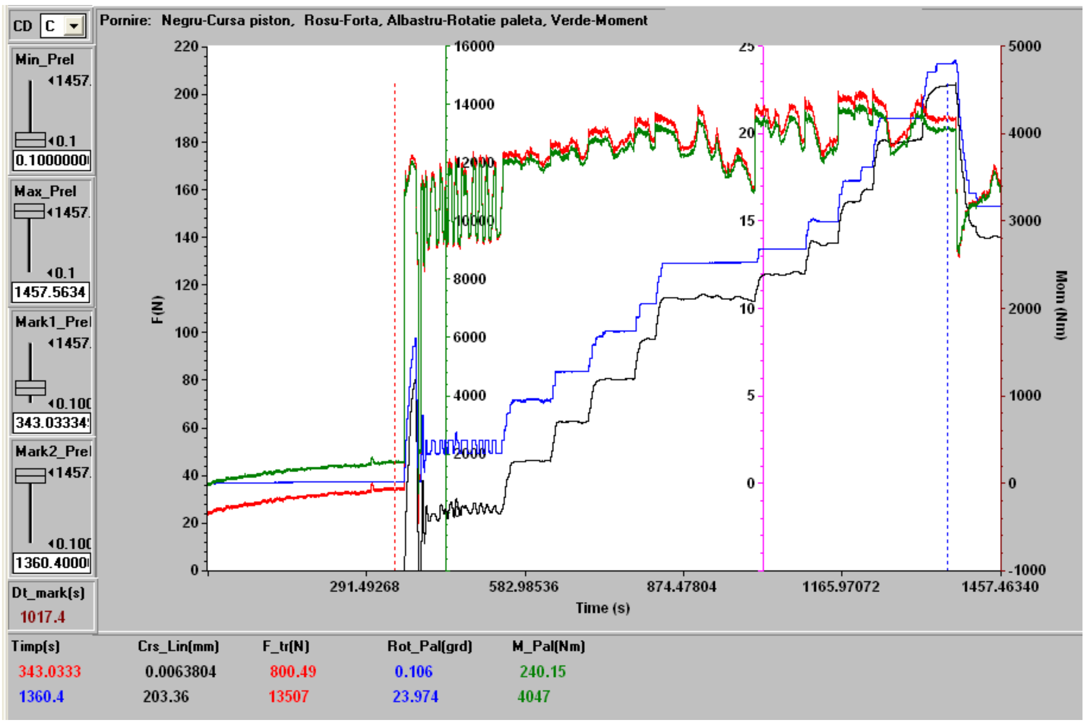

Fig. 11 Functional parameters evolution at the hydraulic group barring

Conclusions on the experiments performed on the 50 MW Francis turbine wicket gate mechanism

Experimental researches have analyzed the dynamics and stability of the Francis turbine unit of 50 MW during the maneuvers of barring, functioning at rated load and locking of the hydraulic group from SH Tismana. As characteristic parameters of the wicket gate dynamics there were measured or determined by calculation the followings: the tensile force acting on the fork, control blade angle of rotation, the actuator piston linear stroke, driving moment acting upon the wicket gate fork.

Vibration measurement and analysis generated by the hydraulic group, identifying the vibration sources, were performed in order to assess the technical condition of the wicket gate mechanism and hydraulic group, too.

Important conclusions resulted from the performed records analysis during the maneuvers of barring, functioning at rated load and locking of the hydraulic group, such as:

1. When starting the group, the water admission into the turbine is performed with great

instability in the control piston stroke, instability leading to significant variation in control force and moment of the wicket gate blades.

2. During the no-load operation, there are little instabilities in maintaining the synchronism speed, instabilities which are highlighted by the changes of the control piston stroke, of the control blade rotation angle and which are reflected by changes of blades driving force and moment.

3. Analyzing the dependency of the blades rotational stroke as a function of the control piston linear stroke, during the maneuvers of barring and locking of the hydraulic group, it is noticed a very good linearity, with a small hysteresis given by the difference between the starting stroke and the locking stroke, explained by the fact that the water stream opposes a resistance moment during the control blades closing.

4. Analyzing the characteristics of the electrical power as a function of the vibration acceleration, the conclusion is that, in terms of vibration, the turbine operates optimally during an electric load regime of 30 – 50MW. In the range of 15 to 25 MW the hydraulic group has higher vibration and therefore it is not recommended to use the electrical load in this area.

5. The vibrations generated during the hydraulic group locking are lower than those generated during the maneuvers of barring and functioning at rated load. During the maneuvers of hydraulic group locking, the vibration generated in the turbine is greater than the vibration generated in the wicket gate mechanism.

ORIGINAL CONTRIBUTIONS

1. Methods and mathematical models database, experimental results and references on dynamic modeling and optimization of mobile mechanical systems in general, and, particularly, controlling mechanisms of hydraulic turbines.

2. Kinematic models for the wicket gate mechanism based on a matrix formalism easily to implement on computers, with multiple possibilities for considering complex kinematic configurations offered by the conversion matrices introduction.

3. Complex geometric modeling of the wicket gate mechanism from FVM 61.5-234 type Francis turbine, component of HPP Tismana Subteran hydraulic system, in computer aided design language, by 2D and 3D systems.

4. Links considered as sub-assemblies of 2D models in compliance with the strict conditions imposed by virtual prototyping.

5. Procedure and mathematical models developed for inverse dynamic analysis of the wicket gate mechanism.

6. Softwares for mathematical models numerical processing in order to identify the variation laws of kinematic parameters and constraint forces of kinematic pairs in dynamic regime.

7. Wicket gate mechanism modeling in kinematic and dynamic regime using ADAMS programming environment.

8. Dynamic analysis of the wicket gate mechanism blade using ANSYS programming environment.

9. Links parametric modeling for structural optimization with the finite element method.

10. Elastic-dynamic analysis by finite element method of the wicket gate mechanism, regarded as a set of deformable links.

11. Experimentally identifying of the dynamic parameters time variation laws required by the mechanism inverse dynamic analysis processing.

12. Algorithm and method for the wicket gate mechanism dynamic optimization using ADAMS software.

13. Reduced experimental model respecting the Francis turbine wicket gate mechanism structure and functionality.

14. Complex experimental analysis of the wicket gate mechanism of the Francis turbine from HPP Tismana Subteran, during the following operating modes:

- Barring with group electrical load constantly stepped up to 50MW, 1457s;
- Constant power operation mode;
- Locking Group, 328s.

15. Experimental identification of the time variation laws change for the following dynamic parameters:

- Tensile force acting on the wicket gate fork;
- Rotation angle of the control blade;
- Piston linear stroke;
- Driving moment acting upon the wicket gate fork.

16. Mechanism Dynamic behavior diagnosing for the wicket gate and the entire hydropower unit by a comprehensive experimental analysis of the vibration.

17. Research considered in an integrated system: kinematic model - parametric computer aided design - experiment to create optimal conditions for the virtual prototyping of the Francis turbine wicket gate mechanism, component of HPP Tismana Subteran.