Dynamic identification of hydraulic turbines of Pelton type

MIRCEA BARGLAZAN, ADRIANA CATANASE
Hydraulic Machinery Department; Energy Engineering Faculty
University "Politehnica" of Timisoara; University of Oradea
Mihai Viteazu Str., No.1, 300222, Timisoara; Universitatii Street, No.1, Oradea
ROMANIA
http://www.upt.ro

Abstract: - It is very difficult to establish an exact model for Pelton turbines, taking into account the few particularities of the flow. Only the dynamic identification of the system will validate or deny the proposed models. In the last years' technical literature, the experimental identification of processes is intensively studied. One of these methods for experimental determination of dynamic characteristics is the identification method using sinusoidal test signals. In this paper we present the testing rig for dynamic identification of Pelton turbines, the system for generate sine wave signals for the testing rig, and, based on the measurements we determine the frequency responses for Pelton turbines.

Key-Words: - Pelton turbines**,** dynamic identification, sinusoidal wave generator, gain, phase, frequency responses.

1 Introduction

Because of the obvious importance of the steady and unsteady characteristics of the automated systems, the issue here is to determine them, as accurate as possible, and synthetically express them as a mathematical model. This model must be most illustrative, and – in the same time – easy enough to use it in calculus.

In the last years' technical literature, the experimental identification of processes is intensively studied. One of these methods for experimental determination of dynamic characteristics is the identification method using sinusoidal test signals.

To determine the frequency response, we examine the processes that appear when we apply to the input parameter some harmonic signals of different angular frequency ω. Therefore, when at the element input we apply a sinusoidal signal, described as:

$$x_i(t) = A_i \sin \omega t \quad (1)$$

then, at element output, after a certain period, stabilized oscillations of output parameter appears, $x_e(t)$, with the same angular frequency ω, but with different amplitude A_e and a phase difference related to the input oscillations:

$$x_e(t) = A_e \sin(\omega t + \varphi) \quad (2)$$

For the frequency response determination, it's adequate only a comparative analysis of the two signals, represented for different angular frequency ω. Therefore we are able to obtain gain-phase characteristics and also the gain – frequency and phase – frequency characteristics for the analyzed system.

In this paper, the target of the experimental identification is the Pelton turbine that belongs to the testing rig for the hydropower-plant "Gemenele" placed in the Hydraulic Machinery Laboratory from the "Politehnica" University of Timisoara.

2 Dynamic model in frequency domain

The stereodynamic model of the turbine is based on the momentum of momentum equation, applied on a solid body in revolution motion, reported on a fixed axis in space. With the form of a transfer function, the stereodynamic model in frequency domain includes near by the turbine elements, also elements of the electric generator, the governor and the penstock. In our case, in the absence of the governor, we take into account only the rest of elements.

In this section of the paper we determined the transfer function of the hydrounit with Pelton turbine. Starting with the momentum of momentum equation applied on the machines, we can build the structural model of the hydrounit. Also, based on these relations and on the transfer functions that we known, we can logical build the structural model of the turbine-generator system, presented in figure 1.

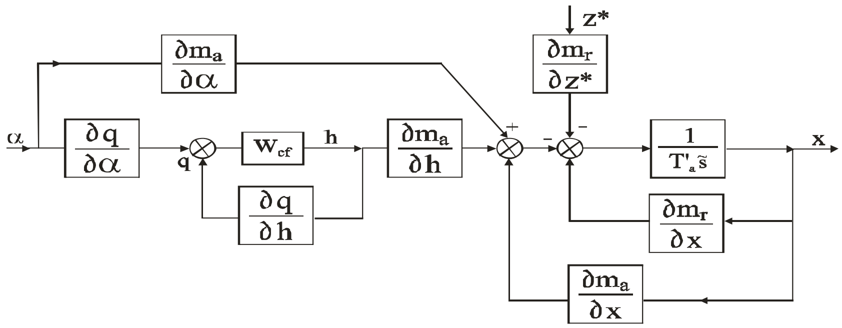

Figure1. The structural model of the hydrounit with Pelton turbine

Using the measurements and the relations for coefficients determination of the transfer function of a Pelton turbine – presented in [4] – we determined the turbine transfer function and also its frequency responses

Therefore, for the testing rig, I calculated the penstock time, $T_w = 0{,}0102$ s, and also the reflection time of the waves, $T_r = 0{,}0071$ s. That means I choose the inelastic water column model for the expression of turbine transfer function.

Based on that, for "Gemenele" testing rig, the hydraulic turbine's transfer function has the expression:

$$W_a = \frac{1{,}375 + 0{,}0073 \cdot s}{0{,}00966 \cdot s^2 + 2{,}471 \cdot s - 1{,}849} \qquad (3)$$

But, s = jω and by replacing it in relation (3), we easily determine the real part and also the imaginary part of this expression. Taking into account the transfer function's absolute value and phase, presented in relation (4) and (5), I obtain the gain – frequency characteristic and phase – frequency characteristic.

$$|W_a| = \sqrt{Re(W_a)^2 + Im(W_a)^2} \qquad (4)$$

$$< W_a = arctg\,\frac{Im(W_a)}{Re(W_a)} \qquad (5)$$

In figure2 and figure3 are represented the real and imaginary part of the turbine transfer function, for each of the angular frequency given, ω.

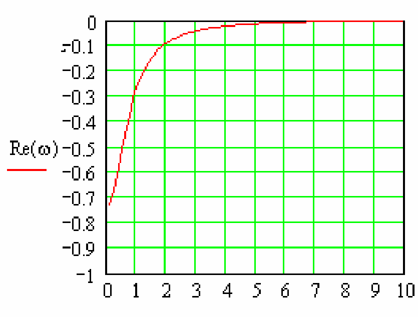

Fig.2 Real part of the transfer function

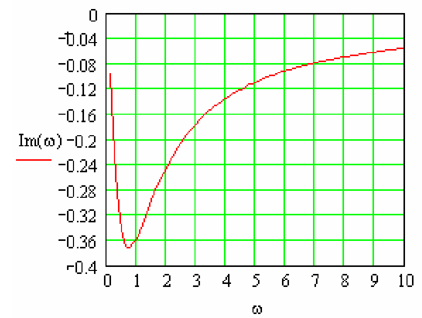

Fig.3 Imaginary part of the transfer function

Also, in figure4 and figure5 the gain – frequency characteristic and phase - frequency characteristic are represented.

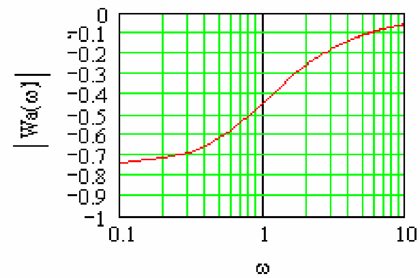

Fig.4 Gain – frequency characteristic

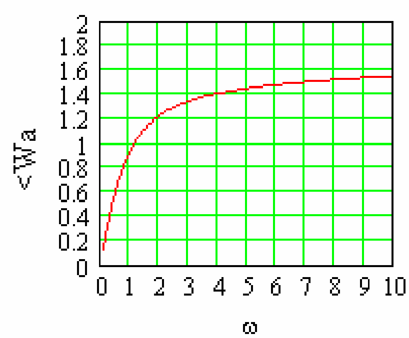

Fig.5 Phase – frequency characteristic

3. Preparation of the testing rig for dynamic identification

As we said before, the target of the experimental identification is the Pelton turbine that belongs to the testing rig for the hydropower-plant “Gemenele” placed in the Hydraulic Machinery Laboratory from the “Politehnica” University of Timisoara.

Beside the advantages of the methods that use sinusoidal testing signals, these methods need special equipment to generate the signals and process the data and – also – a large period of time to perform the experiment.

The input parameter for a Pelton turbine the needle stroke and the output parameter is the speed of the turbine – generator assembly. Therefore, in order to give a harmonic movement to the needle, we designed a sinusoidal signals generator.

In order to prepare the testing rig for dynamic measurements, we have studied several solutions for the sinusoidal signal generators. Therefore, we analyzed the electronic generators of sinusoidal signals. They are easy to use and have the advantage of a great precision (they don’t have moving parts), but we didn’t choose this solution because the complicated electronic scheme. Also, we analyzed the speed variator, presented in [3]. This solution gives both the amplitude and frequency variation for the input parameter, but the size of this equipment is too large and makes it impossible to use in our testing rig. Finally, we choose a cam mechanism with cam displacement follower.

For a hydraulic turbine of Pelton type, the flow rate control is made by modifying the needle stroke that represents exactly the input parameter of the process.

To move the needle upon a sinusoidal law, we designed a cam mechanism. To be able to do that, we re-built the pipe section that has one of the turbines injectors. The new one injector has the same scale and dimensions. Also, this new injector is represented in figure 6.

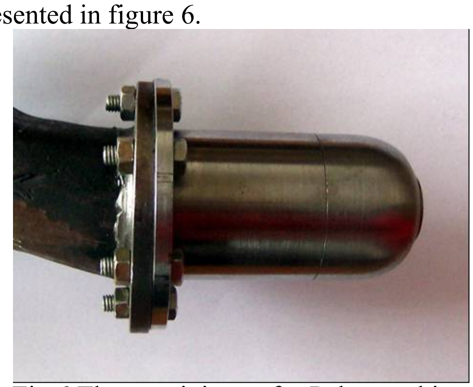

Fig.6 The new injector for Pelton turbine

The cam follower having a displacement movement is exactly the needle shaft (and – of course – is only one for all the cams). This new needle from the regulating nozzle has a longer needle shaft that has on the other end the roller which will move on the real profile of the five cams. The shaft on which the cam is mounted has a conical form for the easiness of cams changing when the measurements take place. All of these are represented in figure 7.

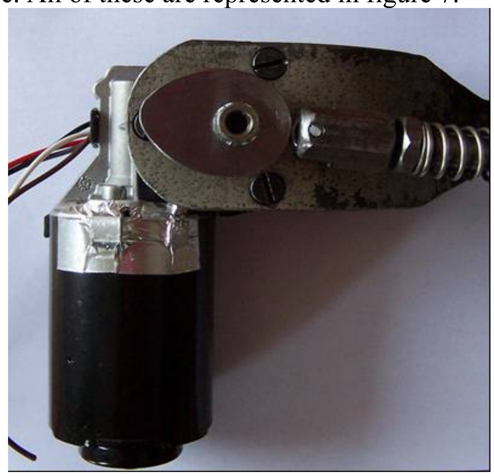

Fig.7 Needle shaft as cam follower

As we said above, in dynamic identification with sinusoidal signals, we need for the input parameter a harmonic variation with different amplitude and frequencies. To obtain different frequencies of the signal, the cam mechanism is run by a d.c. motor having a continuous variable voltage supply. The connection between the electric motor and the cam mechanism is done through a worm driving-gear. For realizing this device, we used a d.c. motor because its speed is a function of voltage.

To give different amplitude for input signal, first of all we designed five sinusoidal cams, having 4, 6, 8, 10 and 12 mm stroke. Analyzing the cam follower displacement, we observed that those sinusoidal cams we designed can’t insure a pure sinusoidal signal for the whole rotation of the cam. With these cams, the input parameter has both sinusoidal and steady variation.

To obtain a continuous sinusoidal signal for the input parameter, finally we designed five cylindrical cams but with different eccentricity of 2, 3, 4, 5 and 6 mm.

In figure8, we present the sinusoidal signals generator that we’ve built and mounted in the testing rig.

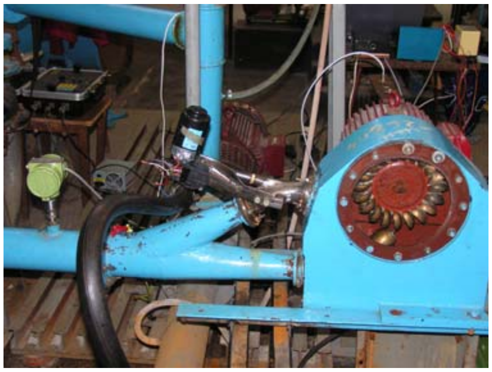

Fig.8 Detail with Pelton turbine and sinusoidal signal generator, mounted in the testing rig

Fig.10 General view of the testing rig

For being able to complete the measurements shown in this paper, after we mounted the sinusoidal signal generator, we improved the testing rig by adding the necessary metering devices.

The characteristic parameters of the Pelton turbine – monitored through the steady and unsteady state – are the flow rate and pressure at the entrance of the turbine, speed of the turbine – generator assembly and electric power measured at the generator terminals. For this purpose, we installed a transducer for each parameter, capable to measure its variation in real time.

The acquisition of signals generated by these four transducers is done using an external data acquisition device (NI-DAQ mx type), produced by National Instruments. This device can be connected to a computer trough a USB port. The computer used for data acquisition and storage is a HP, Pentium III laptop and the application software is VI Logger, delivered together with the data acquisition device. The above presented assembly is shown in figure 9.

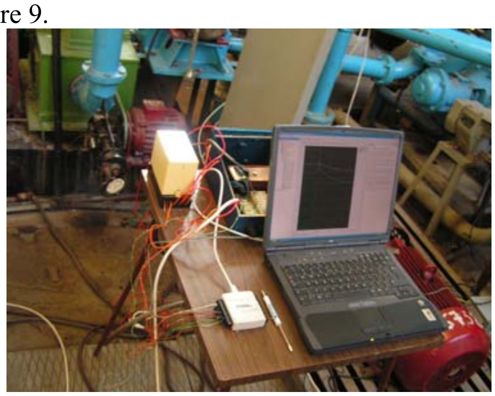

Fig.9 Computer and data acquisition device

Also, in figure 10, we represented a general view of the testing rig, with all the necessary metering devices. At this moment we are able to perform the dynamic measurement and determine the frequency response for Pelton turbine.

4 Frequency response for Pelton turbine

As we presented before, we prepare the testing rig for dynamic identification of hydraulic turbines of Pelton type.

As it was shown in chapter 1, by applying – at the input of the process – a sinusoidal signal of certain amplitude and frequency, at the process output we get a signal having the same frequency, but different amplitude and displaced in phase from the input signal. To determine the frequency response, it is just enough a comparative analysis of the two signals, for different angular frequency ω. Therefore, we are able to obtain $\varphi(\omega)$ and $Y(\omega)$, or other characteristics, like $Re[Y(j\ \omega)]$, $Im[Y(j\ \omega)]$, etc.

In order to perform the dynamic measurements and obtain a sinusoidal variation of the input data, we choose the cam mechanism that we mentioned above.

For each cylindrical cam (that means amplitude of the input signal) I've made a set of measurements for different frequencies. We obtain different frequencies by modifying the supplying voltage of the d.c. motor that runs the cam mechanism. The period of each measurement was one minute, at a sample rate of ten samples per second for every parameter that was measured. The set of data obtained for each measurement was saved in an Excel file and the real-time records were saved in "Stand Probe" file, in VI Logger Tasks, in the data acquisition device software, VI Logger.

In figure 11 we presented one of these real-time records, for four millimeters cam at a frequency of 0,416 Hz.

These real-time variations of the main characteristics of the Pelton turbine, that we presented in the above figures were recorded for all the cams that we designed.

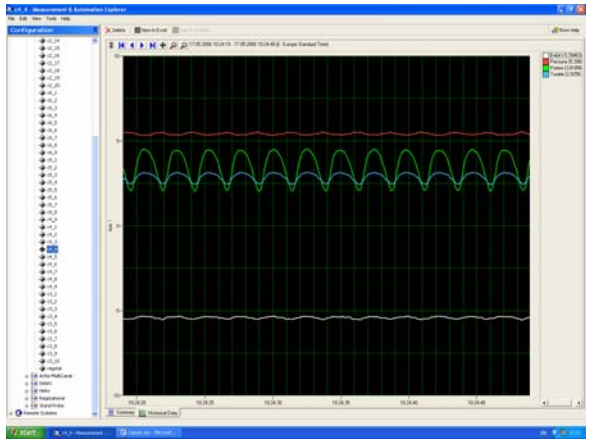

Fig.11 Variation in real time of the main characteristics of Pelton turbine

It means that to each amplitude and frequency of the input signal, the data acquisition device stored the amplitude and phase difference of the output signal. Therefore, a first conclusion results from measurements processing and comparative analysis of the two signals. If the needle stroke is the input parameter, then the flow rate, speed, hydraulic power, electric power and efficiency are in phase with it, and the turbine head and pressure are phase-shifted with the needle stroke.

As we mentioned above, the input parameters of Pelton turbines are the head and the flow rate and the output parameters are the speed and the electric power of the turbine-generator assembly. With the data recorded, for all the cams used, we obtain the gain-phase characteristics.

In the following figures we presented the Nyquist diagrams and the gain-phase characteristics for the cylindrical cam that generate a sinusoidal signal with 4 mm amplitude and 0,416 Hz frequency.

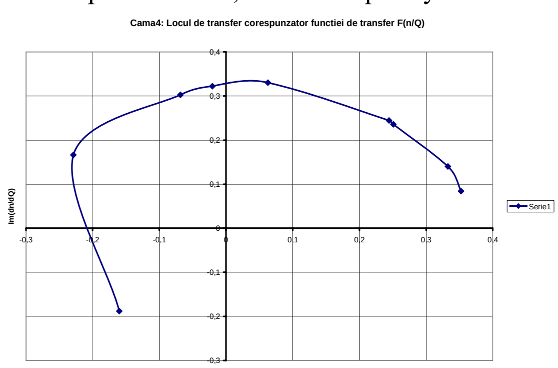

Fig.12 Nyquist diagram for Δn/ΔQ

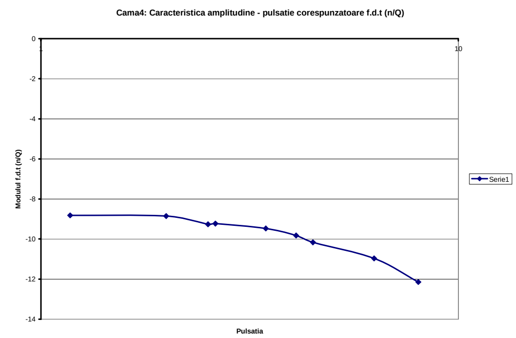

Fig.13 Gain-frequency characteristic corresponding for the transfer function n/Q

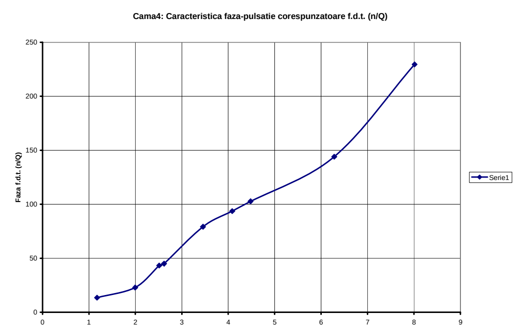

Fig.14 Phase-frequency characteristic corresponding for the transfer function n/Q

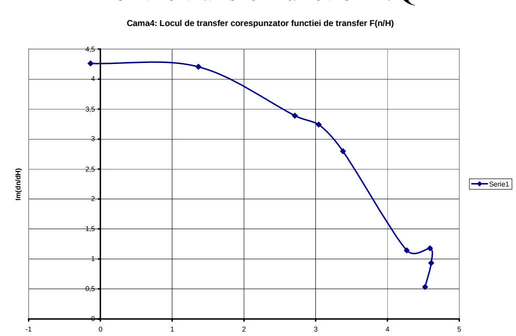

Fig.15 Nyquist diagram for Δn/ΔH

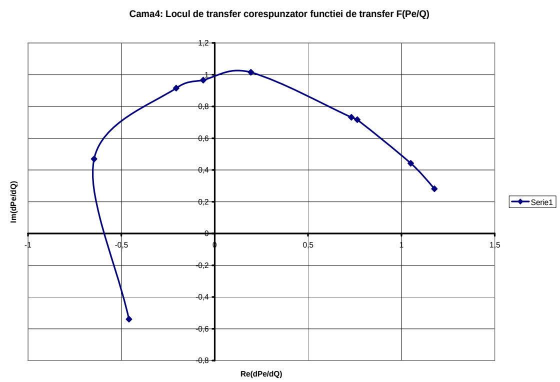

Fig.16 Nyquist diagram for $\Delta P_e/\Delta Q$

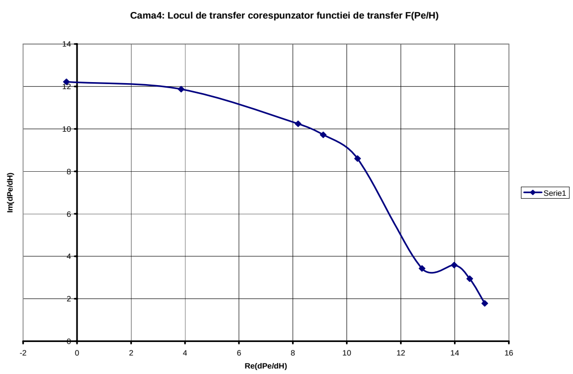

Fig.17 Nyquist diagram for $\Delta P_e/\Delta H$

5 Conclusions

In this paper, we wanted to prove that one of the methods used for experimental determination of dynamic characteristics is the identification method with sinusoidal test signals. For this purpose, we designed and built the sinusoidal signals generator, described in the paper. We improved the testing rig by adding the sinusoidal signals generator and also the necessary metering devices.

To determine the frequency response, it is just enough a comparative analysis of the two signals, for different angular frequency ω. Therefore, we are able to obtain φ(ω) and Y(ω), or other characteristics, like Re[Y(j ω)], Im[Y(j ω)], etc.

Based on the measurements, we determined the variation in time of all Pelton turbine parameters. These variations result when the position of nozzle's needle is modified upon a sinusoidal law.

Also, based on the experimental measurements, we determined the frequency responses and Pelton turbine transfer function

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