MODELING OF MARINE SYSTEMS AND PROCESSES AIMED AT OPTIMAL SHIP HANDLING

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ABSTRACT
The aim of this paper is to demonstrate the successful application of system dynamic simulation modelling at investigating performance dynamics of the marine steam turbine in load conditions, in the example of load of marine synchronous generator. Marine steam turbine at the load of synchronous generator is a complex non-linear system, which needs to be systematically investigated as a unit consisting of a number of subsystems and elements, which are linked by cause-effect (UPV) feedback loops (KPD), both within the propulsion system and with the relevant surrounding. Marine steam turbine will be presented by a set of non-linear differential equations, after which mental-verbal structural models and flowcharts in System dynamics symbols [1 and 2] will be produced, and the performance dynamics in load condition will be simulated in DYNAMO simulation language.
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Keywords: steam turbine, synchronous generator, simulation modelling, simulation

1. SIMULATION MODELLING OF MARINE STEAM TURBINE

1.1. Mathematical model of marine steam turbine

Figure 1. shows (Isakov and Kutljin 1984), a model of marine steam turbine machinery which drives electric synchronous generator.

In the presented case there are two essential situations of ability of energy accumulation:

1. in steam volume (steam area, steam volume of the turbine) and
2. in the turbine rotor,

while the main condenser is observed as a special governing object.

Each of the stated parts is described by its mode equation, that is, by the differential equation which describes the performance dynamics.

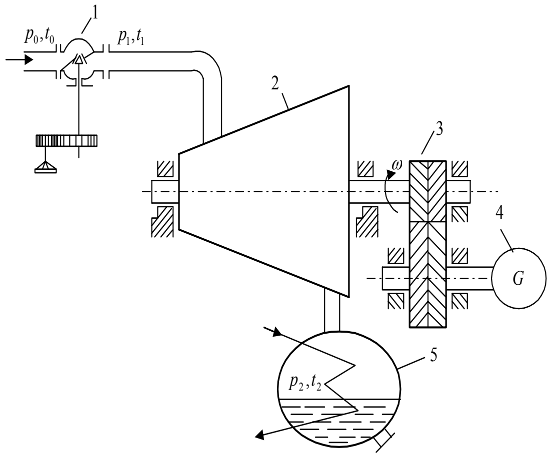

Figure 1: Steam Condensation Machinery of the Marine Turbine Generator
1- governing valve, 2- turbine, 3- reduction gear,
4- generator, 5- condenser

System dynamic mathematical model of the marine steam turbine is defined by means of explicit form of differential equation, or terms, (Isakov and Kutljin 1984):

Equation of the turbine steam volume

$$\frac{d\psi_1}{dt} = \frac{\mu}{R_\mu} + \frac{\Psi_0}{R_{\psi 0}} - \frac{\Psi_1}{R_{\psi 1}} \quad (1)$$

Equation of the turbine rotor dynamics

$$\frac{d\varphi}{dt} = \frac{\psi_1}{T_{\psi 1}} - \frac{\psi_2}{T_{\psi 2}} - \frac{\varphi}{T_\varphi} \quad (2)$$

Where the following symbols stand for:

ψ_1 - relative increment of the steam pressure in the steam volume,
φ - relative increment of the turbine rotor angular velocity,
$T_{\psi 1}$ - time constant of the turbine rotor,
T_φ - time constant of the turbine rotor,
R_μ - time constant of the steam volume,
$R_{\psi 1}$ - time constant of the steam volume,
ψ_0 - relative increment of the steam pressure before the manoeuvring valve,
$R_{\psi 0}$ - time constant of the turbine rotor,
μ - relative change of the position of the manoeuvring valve,
ψ_2 - relative increment of the steam pressure in the main condenser,
$T_{\psi 2}$ - time constant of the boiler.

1.2. System dynamic mental-verbal model of marine steam turbine

On the basis of a mathematical model, or the explicit form of the mode equation of the marine steam turbine (1) it is possible to determine the mental-verbal model of the marine steam turbine:

- If the relative increment of the steam pressure in the turbine steam volume ψ_1 increases the speed of the relative increment of the steam pressure in the turbine steam volume ψ_1 will decrease, which gives a negative cause-effect link (-).

- If the relative increment of the steam pressure before the manoeuvring valve ψ_o increases the speed of the relative increment of the steam pressure in the turbine steam volume will increase, which gives a positive cause-effect link (+).

- If the relative change of the position of the manoeuvring valve μ increases the speed of the relative increment of the steam pressure in the turbine steam volume will increase, which gives a positive cause-effect link (+).

- If the time constant of the steam volume R_μ increases the speed of the relative increment of the steam pressure in the turbine steam volume will decrease, which gives a negative cause-effect link (-).

- If the time constant of the turbine rotor $R_{\mu 0}$ increases the speed of the relative increment of the steam pressure in the turbine steam volume will decrease, which gives a negative cause-effect link (-).

- If the time constant of the steam volume $R_{\mu 1}$ increases the speed of the relative increment of the steam pressure in the turbine steam volume will increase, which gives a positive cause-effect link (+).

On the basis of the mathematical model, or the explicit form of the mode equation of the marine steam turbine (2) it is possible to determine the mental-verbal model of marine steam turbine:

- If the relative increment of the steam pressure in the steam volume ψ_1 increases the speed of the relative increment of the turbine rotor angular velocity will increase, which gives a positive cause-effect link (+).

- If the relative increment of the turbine rotor angular velocity φ increases the speed of the relative increment of the turbine rotor angular velocity will decrease, which gives a negative cause-effect link (-).

- If the relative increment of the steam pressure in the main condenser ψ_2 increases the speed of the relative increment of the turbine rotor angular velocity will decrease, which gives a negative cause-effect link (-).

- If the time constant of the turbine rotor $T_{\psi 1}$ increases the speed of the relative increment of the turbine rotor angular velocity will decrease, which gives a negative cause-effect link (-).

- If the time constant of the turbine rotor T_{φ} increases the speed of the relative increment of the turbine rotor angular velocity will increase, which gives a positive cause-effect link (+).

- If the time constant of the turbine rotor $T\psi_1$ increases the speed of the relative increment of the turbine rotor angular velocity will decrease, which gives a negative cause-effect link (-).

- If the time constant of the turbine rotor $T_{\psi 2}$ increases the speed of the relative increment of the turbine rotor angular velocity will increase, which gives a positive cause-effect link (+).

1.3. System dynamic structural model of the marine steam turbine

On the basis of the stated mental-verbal models it is possible to produce structural diagrams of the marine steam turbine, as shown in Figures 2, 3 and 4.

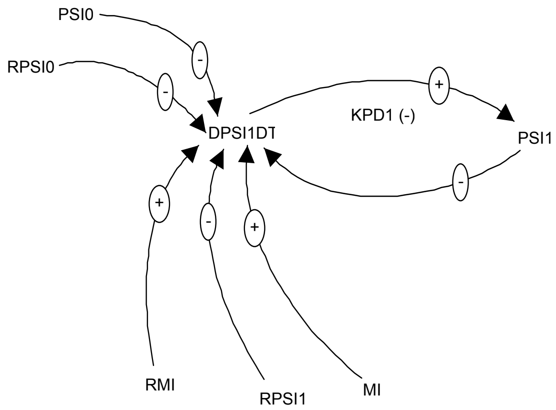

Figure 2: Structural Model of the Steam Turbine Steam Volume

In the observed system there is the feedback loop (KPD1).

KPD1(-):PSI1=>(-)DPSI1DT=>(+)DPSI1DT=> (+)PSI1; which has self-regulating dynamic character (-), because the sum of negative signs is an odd number.

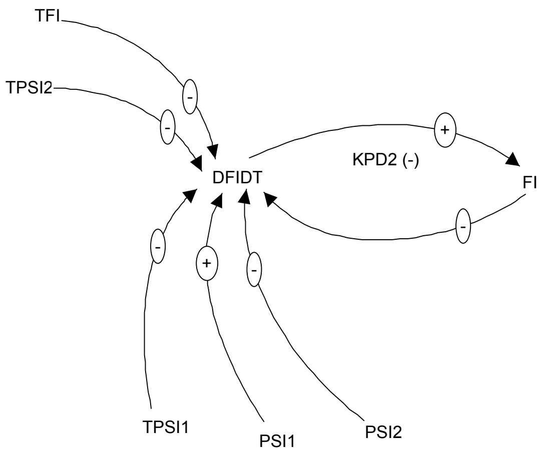

Figure 3: Structural Model of the Marine Steam Turbine – Rotor Dynamics

In the observed system there is the feedback loop (KPD2).

KPD2(-):FI=>(-)DFIDT=>(+)DFIDT=>(+)FI; which has self-regulating dynamic character (-), because the sum of negative signs is an odd number.

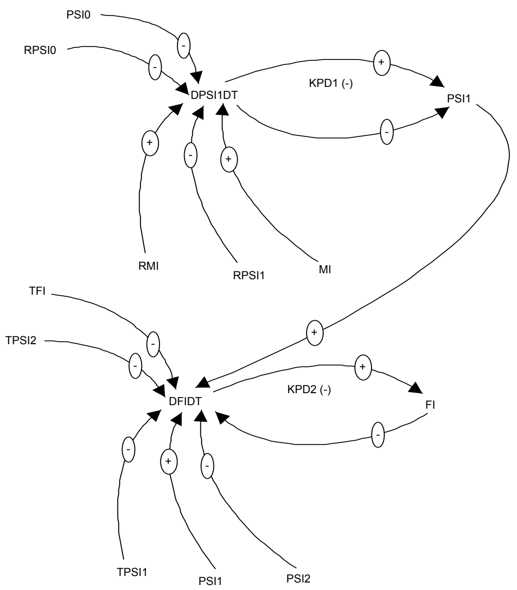

Figure 4: Global and Structural Model of the Marine Steam Turbine

1.4. System dynamic flowcharts of the marine steam turbine

Flowcharts shown in Figures 5, 6 and 7 are based on the produced mental-verbal and structural models.

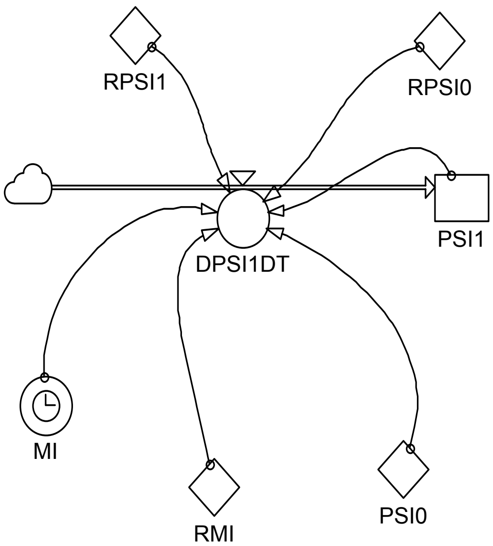

Figure 5: Marine Steam Turbine Flowchart – Steam Volume

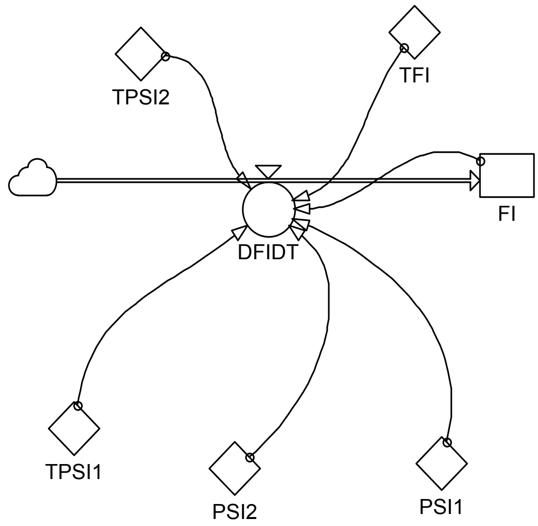

Figure 6: Marine Steam Turbine Flowchart – Rotor Dynamics

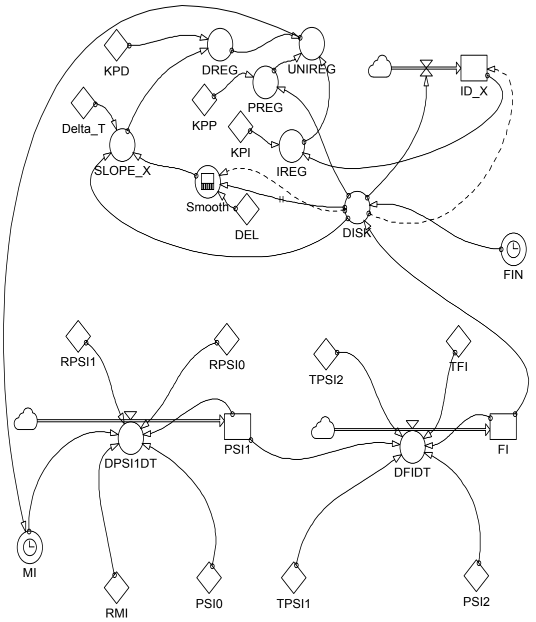

Figure 7: Global Flowchart of the Marine Steam Turbine with built-in PID Governor

MACRO DYNAMO functions built in the simulation model of the marine steam turbine: CLIP, STEP, UNIREG

2. QUANTITATIVE SIMULATION MODEL OF THE MARINE STEAM TURBINE

Simulation model of the marine steam turbine in the DYNAMO simulation language:

```
MACRO SLOPE(X, DEL)
*
A SLOPE.K=(X.K-SMOOTH(X.K,DEL))/DT
*
MEND
* ...............................
* UNIREG-PID REGULATOR:
*
MACRO UNIREG(X, KPP, KPI, KPD)
*
INTRN IBD, PREG, IREG, DREG
*
A PREG.K=KPP*X.K
*
L IBD.K=IBD.J+DT*X.J
*
N IBD=X
*
A IREG.K=KPI*IBD.K
*
A DREG.K=KPD*SLOPE (X.K, DT)
*
A UNIREG.K=PREG.K+IREG.K+DREG.K
*
MEND
*
R DPSI1DT.KL=(MI.K/RMI.K)+
(PSIO.K/RPSIO.K)-(PSI1.K/RPSI1.K)
*
L PSI1.K=PSI1.J+DT*DPSI1DT.JK
*
N PSI1=0
*
A MI.K=CLIP(STEP(.05,10)+STEP(.95,50)+
PIDFI.K,0,DELAY1(RE.K,2),1E-16)
*
A RMI.K=5
*
A PSIO.K=0
*
A RPSIO.K=5
*
A RPSI1.K=5
*
SAVE DPSI1DT, PSI1, MI, RMI, PSIO, RPSIO, RPSI1
*
R DFIDT.KL=(PSI1.K/TPSI1.K)-
(PSI2.K/TPSI2.K)-(FI.K/TFI.K)
*
L FI.K=FI.J+DT*DFIDT.JK
*
N FI=0
*
A TPSI1.K=5
*
A PSI2.K=0
*
A TPSI2.K=5
*
A TFI.K=.1+MEL.K
*
* UNIREG-PID REGULATOR INSTALLING:
*
A DISK.K=FIN.K-FI.K
*
A FIN.K=STEP (.05, 10) +STEP (.95, 50)
*
A PIDFI.K=CLIP (UNIREG (DISK.K, KPP, KPI,
KPD), 0, TIME.K, 10)
*
C KPP=100
*
C KPI=0.1
*
C KPD=100
SAVE DISK, PIDFI, FIN
*
SAVE TPSI1, PSI2, TPSI2, FI, TFI
```

3. INVESTIGATING PERFORMANCE DYNAMICS OF THE MARINE STEAM TURBINE IN LOAD CONDITIONS

After system dynamics qualitative and quantitative simulation models were produced, all possible operating modes of the system will be simulated in a laboratory, using one of the simulation packages, most frequently DYNAMO (Richardson and Aleksander 1981) or POWERSIM (Byrknes 1993).

After the engineer, designer or a student have conducted a sufficient number of experiments, or scenarios, and an insight has been obtained about the performance dynamics of the system using the method of heuristic optimisation, optimisation of any parameters in the system may be performed, provided that the model is valid.

In the presented scenario the two phases of the momentum (starting) of the marine steam turbine will be presented, as well as connecting the marine synchronous generator in TIME = 100 seconds in the following way:

1. The manoeuvring valve of the marine steam opens for 5% of the rated opening in TIME = 10 seconds. The lower RPM is maintained for 50 seconds (about 5% of the rated RPM or 500-600/min.) for even heating of turbine masses.
2. In TIME = 50 seconds the manoeuvring (governing) valve opens to the rated opening (100%) MI=STEP (.05, 10) +STEP (.95, 50) and increases the marine steam turbine to the rated RPM.

   In TIME = 10 seconds the relative increment of the steam pressure in steam volume is increasing (PSI1) and also the relative increment of the angular speed of the marine steam turbine rotor (FI).

3. In TIME = 100 seconds a step load is made from 50% of the rated load, the same as in the previous scenario, and by adding stochastic load:
   TFI.K=STEP (2.5,100)*(1-NOISE())
4. Electronic PID governor has been installed, of parameters: KPP = 100, KPI= .1 and KPD = 100.

Graphic presentation of the simulation results:

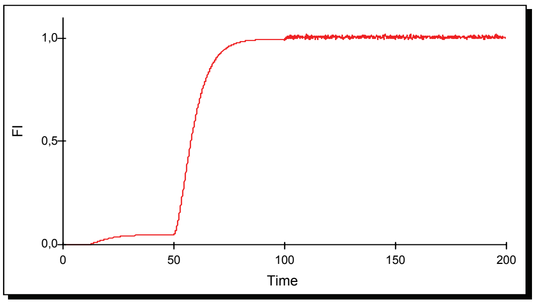

Figure 8: Relative Increment of the Angular Speed of the Rotor FI

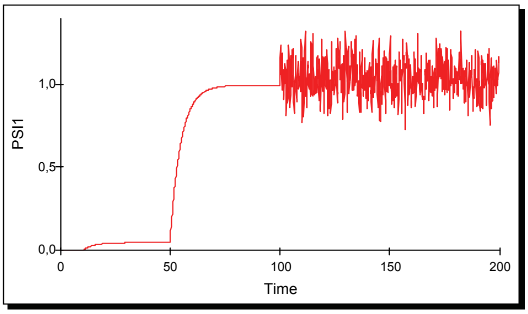

Figure 9: Relative Increment of the Steam Pressure in the Steam Volume PSI1

The results of the simulation show the real performance dynamics of the marine steam turbine, which at idle speed starts in at least two stages, and which gives sufficient time for all the parts to heat equally. This scenario may be used in heuristic optimisation of the PID governor coefficient. In fact, if the allowed criteria are reached, then in normal operating conditions the selected combination of PID governor will certainly be satisfactory. The scenario shows that when selecting the coefficient of the universal PID governor (KPP = 100, KPI = .1, KPD = 100), it will soon lead to stabilisation of the transition phase, within the limits of the rated speed deviation of the marine steam turbine rotor (approx. 4% of the rated RPM).

4. CONCLUSION

System dynamics is a scientific method which allows simulation of the most complex systems. The method used in the presented example demonstrates a high quality of simulations of complex dynamic systems, and provides an opportunity to all interested students or engineers to apply the same method for modelling, optimising and simulating any scenario of the existing elements.

Furthermore, the users of this method of simulating continuous models in digital computers have an opportunity to acquire new information in dynamic system performance. The method is also important because it does not only refer to computer modelling, but also clearly determines mental, structural and mathematical modelling of the elements of the system.

This brief presentation gives to an expert all the necessary data and the opportunity to collect information about the system in fast and scientific method of investigation of a complex system.

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