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SYSTEM DYNAMICS SIMULATION MODEL OF THE MARINE DIESEL ENGINE

SUSTAV DINAMIČKI SIMULACIJSKI MODEL BRODSKOG DIESEL MOTORA

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1. Abstract

Dynamic research of the marine Diesel engine is relatively a big problem , because it is a "complex system" where particular elements and system as a whole should be analysed.

In the paper, this problem is elaborated with system dynamics and by forming simulation models:

- System dynamics mathematical model of marine Diesel engine
- *System dynamics structural model of marine Diesel engine*
- *System dynamics computer model of marine Diesel engine.*

Authors suggest using the represented models in education process, and when designing new constructions.

2. Introduction

In the marine propulsion Diesel engine, the heat energy is transformed in dynamic process to assure, in the first place, movement of the ship. In consideration of event dynamics and complex process in the marine propulsion Diesel engine, the process should be systematically analysed and examined.

Dynamics work regulation is a process where balance state of energy, materials or signals are disturbed at definite time.

System dynamics is methodology of research, modelling, simulation and optimising of complex dynamic processes.

Quantitative systematic dynamic modelling is mathematical modelling where equations state system are given as a whole or as a total amount of equations of component systems. System dynamic quantitative model is an efficient and rational method for modelling complex systems.

Qualitative modelling enables dynamics observation and solution to the problem. At that approach, special importance has qualitative modelling supported by mental-verbal flow graph and structural model.

3. System dynamics mathematical model of the marine Diesel engine

Marine Diesel engine could be presented schematically as on fig. 3.1. where the parts of the engine are shown: basic Diesel engine (DM) , exhaust gas receiver (KIP), air receiver (KZ), gas turbine (PT), compressor (TK), high pressure fuel pump (VTSG), regulator (R). Mathematical model presents static and dynamics work regulations for each component and the system as a whole.

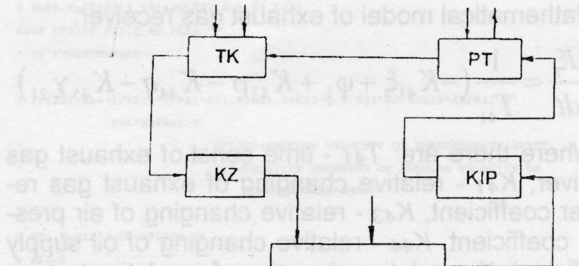

Figure 3.1. Scheme of marine Diesel engine

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Mathematical model DM (1) is:

$$\frac{d\varphi_1}{dt}=\frac{1}{T_{11}}\left(-K_{11}\varphi_1+q+K_{13}\rho-K_{14}\alpha_{11}\right)$$

Where there are: φ_1 - relative changing of angular velocity, q -relative changing of fuel, ρ - relative changing of air pressure, α_{11} relative changing of load power, T_{11}-time const., K_{11} -relative changing of coefficient self-adjusting, K_{13}-relative changing of air pressure coefficient, K_{14} - relative changing of loading coefficient.

Mathematical model of turbocharger is:

$$\frac{d\varphi_2}{dt}=\frac{1}{T_{21}}\left(-K_{21}\varphi_2+\xi+K_{23}q+K_{24}\rho+K_{25}\chi_{21}-K_{26}\chi_{22}\right)$$

Where there are: φ_2- relative changing of angular velocity of turbocharger shaft, ξ - relative changing of exhaust gas pressures , χ_{21}-relative changing of regulating turbine blade, χ_{22} - relative changing of regulating compressor blade, T_{21} - time const. of the turbocharger, K_{21} - relative changing of self adjusting turbocharger coefficient, K_{23} - relative changing of fuel coefficient, K_{24} - relative changing of air pressure coefficient, K_{25}- relative changing of turning angular of regulating turbine blade coefficient, K_{26} - relative changing of turning angular of regulating compressor blade coefficient.

Mathematical model od air receiver:

$$\frac{d\rho}{dt}=\frac{1}{T_{31}}\left(-K_{31}\rho+\varphi_2+K_{33}\varphi_1-K_{34}\chi_{22}\right)$$

Where there are: T_{31}- time const.of air receiver, K_{31}- relative changing of air receiver coefficient, K_{33}- relative changing of angular velocity of turbocharger shaft coefficient, K_{34}- relative changing of the compressor coefficient.

Mathematical model of exhaust gas receiver:

$$\frac{d\xi}{dt}=\frac{1}{T_{41}}\left(-K_{41}\xi+\varphi_1+K_{43}\rho-K_{44}q-K_{45}\chi_{21}\right)$$

Where there are: T_{41} - time const.of exhaust gas receiver, K_{41} - relative changing of exhaust gas receiver coefficient, K_{43} - relative changing of air pressure coefficient, K_{44} - relative changing of oil supply coefficient, K_{45} -relative changing of regulating turbine blade.

Mathematical model of VTSG:

$$q=K_{51}\chi_{51}-K_{52}\varphi_1$$

Where there are: K_{51} - relative changing of self regulating VTSG coefficient, K_{52} - relative changing of VTSG coefficient, χ_{51}- relative changing.

$\frac{d\varphi_1}{dt}$ - angular velocity, $\frac{d\varphi_2}{dt}$ -angular velocity of turbocharger shaft, $\frac{d\rho}{dt}$ - velocity changing of air pressure, $\frac{d\xi}{dt}$ - velocity changing of exhaust gases pressure.

4. System dynamics structural model of the marine Diesel engine

Based on dynamics mathematical model of the marine Diesel engine, dynamics structural model is formed. On figure 4.1. there is dynamics structural model of Diesel engine consisted of models: Diesel engine, turbocharger, exhaust gas receiver, air receiver and high pressure fuel pump.

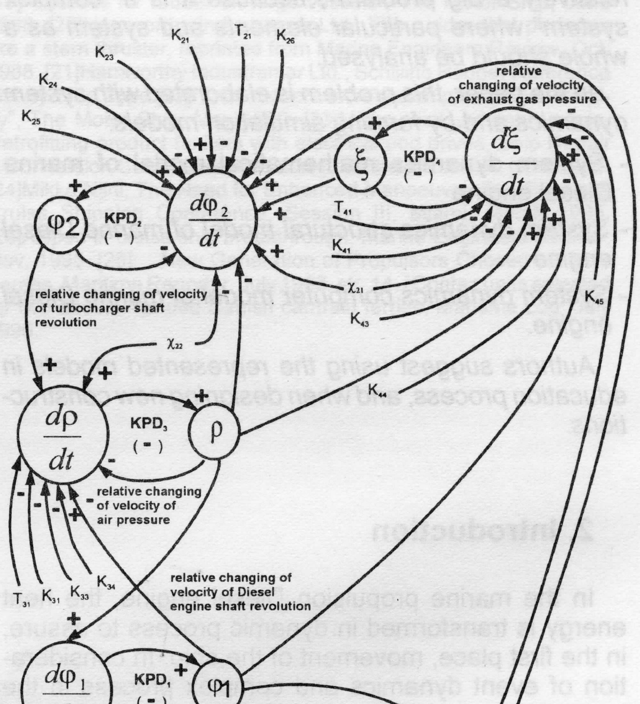

Figure 4.1. Structural dynamics model of marine Diesel engine.

On figure 4.1. the interaction between particular elements of system is visually presented and the influence of all parameters upon the individual elements through which other elements of the systems are affected.

Feedback loop of Diesel engine is "negative", it has selfcontrol character in consideration of two feedbacks where one of them has "positive" and the other "negative" dynamic character. If $\frac{d\varphi_1}{dt}$ increases, φ_1 will also increase, what means "positive" dynamics charactef o internal feedback. If relative angular velocity φ_1 increases, the speed change of relative angular velocity will decrease, i.e. "negative" sign of dynamic character of internal feedback. The influence of other parameters on relative angular velocity of the shaft of the engine is also seen on the structural dynamic of Diesel engine, for example: if T_{11} increases, $\frac{d\varphi_1}{dt}$ decreases, that is the sign of internal feedback is "negative".

The second part of the dynamics model enables the changing of relative velocity of the turbocharger shaft φ_2 to be examined, if $\frac{d\varphi_2}{dt}$ increases, φ_2 will also increase, what means "positive" dynamic character of internal feedback. If φ_2 increases, the speed change of relative angular velocity will decrease, i.e. the dynamic character of internal feedback is "negative". In this feedback loop there are two internal feedbacks, one is of "positive" and the other of "negative" dynamic character i.e. the feedback circle of turbocharger is of "negative global dynamic character".

If the time constant T_{21} increases, the speed change of the turbocharger camshaft angular velocity decreases, i.e. the sign of internal feedback is "negative". If coefficient K_{21} increases, $\frac{d\varphi_2}{dt}$ decreases i.e. the sign of internal feedback is "negative".

If coefficient K_{23} increases, the speed change of turbocharger angular velocity will increase i.e. the sign of internal feedback is "positive".

Similarly, the influence of other coefficients of dynamic regulations of turbocharger can be analysed. Influences on dynamic regulations of air receiver can be determined on the basis of structural model. If the speed change of relative air pressure $\frac{d\rho}{dt}$ increases, the change of relative air pressure ρ in the air receiver will also increase, that is the dynamic character of internal feedback is "positive". If ρ increases, $\frac{d\rho}{dt}$ will decrease that is the dynamic character of internal feedback is "negative".

There are two feedbacks in the feedback loop of air receiver, one is of "positive" and the other is of "negative" dynamic character, it means that the feedback loop has "negative" global dynamic character, and selfcontrol is carried out. The influence of the particular parameters on the air receiver could be easily determined considering the sign of adequate coefficient.

In structural dynamic model on figure 4.1. global dynamic character of exhaust gas receivers and high pressure fuel pumps can be similarly determined and the influence of particular parameters as well.

5. System dynamics computer simulation model of marine Diesel engine

System dynamics computer simulation model of marine Diesel engine is determined by DYNAMO - high level software package. This model is, at the same time, "continual" and "discrete", because the solution time interval DT can be chosen as "half or less of the shortest first-order time delay in the marine Diesel engine". This means that time interval can be chosen so short that the analysis shows as if the model were "continual".

Program 1

```
* SYSTEM DYNAMICS COMPUTER SIMULATION MODEL
* ***************************************************************************
* I DIESEL ENGINE:
R DFI1DT.KL=(1/T11)*(-K11*FI1.K+Q.K+K13*RO.K-K14*ALFA.K)
*                          DFI1DT=ANGULAR VELOCITY
*                          T11=TIME CONST. ENGINE
*                          K11=RELATIVE CHANGING OF SELF-ADJUSTING COEFFICIENT
*                          FI1=RELATIVE CHANGING OF ANGULAR VELOCITY
*                          K13=RELATIVE CHANGING OF AIR PRESSURE COEFFICIENT
*                          Q=RELATIVEE CHANGING OF FUEL
*                          RO=RELATIVE CHANGING OF AIR PRESSURE
*                          K14=RELATIVE CHANGING OF LOADING COEFFICIENT
*                          ALFA11=RELATIVE CHANGING OF LOAD POWER
L FI1.K=FI1.J+DT*DFI1DT.JK
N FI1=0
*
*                          DT=TIME OF COMPUTING
*
C T11=1
C K11=1.6
C K13=.3
C K14=.2
*
A ALFA.K=STEP(.3,40)+PULSE(.5,1,60,160)
SAVE DFI1DT,FI1,Q,RO,ALFA
* II TURBOCHARGER:
*
R DFI2DT.KL=(1/T21)*(-K21*FI2.K+KSI.K+K23*Q.K-K24*RO.K+K25*KAPA21.K^
        -K26*KAPA22.K)
*                          DFI2DT=ANGULAR VELOCITY OF TURBOCHARGER SHAFT
*                          FI2=RELATIVE CHANGING OF ANGULAR VELOCITY OF
*                              TURBOCHARGER SHAFT

L FI2.K=FI2.J+DT*DFI2DT.JK
N FI2=0
*
C T21=1
C K21=1
*
C K23=.3
C K24=.5
C K25=.2
A KAPA21.K=STEP(.3,10)
C K26=1
A KAPA22.K=STEP(.4,5)
SAVE DFI2DT,FI2,KSI,KAPA21,KAPA22
* III AIR RECEIVER:
```

```
R DRODT.KL=(1/T31)*(-K31*RO.K+FI2.K-K33*FI1.K+K34*KAPA22.K)
*
L RO.K=RO.J+DT*DRODT.JK
N RO=0
*                          DRODT=VELOCITY CHANGING OF AIR PRESSURE
*                          T31=TIME CONST. OF AIR RECEIVER
C T31=1
C K31=2
C K33=2
C K34=2
*
SAVE DRODT
* IV EXHAUST GASES RECEIVER:
R DKSIDT.KL=(1/T41)*(-K41*KSI.K+FI1.K+K43*RO.K-K44*Q.K-K45*KAPA21.K)

L KSI.K=KSI.J+DT*DKSIDT.JK
*
N KSI=0
*                          DKSIDT=VELOCITY CHANGING OF EXHAUST GASES PRESSURE
*                          T41=TIME CONST.OF EXHAUST GASES RECEIVER
C T41=1
C K41=1
C K43=.1
C K44=.2
C K45=.1
*
SAVE DKSIDT
* V FUEL PUMP:
*
A Q.K=K51*KAPA51.K-K52*FI1.K
C K51=1.15
*
A KAPA51.K=STEP(.5,20)
C K52=.1
*
*                                KAPA51=RELATIVE CHANGING
*                                K52=RELATIVE CHANGING OF VTSG COEFFICIENT
*                                K51=RELATIVE CHANGING OF SELF REGULATING VTSG
*                                        COEFFICIENT
SAVE KAPA51
SPEC DT=.01,LENGTH=100,SAVPER=1
* ***********************************************************************
```

5.1. The scenario of simulation

Scenario of the simulation for the marine Diesel engine operation is: observed engine loading has been changed in 40 sec. for 30% of the nominal value in accordance with STEP function, in 60 sec. it has been changed for 50% in accordance with PULSE function. In 10 sec. χ_{21} has been changing for 30% in accordance with STEP function. In 5 sec χ_{22} has been changing for 40% in accordance with STEP function. In 20 sec χ_{51} has been changing for 50% in accordance with STEP function.

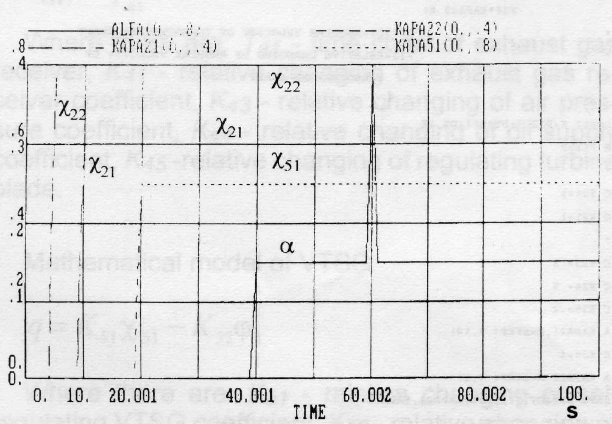

Figure 5.1. Parameters changing in accordance with I scenario

Figure 5.1. shows the flow graphs of changing parameters according to scenario I: curve α shows the changing of loading in 40. and 60. sec, curve χ_{21} shows the changing of turning of regulating turbine blade in 10. sec, curve χ_{22} shows the changing of turning of regulating compressor blade in 5. sec., and curve χ_{51} shows relative changing of selfregulating fuel pump in 20 sec.

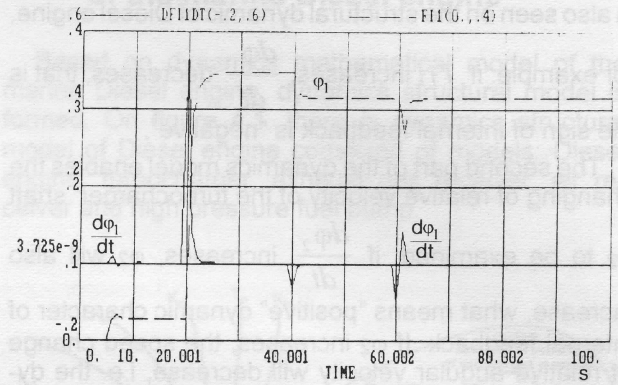

Figure 5.2. Changing of relative angular velocity of Diesel engine camshaft φ_1 and $\frac{d\varphi_1}{dt}$

Figure 5.2. shows the flow graphs changing of $\frac{d\varphi_1}{dt}$ and φ_2, and with those curves influences of changing of particular parameters can be analysed according to the scenario I. If changing φ_1 has been analysed, in 5. sec. because of changing χ_{22} for 40%, φ_1 is changed for 3%, in 20 sec. φ_1 is changed, because of changing χ_{51}, for 50% with delay and φ_1= 34,8% in t = 29 sec, in 40 sec. φ_1 is changed with delay because of changing of loading and φ_1= 31,5% in t = 50 sec, in 60 sec as well - to settle itself in 70 sec.

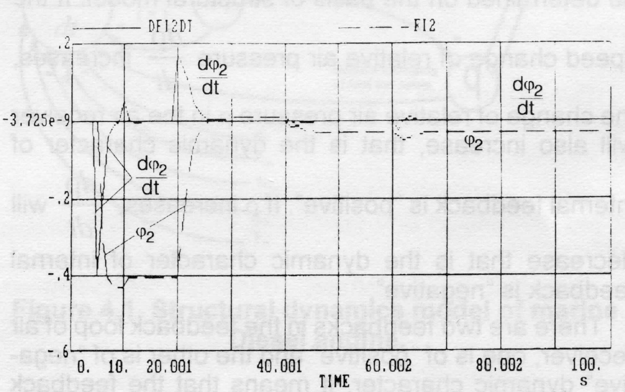

Figure 5.3. Changing of relative angular velocity of turbocharger camshaft φ_2 and $\frac{d\varphi_2}{dt}$

On figure 5.3. influence of changing known parameters an $\frac{d\varphi_2}{dt}$ and φ_2 can be analysed according to scenario I.

Those influences are different, and noticable on the graphs, for exaple: in 5 sec. φ_2 is changed from 0. to -0,432 in 10 sec, φ_2 in 15 sec. is - 0,407 and in 25 sec φ_2 = - 0,008.

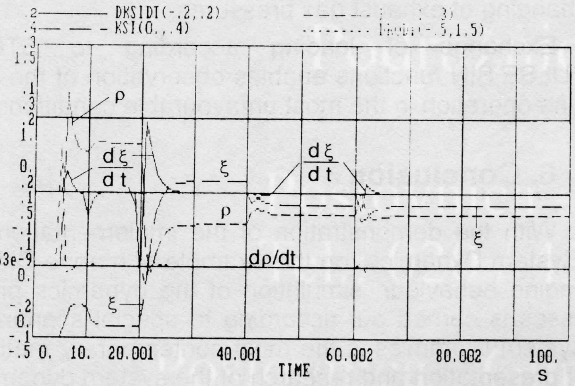

Figure 5.4. Changing of relative value of air pressure ρ and exhaust gas pressures and the velocity of those changes

Figure 5.4. enables analysing $\frac{d\zeta}{dt}$, ζ, ρ, $\frac{d\rho}{dt}$ by changing parameters set in I scenario.

II Scenario of the simulation for the marine Diesel engine: observed engine loading has been changed in 40 sec. for 40% in accordance with STEP function and in 50 sec. has been changed in accordance with SIN function with amplitude which is 10% of nominal value. In 5 sec. χ_{22} has been changing for 40% in accordance with STEP function, in 10 sec χ_{21} has been changing for 30% in accordance with STEP function , and in 20 sec. χ_{51} has been changing for 50% in accordance with STEP function.

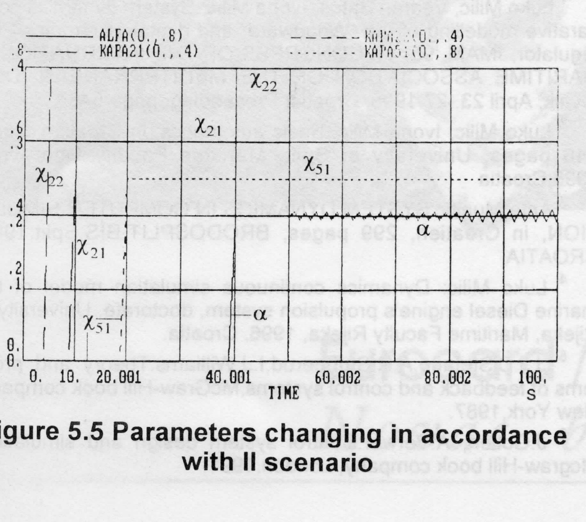

Figure 5.5 Parameters changing in accordance with II scenario

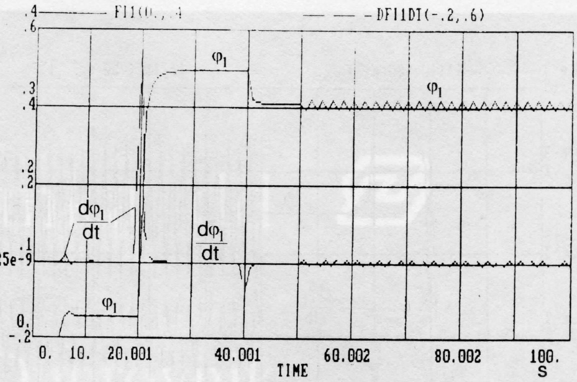

Figure 5.6.Response φ_1 and $\frac{d\varphi_1}{dt}$ on parameters changing according to the II scenario

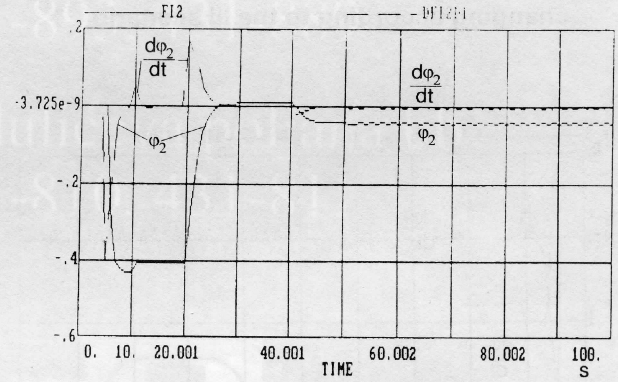

Figure 5.7. Response φ_2 and $\frac{d\varphi_2}{dt}$ on parameters changing according to the II scenario

III Scenario of the simulation for the marine Diesel engine: loading of Diesel engine is changing in 30 sec. for 20% according to STEP function, and in 50 sec it is changing according to SIN function with amplitude which is 20% of the nominal value. The value of χ_{21} is changing in 10 sec. for 20% of nominal value, χ_{22} is changing in 5 sec. for 10% and χ_{51} in 20 sec. for 10%. The values of the χ_{21}, χ_{22} and χ_{51} and are changing according to STEP function.

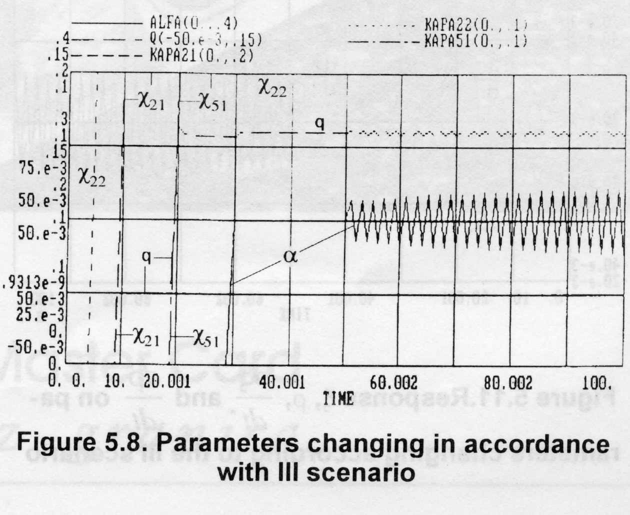

Figure 5.8. Parameters changing in accordance with III scenario

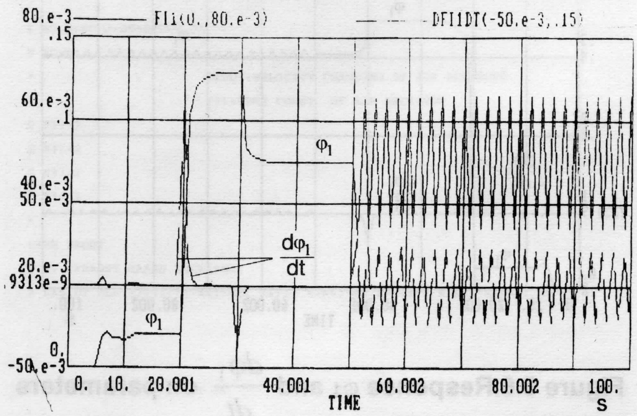

Figure 5.9. Response φ_1 and $\frac{d\varphi_1}{dt}$ on parameters changing according to the III scenario

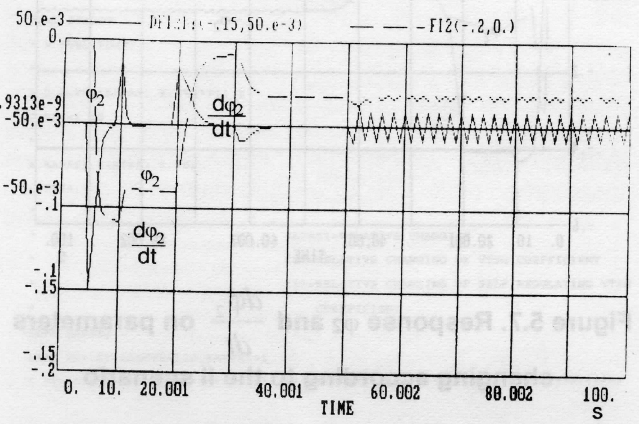

Figure 5.10. Response φ_2 and $\frac{d\varphi_2}{dt}$ on parameters changing according to the III scenario

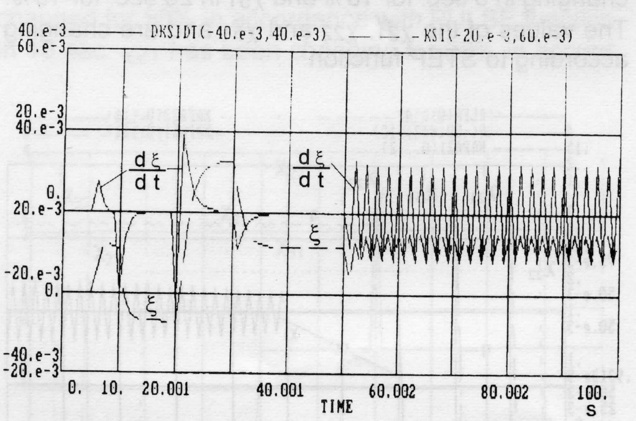

Figure 5.11.Response ξ, ρ, $\frac{d\xi}{dt}$ and $\frac{d\rho}{dt}$ on parameters changing according to the III scenario

5.2. Results of the simulation

From numerical tables and flow graphs from figures 5.1. to 5.11, engine operation and changing of parameters value relevant to that operation can be observed. Only few parameters are simulated which clearly illustrate dynamic operation regulation of Diesel engine, primarily, relative changing of angular velocity of the engine shaft, relative changing of angular velocity of the turbocharger, changing of the air pressure and changing of exhaust gas pressures.

Exchange of loading according to STEP, PULSE,SIN functions enables observation of the engine operation in the most unfavourable conditions.

6. Conclusion

With the demonstration of the implementation of "System Dynamics" on the example of marine Diesel engine behaviour, simulation of the dynamics processes is carried out according to special scenarios. System Dynamics is the most contemporary method of presentation and research of the system dynamics behaviour.

Structural dynamics model enables visual representation of very complex systems such as marine Diesel engine. Based on structural model, mental-verbal model can be determinated and through dynamic mathematical models and structural dynamic model, flow graphs are formed in DYNAMO symbols, which show the state of the system, flows between certain conditions , function of the operation between certain conditions of the system, information connections between conditions of the systems and operating function.

Set scenarios would be a disaster on the real marine Diesel engine, however, digital computer and this software model can experiment without danger to reality.

The use of computer simulation can chose optimal values of the parameters of marine Diesel engine

Computer simulation is convenient for dynamic processing demonstration in education process.

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