A SYNTHETIC ALGORITHM FOR UNDESIRED DYNAMICS ELIMINATION WITH APPLICATION TO MARINE BOILER CONTROL

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ABSTRACT

In multi-variable control systems, each output depends on all inputs, each multiplied by a sum of transfer functions which constitute an element of the transfer matrix. In other words, in boilers control, the deviation of actual steam pressure and drum water level depend on the deviations in pressure and level command signals and on the deviation in the steam evaporation rate, too. It is intended in this algorithm to realize the disengagement and elimination of the interaction in steady state between the pressure and level-evaporation elements and similarly to eliminate the dependence of level on pressure and evaporation transfer functions, in steady state.

Keywords: Steam plants, Identification, Boiler models, Boiler control, Computer-aided control systems design.

Nomenclature

[A]	(2x2) Matrix of transfer functions	
[B]	(2x3) Matrix of transfer functions	
[C]	(2x3) Matrix of transfer functions	
[D]	(2x2) Matrix of transfer functions	
F_F	Burned fuel rate	(kg/s)
F_s	Evaporation steam rate	(kg/s)
F_w	Feed water rate	(kg/s)
G_i,	(i=1,6) i^{th} transfer function of interacting controller	
H_i,	(i=1,6) i^{th} transfer function of the boiler	
H_p	Arbitrary chosen transfer function for $\Delta P_c/\Delta P_c = G_1 H_1 + G_2 H_6 = \frac{49}{1+2S}$	
H_y	Arbitrary chosen transfer function for $\Delta Y_c/\Delta Y_e = G_4 H_4 + G_4 H_2 = \frac{49}{1+2S}$	
K_i(i=1,6)	Gains of H_i, (i=1,6)	
P_c	Actual steam pressure	(kP_a)
P_e	Error signal of steam pressure	($K P_a$)
P_R	Reference steam pressure	(KP_a)
S	Laplace operator	(s^{-1})
Y_c	Actual water level in steam drum	(mm)
Y_e	Error signal of water level in steam drum	(mm)
Y_R	Reference water level in steam drum	(mm)
τ_i, (i=1,6)	Time constants of H_i, (i=1,6)	(s)
Δ...	Change in ...	

INTRODUCTION

1. *Identification of Control Plants:-*

Identification is the experimental or theoretical experimental modeling of control plants either in time or frequency domain, since the classical theoretical identification or mathematical simulation of complex control systems does not guarantee the required precision. Since the second half of the fifth decade, identification was developed by reputed scientists like Levy who introduced complex curve fitting for systems identification in the frequency domain [1,2].

Progressive advances in this field were continued and enriched by Schwarze [3,4,5], Unbehaun [6,7], Isermann [8] and Petz [9,10,11]. Time domain identification can be performed either in continuous time or in discrete time [12] systems. In general, the Reccursive Least Square (RLS) or Extended Kalman's Filter (EKF) approaches are applied for parameter estimation to get either the transfer function or the Z-transfer function or the state space matrices or the discrete state space model of the plant.

Illustrative principles for experimental determination of time-domain or frequency domain responses are demonstrated in Figures (1-a,b,c) [13].

The algorithm discussed in this paper depends on a previous research [14] which applied the concept of time-domain identification of continuous time boiler control plants.

2. *Boiler Models and Control:*

Contemporary investigations of marine boiler models and control date back to the fifth decade where Profos tackled this problem and his researches were gathered in [15]. Meanwhile, other research workers dealt with such domain e.g Spliethoff [16]. Afterwards, an advanced tremendous leap was achieved by the scientific cooperation between Dolezal and Varcop who continued and accomplished the works of Profos and their valuable developments in boiler control territory were collected in [17].

Besides, other scientists participated in enriching the literature in this territory. Thompson [18] developed a dynamic state space model of a drum-type electric utility boiler suitable in designing and evaluating a multivariable controller where the superheater model provides the transient response of steam temperature, pressure, enthalpy and mass flow rate. Rydland and others [19] derived a 12th order mathematical model for Foster Wheeler ESD III type boiler with special attention to the calculation of water circulation, two-phase flow of water and steam in risers and the variations of the drum water level due to Swell and Shrink beside masses, volume and energy balances between heat transfer and heat absorbed rates. Tyssϕ [20,21,22] designed a multivariable control system for a large scale ship boiler by modern control theories and extensive use of digital computers.

The concept is based on linear regulator theory for non-linear processes [21].

Besides, Tyssϕ presented too an identification and parameter estimation by Extended Kalman Fitter approach of an adaptive control system for time continuous and discrete ship boiler [22]. Beside their contribution in developing identification topics, Petz and Czinder extensively participated in developing boiler models and improving their control [23, 24, 25, 26] with experimental validation in hungarian power stations.

Recently, additional literature came into existence in boiler control domain by Jarkovsky and Fessl e.g. [27]. In their treatment, the dynamic once-through subcritical steam generator model, based on the plant design data, is presented. This model allows the investigation of power plant system transients. At the first level the plant was decomposed on the basis of technological structure on the following partial controlled systems: combustion system, evaporator (including reducer), superheater system (first superheater uncontrolled, 2nd to 4th superheaters controlled), main steam line. When the dynamic properties of the steam generator are investigated, the influence of the steam consumer (turbine) should be considered, especially for power-output control.

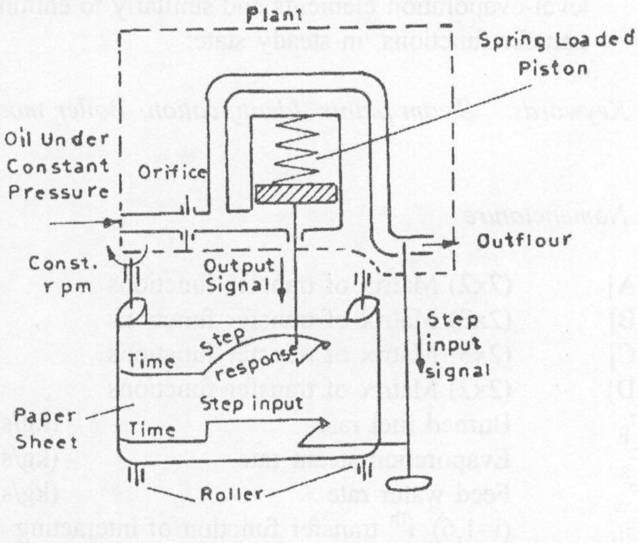

Figure 1a. Experimental determination of step response for plant identification in time domain.

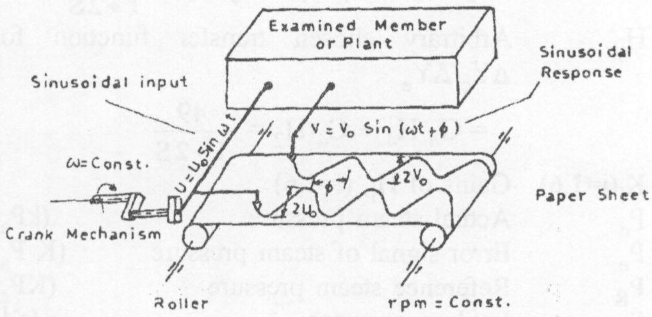

Figure 1b. Experimental measurement of sinusoidal response.

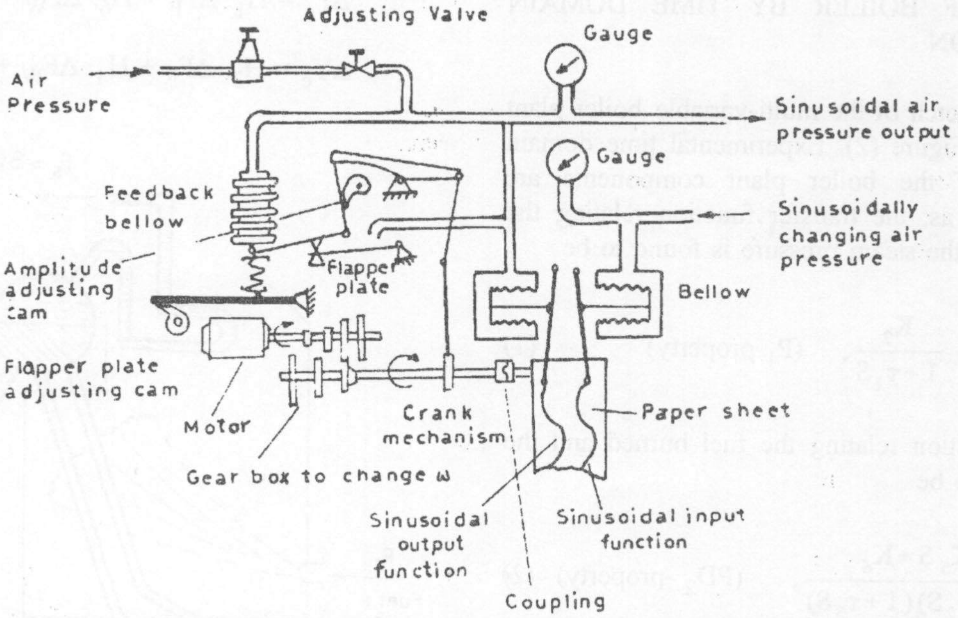

Figure 1c. Experimental determination of sinusoidal response for plant identification frequency domain.

Kee's investigation [12] is based on the concept that, in practice, it is not always possible that the theoretical prerequisites for statistical identification be fulfilled. He discussed the practical problems involving the statistical modeling of a discrete time boiler system for an electric power plant using real plant data, and developed a methodology that yields good results in practical identification when the sample data used is non-ideal in the statistical sense. Simulation methods together with statistical tools, including a series of statistical tests, that are used to validate the model are discussed in his treatment.

In their research, Chawdhry and Hogg [28] describe the application of system identification techniques to obtain models of boilers in power stations. Initial work involved extensive simulation studies, using a detailed nonlinear boiler model, to evaluate methods of identification and investigate model structures, disturbance levels etc. Three sets of tests were performed in power stations, using a computer-based data-acquisition system. Pseudorandom binary sequence inputs were applied processed to derive models of the plant, using a two-stage Recursive-Least-Squares algorithm. Results are presented which compare the responses of the identified models with those of the plant, and show that the models provide an accurate representation of the real system.

The works of de Mello concerning boiler models for system dynamic performance studies e.g. [29] depend on the following assumptions:

(1) Feedwater at its enthalpy rate and at its mass flow rate mixes with saturated water from drum and the mixture flows down the downcomer at a constant recirculation rate. In natural circulation boilers the buoyancy head versus head loss due to friction drop characteristics also tend to maintain a constant recirculation.
(2) Heat absorbed by fluid in waterwalls is uniformly distributed i.e. proportional to length or volume.
(3) Velocities of steam and water are assumed equal.

The principles of his model involve the mass balance, the volume balance, the energy balance, deriving the enthalpy of the water entering the downcomers, the subcooled resident mass, computation of enthalpy at waterwall inlet, calculation of heat flux from tubes to fluid in waterwalls and storage in superheaters-dealt with as lumped parameters instead of distributed parameters. At the lumped portions the pressures and mass flow rates are calculated by a set of algebraic and differential equations and finally the change in drum level is computed.

MODELING OF BOILER BY TIME DOMAIN IDENTIFICATION

A schematic sketch of the multi-variable boiler plant is illustrated in Figure (2). Experimental time domain identification of the boiler plant components are determined [14] as: the transfer function relating the fuel burned and the steam pressure is found to be

$$H_1 = \frac{K_2}{1+\tau_1 S}, \quad (P_1 \text{ property}) \quad (1)$$

the transfer function relating the fuel burned and the water is found to be

$$H_2 = \frac{K_5 S + K_6}{(1+\tau_2 S)(1+\tau_3 S)}, \quad (PD_2 \text{ -property}) \quad (2)$$

the transfer function relating the delivered steam evaporation and the steam pressure is found to be

$$H_3 = \frac{K_3}{1+\tau_4 S}, \quad (P_1 \text{ property}) \quad (3)$$

the transfer function relating the feedwater and the water level is found to be

$$H_4 = \frac{K_4}{S}, \quad (I_o \text{ -property}) \quad (4)$$

the transfer function relating the delivered steam evaporation and the water level is found to be

$$H_5 = \frac{K_7 S + K_8}{S(1+\tau_5 S)}, \quad ((PI)_1 \text{ -property}) \quad (5)$$

and finally the transfer function relating the feedwater to the steam pressure is found to be

$$H_6 = \frac{K_1}{1+\tau_6 S}, \quad (P_1 \text{ -property}) \quad (6)$$

The deviations in actual steam pressure and actual water level can be written as

$$\Delta P_c = H_1 \cdot \Delta F_F + H_6 \cdot \Delta F_W + H_3 \cdot \Delta F_S \quad (7)$$

$$\Delta Y_c = H_2 \cdot \Delta F_F + H_4 \cdot \Delta F_W + H_5 \cdot \Delta F_S \quad (8)$$

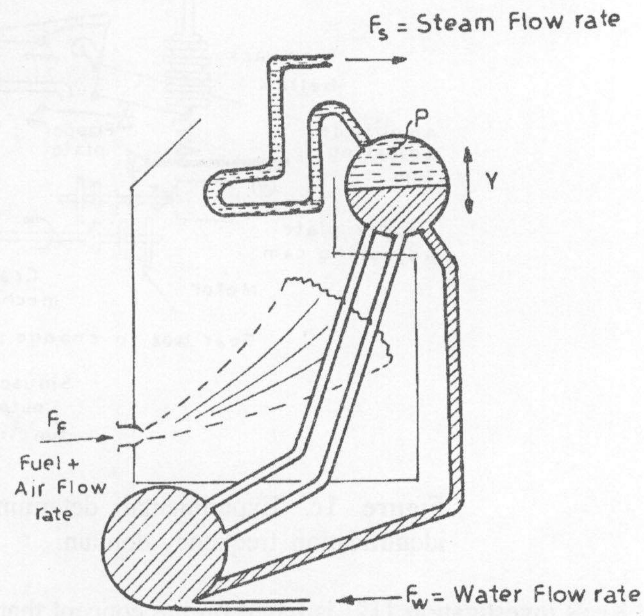

Figure 2. Schematic representation of multi-variable boiler plant.

With non-interacting controllers, the deviations in fuel burned and feedwater are proportional to the deviations in pressure error signal and level error signal respectively, i.e.

$$\Delta F_F = G_1 \cdot \Delta P_e \quad (9)$$

$$\Delta F_W = G_4 \cdot \Delta Y_e \quad (10)$$

Substituting from equations (9) and (10) into equations (7) and (8) yield

$$\Delta P_c = H_1 \cdot G_1 \cdot \Delta P_e + H_6 \cdot G_4 \cdot \Delta Y_e + H_3 \cdot \Delta F_s \quad (11)$$

$$\Delta Y_c = H_2 \cdot G_1 \cdot \Delta P_e + H_4 \cdot G_4 \cdot \Delta Y_e + H_5 \cdot \Delta F_s \quad (12)$$

Equations (11) and (12) are pictorially assembled to display the block diagram shown in Figure (3).

If interacting controller is selected then

$$\Delta F_F = f(\Delta P_e, \Delta Y_e, \Delta F_s) \quad (13)$$

or, $$\Delta F_F = G_1 \cdot \Delta P_e + G_6 \cdot \Delta Y_e + G_3 \cdot \Delta F_s \quad (14)$$

and $$\Delta F_W = f(\Delta P_e, \Delta Y_e, \Delta F_s) \quad (15)$$

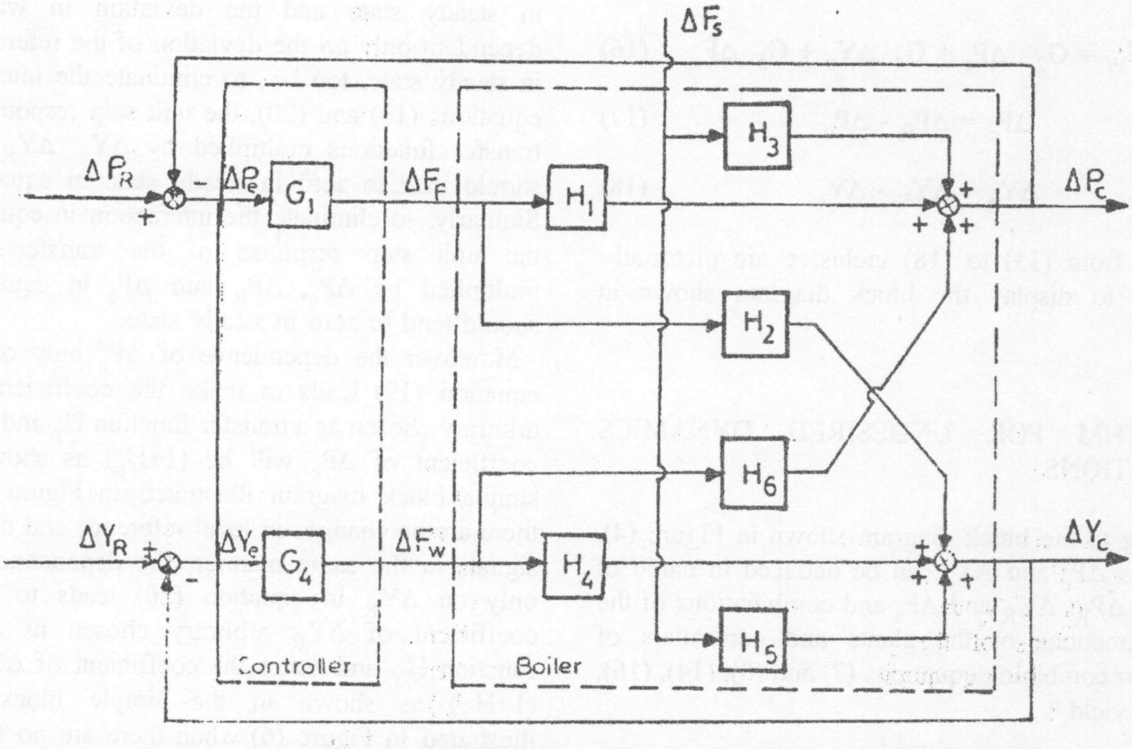

Figure 3. Block diagram of multi-variable boiler control with non-interacting controller.

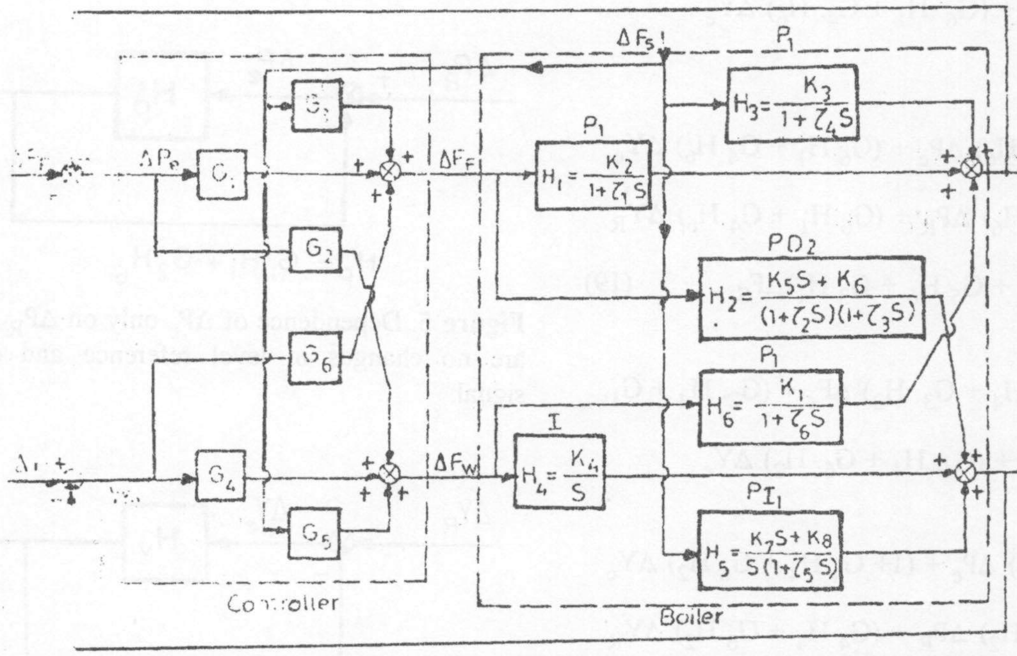

Figure 6. Block diagram for multi-variable boiler control with interacting controller.

or,

$$\Delta F_W = G_2 \, . \, \Delta P_e + G_4 . \, \Delta Y_e + G_5 . \, \Delta F_s \quad (16)$$

where

$$\Delta P_e = \Delta P_R - \Delta P_c \quad (17)$$

and

$$\Delta Y_e = \Delta Y_R - \Delta Y_c \quad (18)$$

Equations from (13) to (18) inclusive are pictorially assembled to display the block diagram shown in Figure (4).

ALGORITHM FOR UNDESIRED DYNAMICS ELIMINATIONS

Referring to the block diagram shown in Figure (4), the outputs ΔP_c and ΔY_c can be deduced in name of the inputs ΔP_R, ΔY_R and ΔF_s and combinations of the transfer functions of the plants and controllers of elements or combining equations (7) and (8), (14), (16), (17), (18) yield

$$\Delta P_c = (H_3 + G_5 . \, H_6 + G_3 . \, H_1) \, \Delta F_s + (G_1 . \, H_1 + G_2 . \, H_6) \, \Delta P_e + (G_6 . \, H_1 + G_4 . \, H_6) \, \Delta Y_e$$

or:

$$(1 + G_1 H_1 + G_2 H_6) \, \Delta P_c + (G_6 H_1 + G_4 H_6) \, \Delta Y_c = (G_1 H_1 + G_2 H_6) \, \Delta P_R + (G_6 H_1 + G_4 H_6) \, \Delta Y_R + (H_3 + G_5 H_6 + G_3 H_1) \Delta F_S \quad (19)$$

and

$$\Delta Y_c = (H_5 + G_5 . \, H_4 + G_3 . \, H_2) \, \Delta F_s + (G_2 . \, H_4 + G_1 . \, H_2) \, \Delta P_e + (G_4 . \, H_4 + G_6 . \, H_2) \, \Delta Y_e$$

or

$$(G_2 H_4 + G_1 H_2) \, \Delta P_c + (1 + G_4 H_4 + G_6 H_2) \, \Delta Y_c = (G_2 H_4 + G_1 H_2) \, \Delta P_R + (G_4 H_4 + G_6 H_2) \, \Delta Y_R + (H_5 + G_5 H_4 + G_3 H_2) \Delta F_S \quad (20)$$

In order to make the deviation in actual pressure dependent only on the deviation in reference pressure in steady state and the deviation in water level dependent only on the deviation of the reference level in steady state, too i.e., to eliminate the interaction in equations (19) and (20), the unit step responses of the transfer functions multiplied by ΔY_c, ΔY_R and ΔF_s should tend to zero in steady state in equation (19). Similarly, to eliminate the interaction in equation (20) the unit step response of the transfer functions multiplied by ΔP_c, ΔP_R and ΔF_s in equation (20) should tend to zero in steady state.

Moreover the dependence of ΔP_c only on ΔP_R in equation (19) leads to make the coefficient of ΔP_R arbitrary chosen as a transfer function H_p and hence the coefficient of ΔP_c will be $(1+H_p)$ as shown in the simple block diagram illustrated in Figure (5) when there are no changes in level reference and disturbance signal. In the same manner, the dependence of ΔY_c only on ΔY_R in equation (20) leads to make the coefficient of ΔY_R arbitrary chosen as a transfer function H_Y and hence the coefficient of ΔY_c will be $(1+H_Y)$ as shown in the simple block diagram illustrated in Figure (6) when there are no changes in pressure reference and disturbance signal.

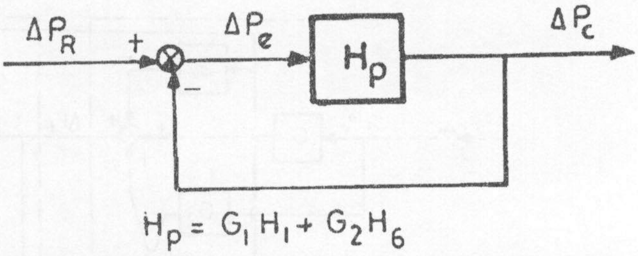

Figure 5. Dependence of ΔP_c only on ΔP_R when there are no changes in level reference and disturbance signal.

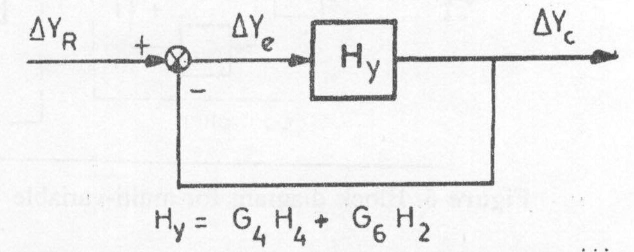

Figure 6. Dependence of ΔP_c only on ΔP_R when there are no changes in pressure reference and disturbance signal.

The aforementioned six conditions imply the following six equations taking into account the following error preventing transformation:-

1- When any of the transfer function H_i, (i=1,6) involves an integral property, the transfer function G_i, (i=1,6) multiplied by it should be derivative to avoid indeterminate infinite value, i.e.

$$G_2 = S\,G_2$$

and

$$G_4 = S\,G_4$$

2- Based on the prementioned principle

$$G_5 = \frac{S}{1+2S}\,G_5.$$

the delay time is introduced to avoid resulting Dirac function response.

3- Since H_5 includes an integral property and it is not multiplied by any transfer function G_i, (i=1,6), an approximate solution can be reached by choosing $K_8 << K_7$, i.e. $K_8 \simeq o$ to escape too indeterminate infinite value.

Hence,

$$\left.\begin{array}{l}
\lim\limits_{S\to o}\{S.\frac{1}{S}[H_1G_6(S)+H_6G_4(S)]\}=0 \\
\lim\limits_{S\to o}\{S.\frac{1}{S}[H_1G_3(S)+H_6.G_5(S)+H_3(S)]\}=0 \\
\lim\limits_{S\to o}\{S.\frac{1}{S}[H_2G_1(S)+H_4G_2(S)]\}=0 \\
\lim\limits_{S\to o}\{S.\frac{1}{S}[H_2G_3(S)+H_4.G_5(S)+H_5(S)]\}=0 \\
\lim\limits_{s\to 0}\{S.\frac{1}{S}[H_1G_1(S)+H_6.G_2(S)]\}=\lim\limits_{s\to 0}\{S.\frac{1}{S}H_P(S)\} \\
\lim\limits_{s\to 0}\{S.\frac{1}{S}[H_2G_6(S)+H_4.G_4(S)]\}=\lim\limits_{s\to 0}\{S.\frac{1}{S}H_Y(S)\}
\end{array}\right\} \quad (21)$$

Substituting equation from (1) to (6) inclusive in equations (21) result in

$$\left.\begin{array}{c}
K_2G_6+K_1G_4=0 \\
K_2G_3+K_3+K_1G_5=0 \\
K_6G_1+K_4G_2=0 \\
K_6G_3+K_4G_5+k_7\simeq 0 \\
K_2G_1+K_1G_2=49 \\
K_6G_6+K_4G_4=49
\end{array}\right\} \quad (22)$$

Selections of the values of K_j, (j= 1,8) and τ_i, (i=1,6) are based on practical time domain identification with parameter estimation [14] as follows:-

K_1 = -1	k P_a/(kg/s)
K_2 = 1	k P_a/(kg/s)
K_3 = 0.5	k P_a/(kg/s)
K_4 = 0.05	mm/kg
K_5 = 1	mm s^2/kg
K_6 = -0.001	mm/(kg/s)
K_7 = -1	mm/(kg/s)
K_8 = 0.0005	mm/kg
τ_1 = 30	(s)
τ_2 = 50	(s)
τ_3 = 50	(s)
τ_4 = 50	(s)
τ_5 = 30	(s)
τ_6 = 40	(s)

Hence,

$$H_1(S) = \frac{1}{1+30S}$$

$$H_2(S) = \frac{S-0.001}{(1+50S)^2}$$

$$H_3(S) = \frac{0.5}{1+50S}$$

$$H_4(S) = \frac{0.05}{S}$$

$$H_5(S) = \frac{-S+0.0005}{S(1+30S)}$$

$$H_6(S) = \frac{-1}{1+40S}$$

Figures from (7) to (15) inclusive represent the unit step responses of H_1 (S) through $H_6(S)$ and the frequency responses of H_2 (S), $H_5(S)$ and $H_6(S)$ respectively.

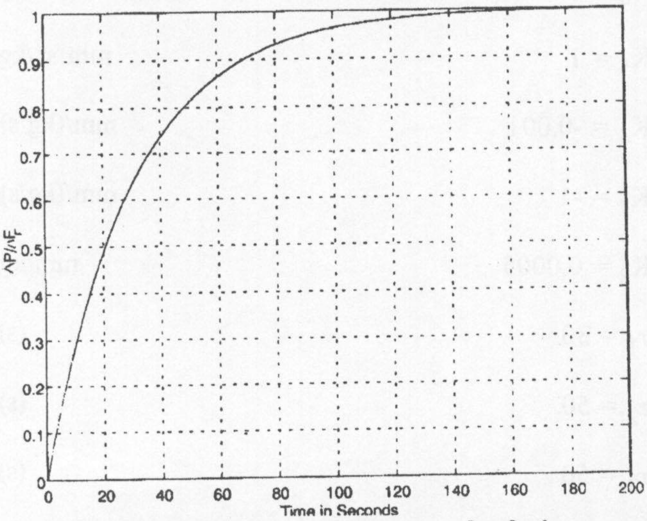

Figure 7. Transient response of fuel-pressure relationship:$k_2/(1+T_1.s)$.

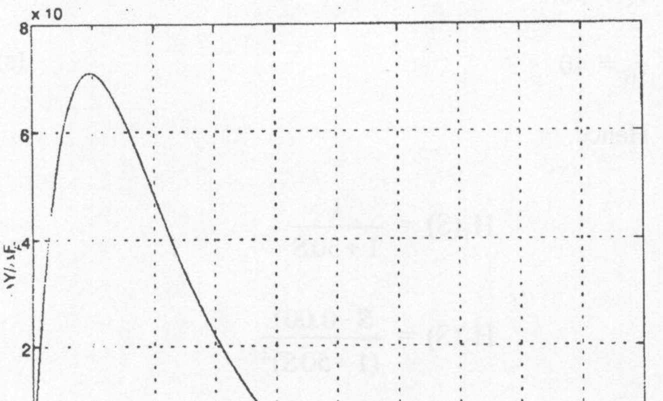

Figure 8.. Trans. response of fuel-level T.F.: $k_5{}^{*}$ $s+k_6)/(1-T_2{}^{2})^{*}(1+T_3{}^{*}s))$.

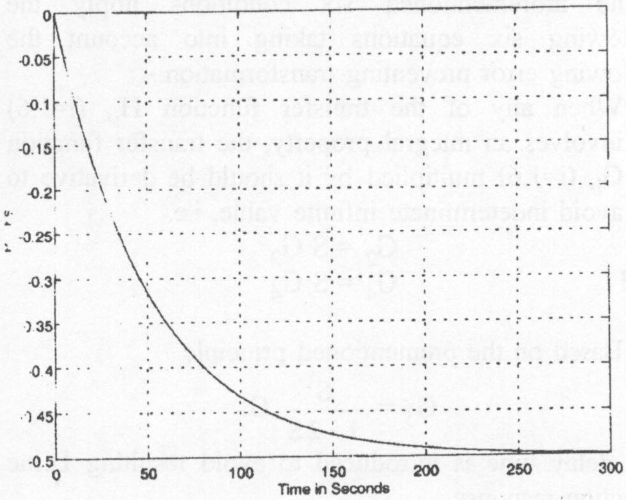

Figure 9. Trans. response of steam-pressure T.F.: $k_3/(1+T_4.S)$.

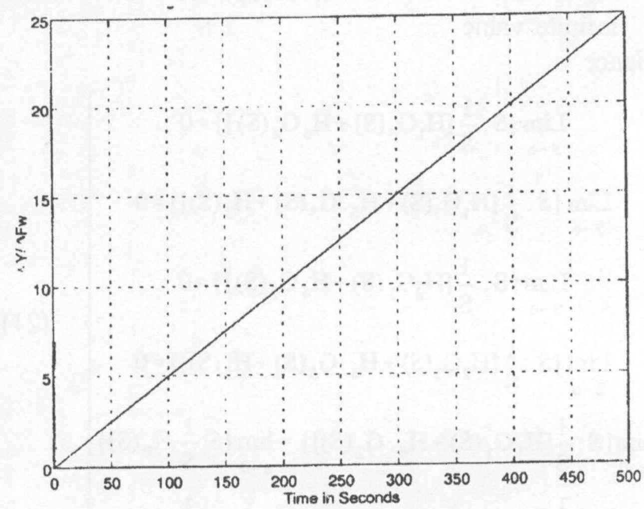

Figure 10. Trans.response of feed water-level T.F.: k_4/s.

Besides H_p and H_y are arbitrary chosen as

$$H_p = \frac{49}{1+2S}$$

$$H_y = \frac{49}{1+2S}$$

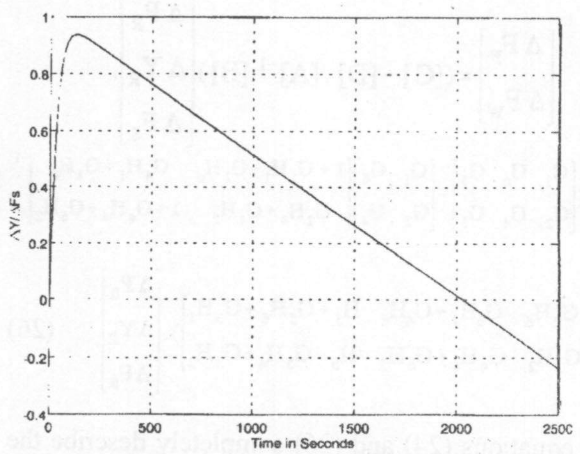

Figure 11. Trans. response of steam-level T.F.: $(k_7^{*}s+k_8)/(s^{*}(1+T_{5*}S))$.

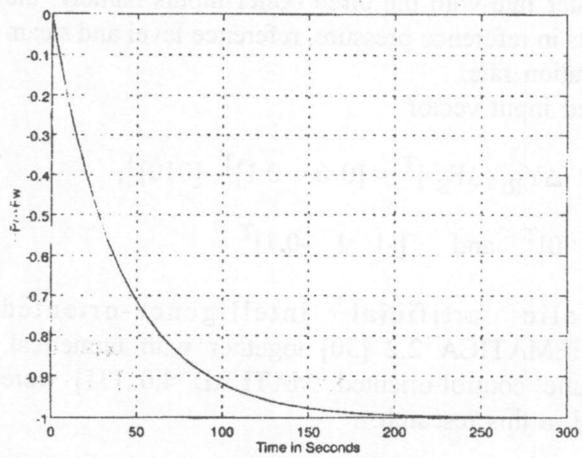

Figure 12. Trans. response of feed water-pressure T.F.: $k_1/(1+T_6^{*}S)$.

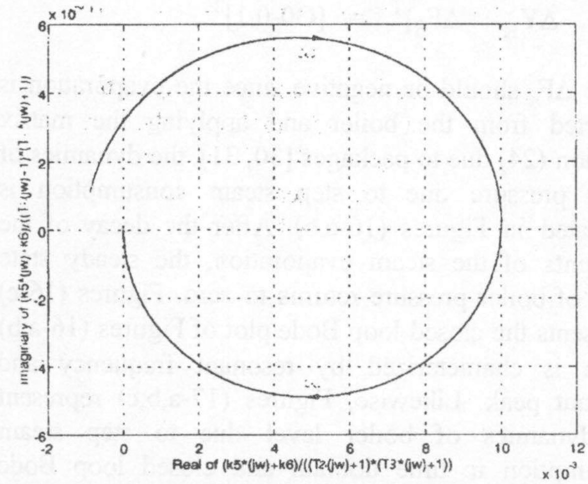

Figure 13. Polar plot of fuel-level frequency function, k_5=1k_6=0.001, w=0.001-10^6.

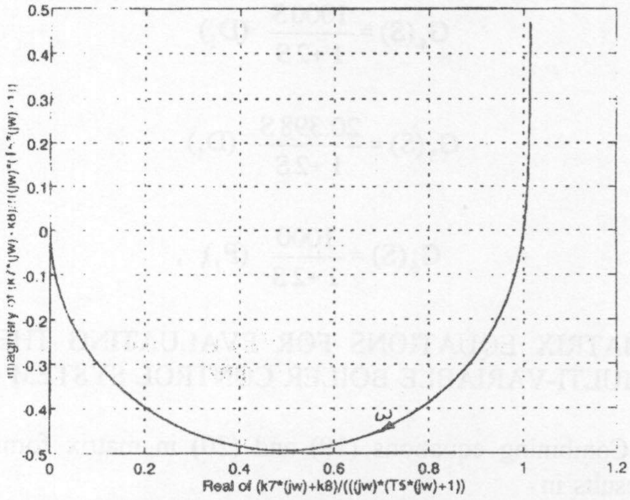

Figure 14. Polar plot of steam-level frequency function, k_7=1,k_8=0.0005, w=0.001-10^6.

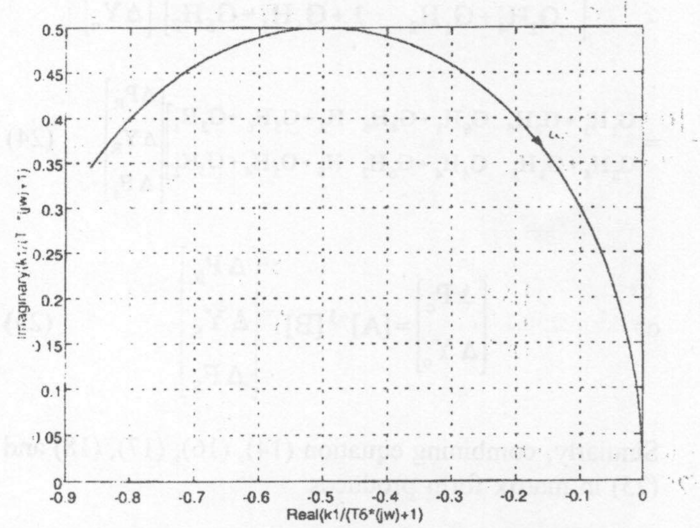

Figure 15. Polar plot of feed water-pressure frequency function, k_1=-1,w=0.01-10^5.

Computer aided control systems design yields the solution of equations (22) with the above mentioned data which represent the transfer functions components of the interacting controller-as follows:

$$G_1(S) = \frac{50}{1+2S} \quad (P_1)$$

$$G_2(S) = \frac{S}{1+2S} \quad (D_1)$$

$$G_3(S) = 19.898 \quad (P_o)$$

$$G_4(S) = \frac{1000\,S}{1+2S} \quad (D_1)$$

$$G_5(S) = \frac{20.398\,S}{1+2S} \quad (D_1)$$

$$G_6(S) = \frac{1000}{1+2S} \quad (P_1)$$

MATRIX EQUATIONS FOR EVALUATING THE MULTI-VARIABLE BOILER CONTROL SYSTEM

Combining equations (19) and (20) in matrix form results in

$$\begin{bmatrix} 1+G_1H_1+G_2H_6 & G_6H_1+G_4H_6 \\ G_2H_4+G_1H_2 & 1+G_4H_4+G_6H_2 \end{bmatrix} \begin{bmatrix} \Delta P_c \\ \Delta Y_c \end{bmatrix}$$

$$= \begin{bmatrix} G_1H_1+G_2H_6 & G_6H_1+G_4H_6 & H_3+G_5H_6+G_3H_1 \\ G_2H_4+G_1H_2 & G_4H_4+G_6H_2 & H_5+G_5H_4+G_3H_2 \end{bmatrix} \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ \Delta F_s \end{bmatrix} \qquad (24)$$

or

$$\begin{bmatrix} \Delta P_c \\ \Delta Y_c \end{bmatrix} = [A]^{-1}[B]. \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ \Delta F_S \end{bmatrix} \qquad (25)$$

Similarly, combining equation (14), (16), (17), (18) and (25) in matrix form produces

$$\begin{bmatrix} \Delta F_F \\ \Delta F_W \end{bmatrix} = \begin{bmatrix} G_1 & G_6 & G_3 \\ G_2 & G_4 & G_5 \end{bmatrix} \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ \Delta F_S \end{bmatrix} - \begin{bmatrix} G_1 & G_6 \\ G_2 & G_4 \end{bmatrix} \begin{bmatrix} \Delta P_C \\ \Delta Y_C \end{bmatrix}$$

or

$$\begin{bmatrix} \Delta F_F \\ \Delta F_W \end{bmatrix} = [C] \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ \Delta F_S \end{bmatrix} - [D] \begin{bmatrix} \Delta P_C \\ \Delta Y_C \end{bmatrix}$$

$$\begin{bmatrix} \Delta F_F \\ \Delta F_W \end{bmatrix} = [C] \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ \Delta F_S \end{bmatrix} - [D].[A]^{-1}.[B]. \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ [\Delta F_S \end{bmatrix}$$

$$\begin{bmatrix} \Delta F_F \\ \Delta F_W \end{bmatrix} = ([C] - [D].[A]^{-1}.[B]) \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ \Delta F_S \end{bmatrix}$$

$$\begin{bmatrix} \Delta F_F \\ \Delta F_W \end{bmatrix} = \left(\begin{bmatrix} G_1 & G_6 & G_3 \\ G_2 & G_4 & G_5 \end{bmatrix} - \begin{bmatrix} G_1 & G_6 \\ G_2 & G_4 \end{bmatrix} \begin{bmatrix} 1+G_1H_1+G_2H_6 & G_6H_1+G_4H_6 \\ G_2H_4+G_1H_2 & 1+G_4H_4+G_6H_2 \end{bmatrix}^{-1} . \right.$$

$$\left. \begin{bmatrix} G_1H_1+G_2H_6 & G_6H_1+G_4H_6 & H_3+G_5H_6+G_3H_1 \\ G_2H_4+G_1H_2 & G_4H_4+G_6H_2 & H_5+G_5H_4+G_3H_2 \end{bmatrix} \right) . \begin{bmatrix} \Delta P_R \\ \Delta Y_R \\ \Delta F_S \end{bmatrix} \qquad (26)$$

Matrix equations (24) and (26) completely describe the boiler dynamics in what concerns the deviations in steam pressure, water level, fuel burning rate and feedwater rate with the three boiler inputs namely: the changes in reference pressure, reference level and steam evaporation rate.

Selected input vector

$[\Delta P_R \quad \Delta Y_R \quad \Delta F_S]^T = [0\ 0\ \ -0.1]^T$, $[010]^T$,

$[-1\ \ 0\ \ 0]^T$ and $[-1\ \ 1\ \ -0.1]^T$.

Symbolic artificial intelligence-oriented MATHEMATICA 2.2 [30] together with numerical, automatic control-oriented MATLAB 4.0 [31] were applied in this research.

RESULTS AND DISCUSSION

Considering the input vector
$[\Delta P_R \quad \Delta Y_R \quad \Delta F_S]^T = [O0\text{-}0.1]^T$

where ΔF_s should be negative since the evaporation is extracted from the boiler and applying the matrix equation (24) due to packages [30, 31], the dynamics of boiler pressure due to step steam consumption is illustrated in Figures (16-a,b). After the decay of the transients of the steam evaporation, the steady state value of boiler pressure returns to zero. Figures (16-c) represents the closed loop Bode plot of Figures (16-a,b) which is characterized by resonant frequency and resonant peak. Likewise, Figures (17-a,b,c) represent the dynamics of boiler level due to step steam consumption in time domain and closed loop Bode form. Similarly, after the decay of steam evaporation transients, the boiler level regains its initial zero condition. The Bode plot is characterized by a large band width. Matrix equation (26) is used too in packages [30,31] and the time and frequency domain responses of the dynamics of boiler fuel due to step steam consumption are indicated in Figures (18-a,b) respectively. By the same matrix equation (26) through the previously mentioned packages, the dynamics of boiler feedwater due to step steam consumption in time and frequency domains are shown in Figures (19-a,b) respectively. After ω=1 rad/s the decibel magnitude remains constant. Considering the input vector:

$$[\Delta P_R \;\; \Delta Y_R \;\; \Delta F_S]^T = [0 \;\; 1 \;\; 0]^T,$$

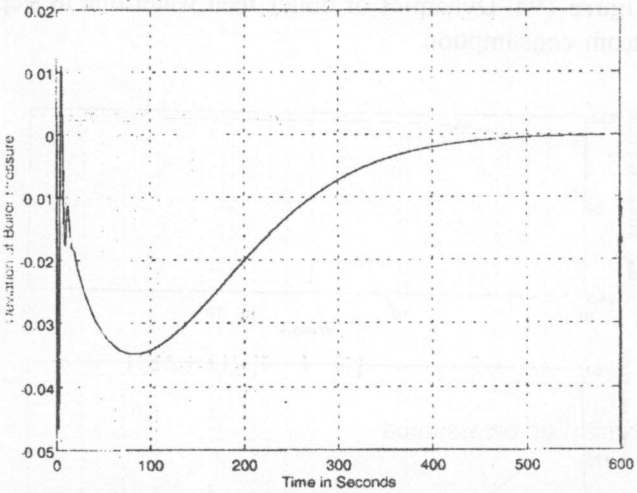

Figure 16a. Dynamics of boiler pressure due to step steam consumption.

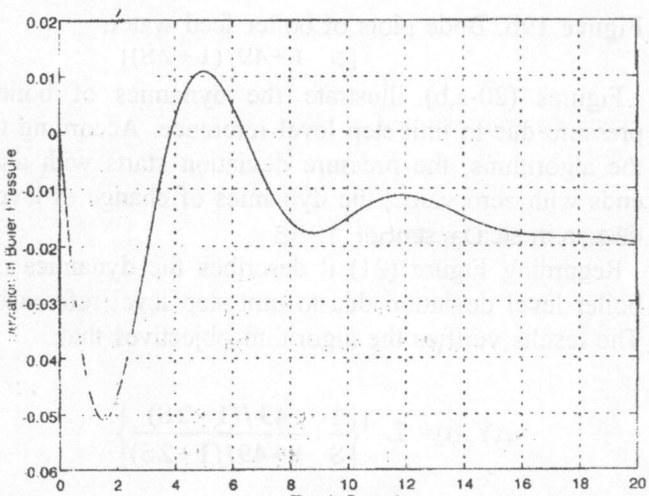

Figure 16b. Dynamics of boiler pressure due to step steam consumption.

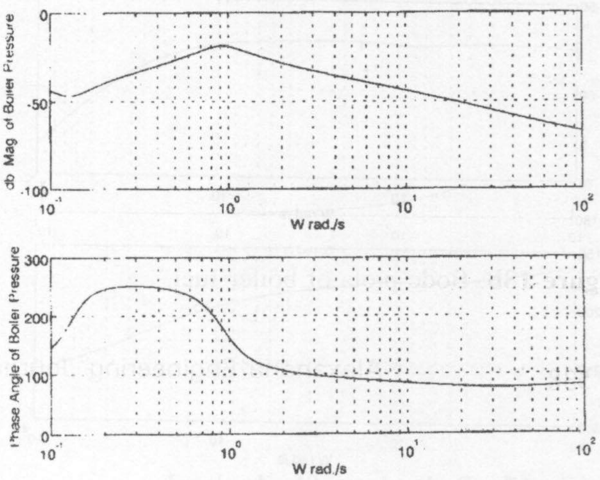

Figure 16-c. Bode plots of boiler pressure.

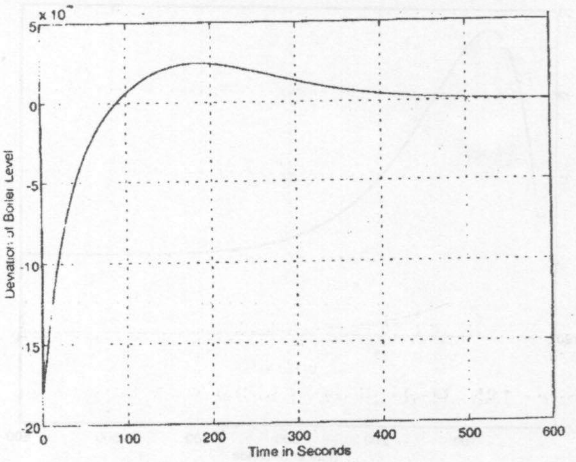

Figure 17a. Dynamics of boiler level due to step steam consumption.

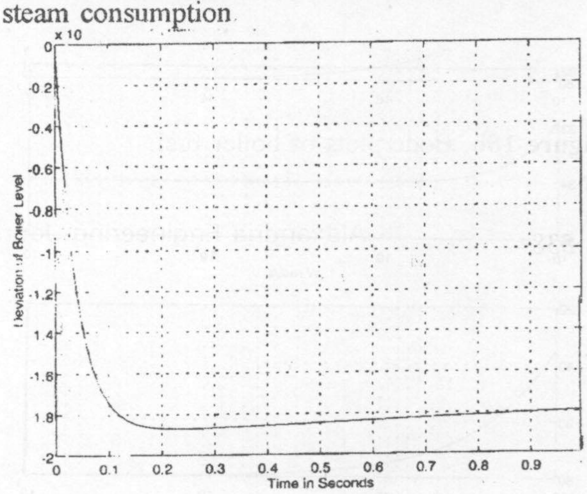

Figure 17b. Dynamics of boiler level due to step steam consumption.

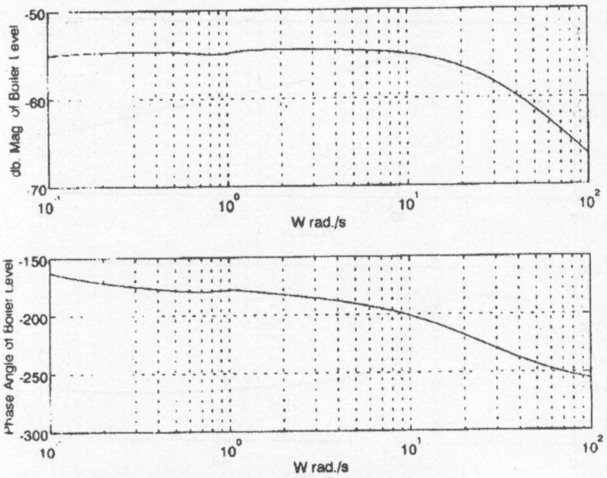

Figure 17c. Bode plots of boiler level.

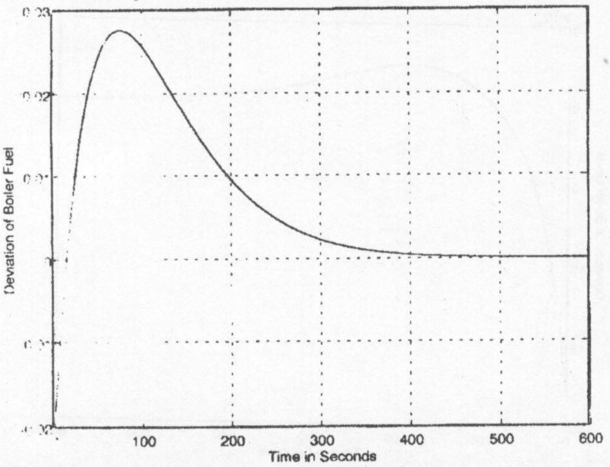

Figure 18a. Dynamics of boiler fuel due to step steam consumption.

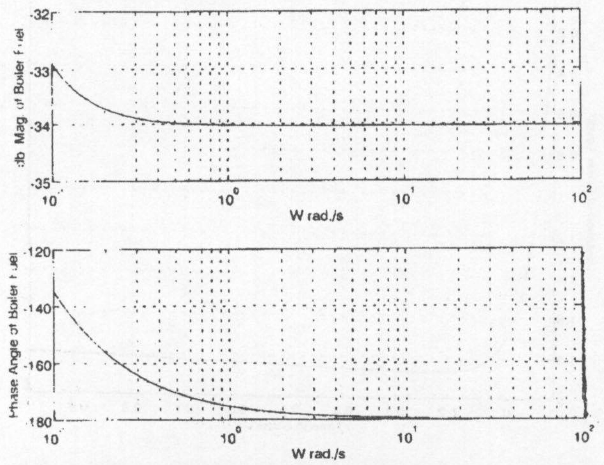

Figure 18b. Bode plots of boiler fuel.

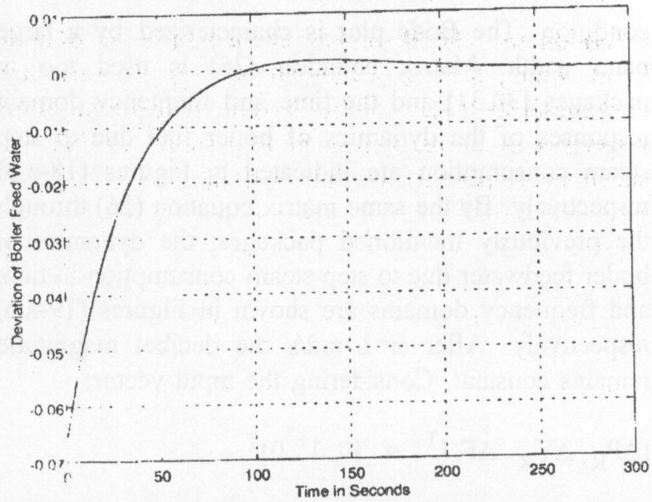

Figure 19a. Dynamics of boiler feed water due to step steam consumption.

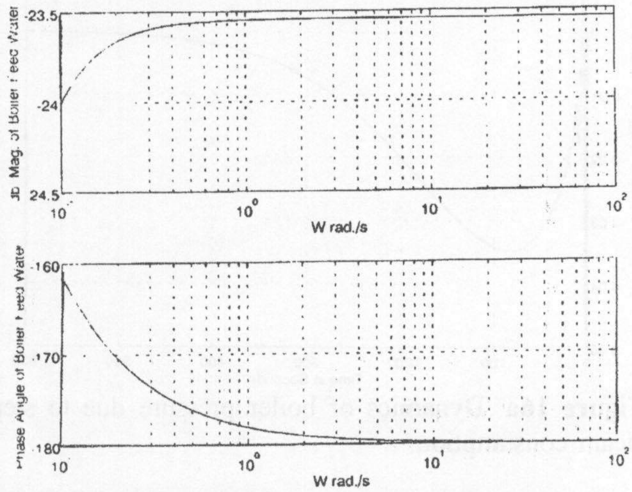

Figure 19b. Bode plots of boiler feed water.

Figures (20-a,b) illustrate the dynamics of boiler pressure due to unit step level reference. According to the algorithms, the pressure deviation starts with and ends with zero value, the dynamics of change of level decays in steady state.

Regarding Figure (21) it describes the dynamics of boiler level deviation due to unit step level reference. The results verifies the algorithm objectives that:

$$\Delta Y_c(t) = L^{-1}\left\{\frac{1}{S}\cdot\frac{49/(1+2S)}{1+49/(1+2S)}\right\}$$

exactly as preassumed.

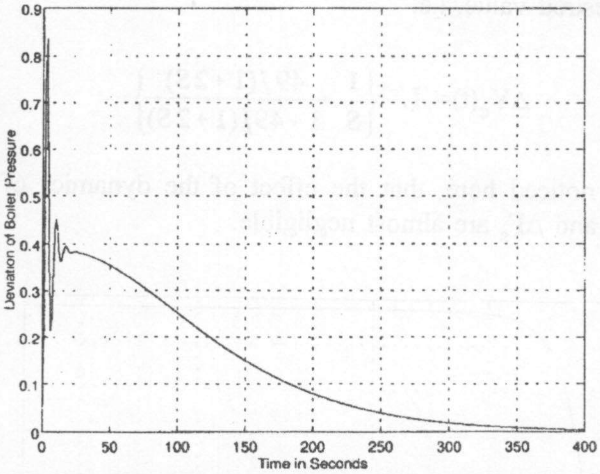

Figure 20a. Dynamics of boiler pressure due to unit step level Reference.

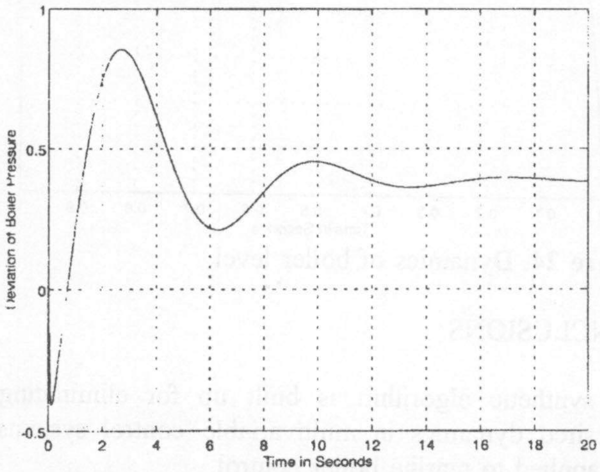

Figure 20b. Dynamics of boiler pressure due to unit step level Reference.

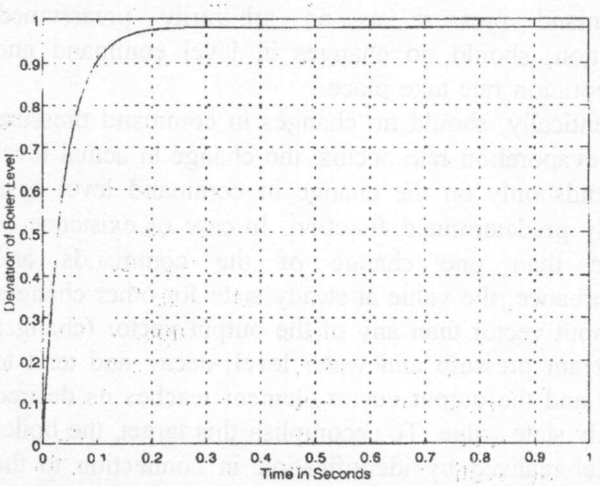

Figure 21. Dynamics of boiler level due to unit step level Reference.

Considering the input vector

$$[\Delta P_R \quad \Delta Y_R \quad \Delta F_S]^T = [-1 \quad 0 \quad 0]^T,$$

Figures (22-a,b) display the boiler level deviation due to negative unit step pressure reference where the transient response starts and ends at zero deviation and in between the transient dynamics of the pressure reference fluctuate and decay.

In what concerns the choice of

$$[\Delta P_R \quad \Delta Y_R \quad \Delta F_S]^T = [-1 \quad 1 \quad -0.1]^T,$$

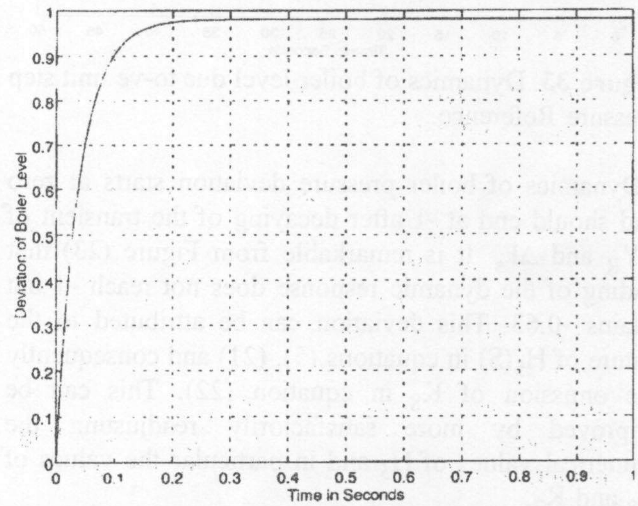

Figure 21. Dynamics of boiler level due to unit step level Reference.

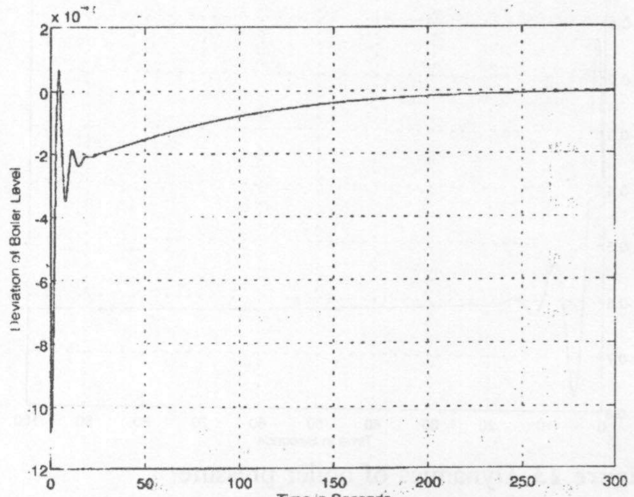

Figure 22a. Dynamics of boiler level due to -ve unit step pressure Reference.

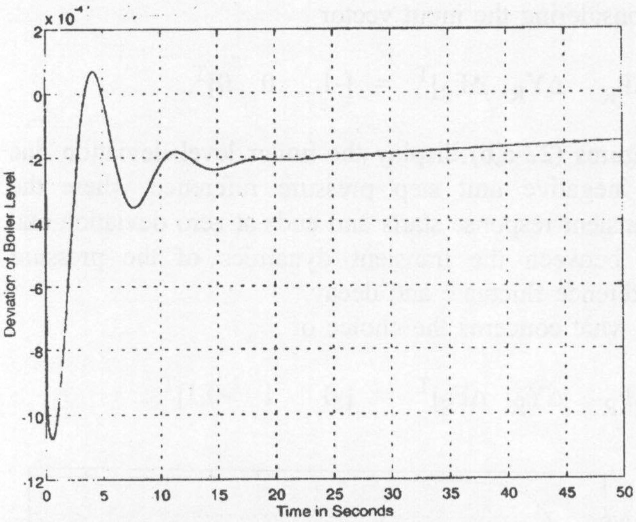

Figure 33. Dynamics of boiler level due to-ve unit step pressure Reference.

Dynamics of boiler pressure deviation starts at zero and should end at -1 after decaying of the transient of ΔY_R and ΔF_s. It is remarkable from Figure (23) that ending of the dynamic response does not reach -1 but attains -0.63. This deviation can be attributed to the nature of $H_5(S)$ in equations (5), (21) and consequently the omission of K_8 in equation (22). This can be improved by more satisfactorily readjusting the numerical values of H_5 and in particular the values of K_8 and K_7.

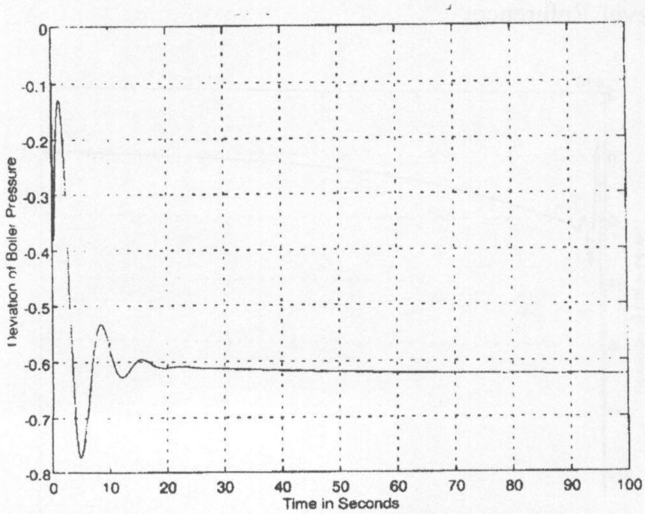

Figure 23. Dynamics of boiler pressure.

Lastly, the dynamics of boiler level deviation is displayed in Figure (24), where it realises precisely the predesired value, i.e.

$$\Delta Y_c(t) = L^{-1}\left\{\frac{1}{S}\cdot\frac{49/(1+2S)}{1+49/(1+2S)}\right\}$$

It is noticed here, that the effect of the dynamics of ΔP_R and ΔF_s are almost negligible.

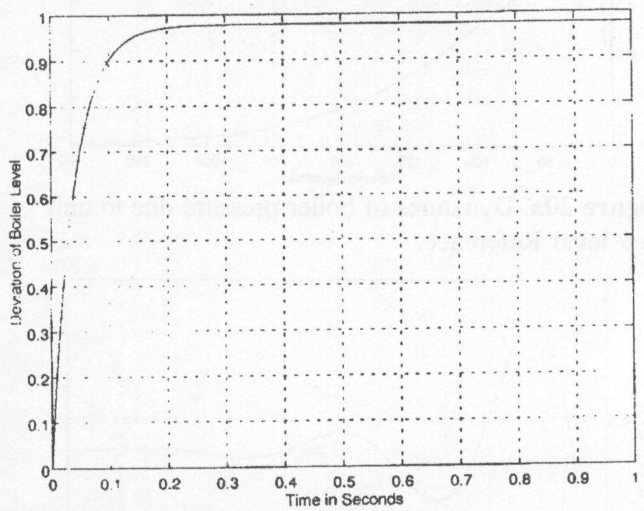

Figure 24. Dynamics of boiler level.

CONCLUSIONS

A synthetic algorithm is built up for eliminating undesired dynamics in multivariable control systems and applied to marine boiler control.

Its fundamental concepts are to make the change in actual pressure depends only on the change in command pressure as an arbitrarily preassumed function, should no changes in level command and evaporation rate take place.

Identically, should no changes in command pressure and evaporation rate occurs, the change in actual level depends only on the change in command level as a freely predetermined function. In case of existence of more than one change of the commands and disturbance, the value at steady state for other changes in input vector than any of the output vector (changes in steam pressure and water level)-decay and tend to zero and the output vector element reaches its desired steady state value. To accomplish this target, the boiler model realized by identification in connection to the interacting controller is derived in equations (19), (20) or in matrix form in equations (24), (26). Six simultaneous equations verifying the steady state or final values theorem are solved symbolically by [30]. To overcome the obstacle of existing of an integrator at any transfer function of the boiler components the interacting controller component multiplied by it should be changed to a derivative one- if it does not contain a first order delay, this delay should be added to avoid a Dirac response.

To reach an appropriate approximation, should any boiler transfer function involves an integrator and it is not multiplied by any controller's transfer function element, adequate proportion of its coefficients of the numerator can be efficiently adjusted to narrow the approximation.

Matrix equations (24), (26) are solved by [31] and the computer results verify and validate successfully this algorithm which is applicable to other control problems.

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