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ABSTRACT

Identification experiments have been performed on a full scale municipal wastewater treatment plant at Käppala, Stockholm. The dissolved oxygen dynamics in the activated sludge process has been examined with respect to air and water flow disturbances. Maximum Likelihood identification has been used for the parameter estimation.

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1. INTRODUCTION

The activated sludge unit is one of the major unit processes in a wastewater treatment system. In the process a waste is stabilized biologically in a reactor under aerobic conditions. The aerobic environment is achieved by the use of diffused or mechanical aeration. After the waste has been treated in the reactor (or aerator) the resulting biological mass is separated from the liquid in a settling tank. A portion of the remaining mass is wasted as sludge.

In order to maintain the aerobic conditions oxygen has to be transferred to the process continuously. The oxygen which is utilized by the organisms must be in a dissolved form. Therefore the oxygen which is added through aeration must be transferred from a gaseous phase to a dissolved phase before it can be utilized by the organisms.

In this report the dissolved oxygen dynamics (DO) is considered and its relations to different process variables and biological variables as well as to external disturbances. There are several reasons why the DO dynamics is interesting and relevant to consider. Here we consider three reasons

- o water quality
- o economy
- o DO as an indicator of the process condition

In order to maintain aerobic conditions in the reactor the DO concentration must exceed a certain concentration, say 1 - 2 mg/l. Below this level the synthesis rate of organisms and consequently the organic substrate utilization, is limited due to the oxygen. On the other hand the organisms cannot make use of an abundant concentration of DO. Of economic reasons it is therefore natural to try to minimize the DO concentration and still maintain an adequate biological activity.

The air flow to the reactor is constrained to a lower limit by hydraulic conditions. In order to maintain a sufficient liquid mixing and to avoid clogging of the diffusers the air flow must not be too small.

The oxygen transfer dynamics from gaseous to liquid phase is therefore the most interesting dynamics from a control point of view. The main control task is to keep the DO concentration constant despite load changes to the plant at a level of 1 - 2 mg/l. The relevant input signal is therefore the air flow rate from the compressors.

Due to changes of the load to the plant the DO concentration can vary significantly. It also depends to a large extent on the biological activity. Therefore the DO concentration is a natural indicator of the process condition. The difficult instrumentation problems in a wastewater treatment system makes the DO concentration even more interesting. This is one of the few variables that can be measured with a reasonable reliability. Thus the dynamics can be used for estimation of other biological variables, such as biological oxygen uptake rate.

When the aerator is built as a long tank the DO concentration is far from uniform along the channel. Instead it is varying considerably along the tank. Because of the high substrate concentration at the raw wastewater inlet the synthesis rate is high there. Consequently the oxygen demand is large and the DO level is low. Towards the tail end of the reactor the biological reactions are getting completed and the corresponding oxygen demand is comparatively low. The DO level can therefore rise to relatively high values.

The DO profile phenomenon has been considered in the design of some plants. The air flow is larger in the head end and decreases along the reactor as the oxygen demand decreases, a so called tapered aeration.

In order to examine the DO dynamics for a full scale municipal plant several series of dynamical identification experiments have been performed on the Käppala wastewater treatment plant at Lidingö outside Stockholm.

The plant was completed in 1969 and has an average influent flow of 1.3 m^3/sec ($\sim$ 30 MGD). The flow is split up into three parallel flows to the grit chambers. It is further split up into six parallel flows for the primary sedimentation and the activated sludge process units. Chemical preciplation follows the biological treatment.

For the dynamical experiments one of the six aerators has been used. The aerator has a volume of 6000 m^3 and is 100 m long. The air is supplied by diffusers uniformly along the tank. The raw wastewater is fed into the tank by step loading at four positions between 30 and 60 m from the head end. The DO profile shows the typical feature, which was indicated above. For a more detailed description of the plant and its instrumentation we refer to [6].

In Chapter 2 the theoretical aspects of the DO dynamics are discussed. A basic structure is presented and the consequences of it are shown. The DO profiles are calculated and compared to experimental data from Kappala and the DO concentration sensitivity to different input variables and disturbances is analyzed to some extent.

The experiments are summarized in Chapter 3. A brief summary of the identification method is given in Chapter 4. There are seven major experiments reported here and the basic results of them are discussed and analyzed in the Chapters 5 - 11. After this the results are summarized in the following three chapters 12 - 14 and further physical interpretations and comparisons between the different experiments are made. The report is summarized in Chapter 15.

2. DISSOLVED OXYGEN DYNAMICS

The dissolved oxygen (DO) concentration is related to both the blower capacity and to the biological activity in the aerator. The equations describing the DO dynamics have been derived elsewhere, Olsson (1975A) but will be repeated here for convenience. In Olsson (1975B) some static analysis of the equations has been performed, and some of the results are relevant for this study.

The DO equations for a complete mix reactor and a plug flow reactor are repeated in 2.1. It is assumed that the Käppala ae rator dynamics is possible to describe as a dispersed plug flow reactor, i.e. some compromize between complete mix and plug flow. Some discussion is made about DO profiles in 2.2. The DO sensitivity with respect to different inputs or disturbances is discussed in 2.3.

2.1 Dissolved oxygen equations.

The DO dynamics for a complete mix reactor can be derived by taking the DO mass balances over the aerator, see fig 2.1.

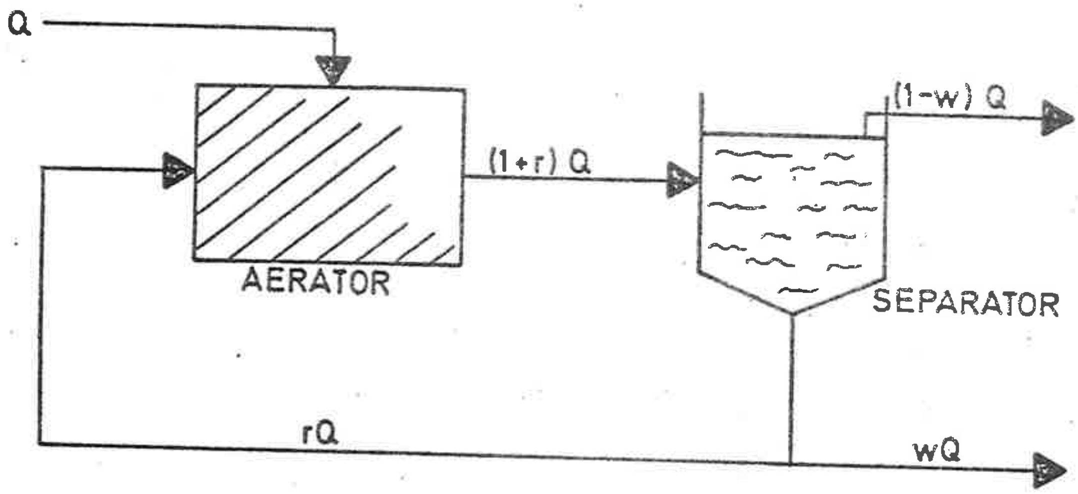

Fig. 2.1. Schematic flow diagram of a complete mix aerator.

Then the dynamics is

$$\frac{dc_o}{dt} = D\,(c_{oi} - (1+r)c_o) + k_L a\, u_{air}\,(c_{os} - c_o) -$$

$$- \frac{1 - Y_x}{Y_x}\,\hat{\mu}_x \cdot \frac{s}{K_s + s}\, c_x\, f(c_o) - k_2\, d_x\, c_x \qquad (2.1)$$

where

c_o = DO concentration (mg/l)

c_{oi} = influent water DO concentration

c_{os} = saturation concentration of DO (mg/l)

D = dilution rate of the aerator (=Q/V)

r = return sludge flow rate ratio

$k_L a$ = oxygen transfer coefficient

u_{air} = air flow from the blowers

Y_x = yield constant

$\hat{\mu}_x$ = maximum specific growth rate of microorganisms (h^{-1})

s = substrate concentration (BOD)

K_s = growth limiting constant

c_x = concentration of viable organisms (mg/l)

k_2 = constant

d_x = decay coefficient (h^{-1})

The function $f(c_o)$ reflects, that the biological activity is oxygen limited for small DO concentrations. It resembles a Monod type function and may be described either by

$$f(c_o) = \frac{c_o}{K_o + c_o} \qquad (2.2)$$

or by

$$f(c_o) = 1 - \exp(-\alpha \cdot c_o) \qquad (2.3)$$

where α is a constant.

The limiting function $f(c_o)$ is illustrated in fig 2.2, where the form (2.3) has been used. Two different values of α are shown.

The first term of (2.1) describes the DO that is coming into the aerator from the primary sedimentation and the amount of DO that flows out into the settler. It is assumed that the DO concentration in the return sludge flow is negligible. This is a reasonable assumption, as the endogeneous respiration in the settler will consume all the DO that is left.

The second term of (2.1) is the oxygen transfer through the blowers. It shows the wellknown fact, that the oxygen transfer is proportional to the difference between the saturation concentration and the actual DO concentration. It is also proportional to the air flow rate, at least for the flow rates that are actual in an aerator. The term $k_L a$ is to be determined in the identifiaation experiments. It is significantly depending on the sludge condition and may be between 50 and 100 % of the value found for clean water. It is also varying along the aerator as the substrate concentration and the reaction speed goes down, see e.g. Eckenfelder et al (1970)

The third term is due to the biological uptake for cell synthesis. The oxygen consumption is directly proportional to the amount of new cells created by synthesis. The synthesis is limited by the DO concentration for DO levels below some 1 - 1.5 mg/l. The function $f(c_o)$

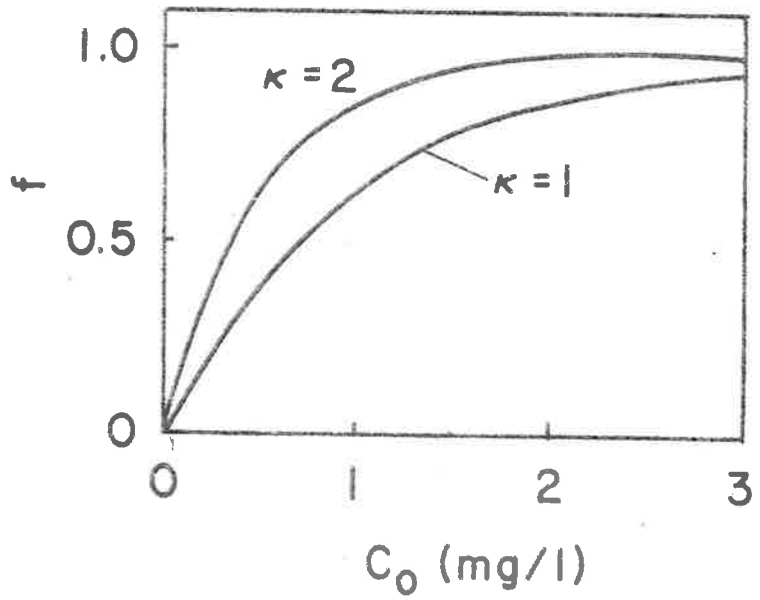

Fig. 2.2. Illustration of the function $f(c_o)$, eq. (2.3).

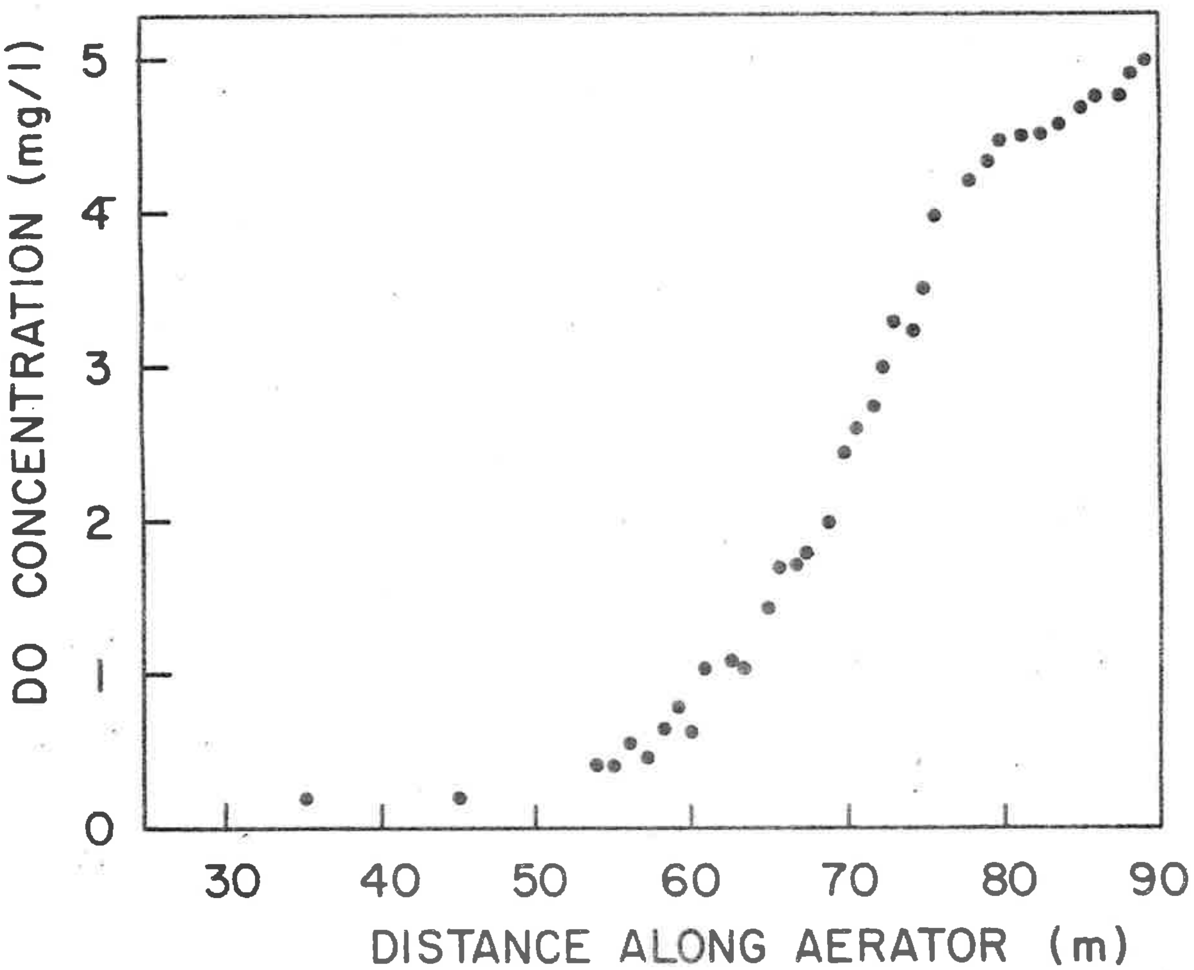

Fig. 2.3. Measured DO profile at the Kappala plant, aerator 2.
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is used to describe this phenomenon. The last term in (2.1) reflects the DO consumption due to endogeneous respiration.

In order to describe the biological activity in the aerator the dynamics for different species of organisms as well as substrate, biosorption, and inert bacteria has to be described. This has been described elsewhere [7] and will not be repeated here. The coupling from the DO equation to the biological reactions actually is by the function $f(c_o)$.

In a plug flow reactor the differential equation (2.1) has to be adjusted for the different hydraulic conditions. The plug flow equations are derived in [7] and are

$$\frac{\partial c_o}{\partial t} = - v \frac{\partial c_o}{\partial \xi} + (c_o)_{prod} - (c_o)_{cons} \tag{2.4}$$

where

v = stream velocity (m/s) in the aerator

The production term is the same as the second term of (2.1), while the consumption term is identical to the third and fourth terms in (2.1).

For the steady state case it is clear that (2.4) is just an ordinary differential equation. The boundary condition is the known DO concentration of the influent wastewater at the head end of the reactor.

The biological equations coupled to (2.4) have more complicated boundary conditions. The concentrations at the head and tail ends of the reactor are actually coupled by the settler dynamics. This is further discussed in [8].

2.2 Dissolved oxygen profiles

If the air inflow to the aerator is uniformly distributed along the reactor, there will be a non-uniform DO profile along the tank. Because of the high biological oxygen uptake rate the demand in the beginning of the tank is very high. This results in a low DO concentration in the head end of the tank. When the substrate concentration decreases along the tank the subsequent synthesis rate decreases and the DO concentration can rise. In the tail end the positive contribution from the compressors is generally much larger than the negative consumption term from the biological uptake. A typical profile from the Käppala wastewater treatment plant is shown in fig 2.3. It does not reflect the true steady state conditions, as the flow rate of wastewater varies during the measurements. It does, however, indicate the qualitative nature of the profile.

DO profiles for different operational conditions have been calculated in [8] for a plug flow reactor. Even if a plug flow pattern does not describe the Käppala plant adequately the profile calculations give a qualitative indication of the causes and effects of the profile. Some of the results are shown here.

The equation (2.4) has been solved together with the viable organism and substrate concentration equations. Fig. 2.4. shows the resulting DO profiles for some different air flows. The parameter in the figure is the product $k_L a\ u_{air}$. For simplicity, let us call it k_1. The value $k_1=10$ corresponds to a flow rate of about the double normal value. The DO profile has the typical S-shape. Even if the flow rate is very high it is not sufficiently high to supply the biological activity in the head end. Still it results in an abundant concentration of DO in the tail end. When the air flow is decreased to 75 % ($k_1=7.5$) the largest change takes place in the middle part of the aerator. The difference between $k_1=7.5$ and $k_1=5$ shows even more, that the DO profile has a maximum sensitivity for air flow changes in the middle of the tank. When the air flow rate is decreased further the character of the DO profile changes. It is no longer almost horizontal at the tail end but significantly positive. This is a sign, that the biological reaction has not been completed in the aerator, and consequently the concentration of substrate in soluble and floc phases are too high.

The calculations above show, that in a "normal" profile the maximum sensitivity for air flow rate changes appears to be in the middle part of the aerator and not in the tail end. This will actually be demonstrated in the first experiment 740626. In [8] an analysis of the sensitivity has been made, and it is shown that the steady state sensitivity actually has a maximum at DO concentrations around 2 - 4 mg/l, depending on the operational conditions.

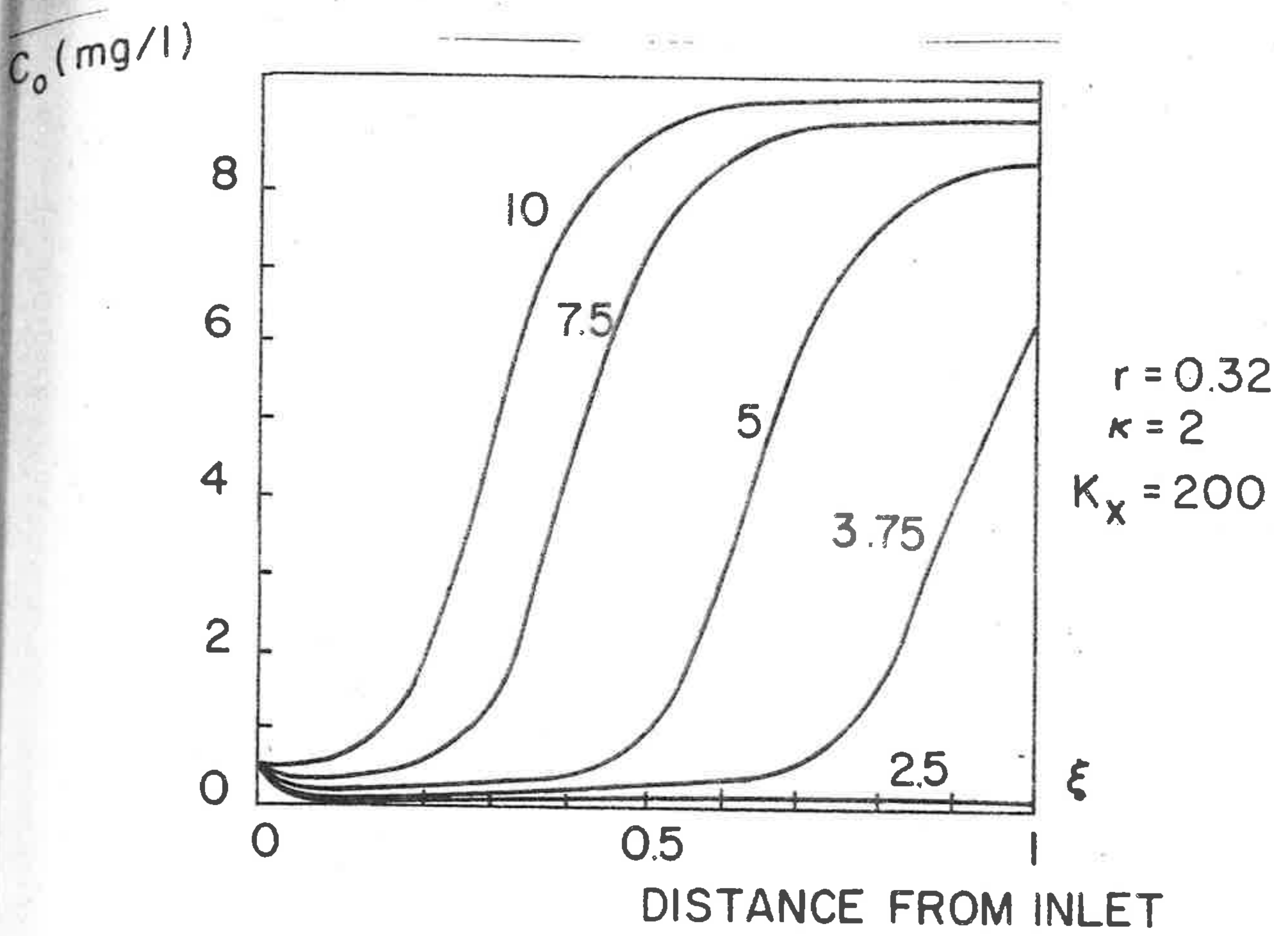

Fig. 2.4. Dissolved oxygen profiles for a plug flow reactor. The value of $k_L a\, u_{air}$ is the parameter.

Numerical values:

$V/Q = 4$ hrs

$c_{oi} = 0.5$ mg/l

$c_{os} = 10$ mg/l

$Y_x = 0.5$

$\hat{\mu}_x = 0.2\ h^{-1}$

$K_s = 200$ mg/l

$k_2 = 0.25$

$d_x = 0.005\ h^{-1}$

Influent substrate conc = 200 mg/l

Compaction ratio in the settler = 4

It is also demonstrated in the experiments, that practicly no DO changes due to air flow rate changes can be observed in the head end of the reactor.

2.3. DO concentration sensitivity

The DO concentration can be manipulated by most three variables, the air flow rate, the influent water flow rate and the return activated sludge flow rate. The two latter ones are not really the control inputs for the DO level, but should be considered as external disturbances for the DO concentration. The major input variables is all the time the air flow rate.

Another two variables will affect the DO concentration, the substrate (BOD) concentration and the viable organism concentration which can be related to the MLSS concentration. The BOD disturbance comes primarily from the influent wastewater and varies in a diurnal pattern. On top of this there are chock loads due to either industrial wastes or due to rain storms, The substrate concentration will be diluted in the latter case.

In order to roughly describe the static gain (or the control authority) from different inputs, let us consider eq (2.1). The static gain from different inputs has been considered in [8]. The air flow input comes from the term u_{air}. The wastewater influent flow is related to the dilution D. The hydraulic disturbance due to the return activated sludge flow rate r is also shown. There is an indirect influence from a disturbance in the term r too. The growth rate of organisms will be affected, as the sludge age of the organisms is depending on the return sludge flow rate. This influence, however, is very slow and takes days. When the return sludge flow is changed the available sludge in the settler, however, will be moved more rapidly to the aerator, and a transportation of sludge follows. Due to this transportation the sludge concentration in the aerator can be influenced within the order of hours.

In order to calculate the DO sensitivity to different inputs and disturbances eq (2.1) is linearized. In steady state and for small disturbances the change in DO due to the inputs can be written

$$\Delta c_o = G_1 \Delta u_{air} + G_2 \Delta Q + G_3 \Delta s + G_4 \Delta c_x$$

The expressions for $G_1, \ldots, G_4$ have been derived in [8] p 103 ff. Consider the normalized values of the steady state transfer functions

$$\Delta c_o = G_1' \frac{\Delta u_{air}}{\bar{u}_{air}} + G_2' \frac{\Delta Q}{\bar{Q}} + G_3' \frac{\Delta s}{\bar{s}} + G_4' \frac{\Delta c_x}{\bar{c}_x}$$

The maximum sensitivity G_1' with respect to air flow changes will be of the order 7. The maximum appears at about 2.5 - 4 mg/l, while there is a zero sensitivity at either zero DO concentration or at saturation concentration.

The sensitivity with respect to influent water flow changes is an order of magnitude smaller. It has a maximum of about 0.5. The sensitivity with respect to disturbances in substrate concentration G_3' or MLSS concentration G_4' is higher and can be estimated to be of the order 3 - 5 for the actual system. The values of the three last transfer functions are negative.

2.4. Nonlinearities in the air flow input

The dynamics of the DO concentration is nonlinear, as eq. (2.1) shows. Even if (2.1) represents a complete mix reactor it can give some qualitative information about the nature of the nonlinearities. The dynamics with respect to air flow input is very fast compared to the metabolism and to the hydraulic response times. Therefore it is reasonable to assume, that both the substrate concentration (s) and the organism concentration (c_x) are constant during changes in air flow.

As the air flow is uniformly distributed along the aerator, the dyaamics is similar all along the tank. The difference between the different parts of the tank is due to different concentrations in substrate and organisms, and this changes of course the operating level of the DO concentration.

For the analysis the tank is divided into small compartments of complete mix reactors, each one with the volume V_k. In the actual time scale s and c_x are constant in eq 2.1 and therefore the DO dynamics can be described by

$$\frac{dc_o}{dt} = D_k(c_{o,k-1} - c_{o,k}) + k_1 u_{air}(c_{os} - c_{o,k}) - g(s,c_x) f(c_o) \qquad (2.5)$$

where D_k = dilution constant

$k_1 = k_L a$

$g(s,c_x)$ = constant function of substrate and organism concentrations

The input u_{air} is not linearly related to the DO concentration. Depending on the biological uptake rate the function g has different values.

An approximate analysis is made by letting c_o and u_{air} vary around the steady state values

$$c_o = c_o^\circ + \Delta c_o$$

$$u_{air} = u^\circ + \Delta u$$

which gives

$$\frac{d(\Delta c_{o,k})}{dt} = D_k\,(c_{o,k-1} - c^\circ_{o,k} - \Delta c_{o,k}) +$$

$$+ k_1(u^\circ + \Delta u)\,(c_{os} - c^\circ_{o,k} - \Delta c_{o,k}) - g(s,c_x) * f(c_o^\circ + \Delta c_o) \qquad (2.6)$$

Only DO concentrations larger than 1 mg/l will be considered why the function f(·) is practicly constant equal to one. The terms that cancel in steady state are cancelled,

$$\frac{d(\Delta c_o)}{dt} = - D_k \Delta c_o - k_1 u^\circ \Delta c_o + k_1 \Delta u (c_{os} - c_o^\circ) - k_1 \Delta u \Delta c_o \qquad (2.7)$$

where the subscript k has been neglected. Eq. (2.7) is rewritten in the form

$$\frac{d(\Delta c_o)}{dt} = - [\, k_1(u^\circ + \Delta u) + D_k \,]\, \Delta c_o + k_1 (c_{os} - c_o^\circ)\, \Delta u \qquad (2.8)$$

Some general observations from (2.8) can now be made

* the "time constant" of the system depends on the amplitude of the input, as the basic system is bilinear in u_{air}
* the gain of the system depends on the operating level and is

$$G = \frac{c_{os} - c_o^\circ}{u^\circ + \Delta u + D_k}$$

It can be observed, that the response time for an input in u_{air} does not depend on the steady state concentration c_o°. In a long channel type aerator, where the DO concentration is widely different in the head end and tail end, the response time should still be the same. Observe, that it is also independent of the biological uptake rate in this time scale. Thus for a constant amplitude of the input u the "time constant" of the system would be the same, as long as u° is constant along the tank. To give a feeling for the numbers involved, assume that

$k_1 u^\circ \approx 5$. D_k is less than 0.1 and can therefore be neglected here. For very small disturbances the real time constant therefore is about 12 minutes. If Δu is 50 % of u° the time constant can be 8 minutes in the estimated model.

The gain of the system is lower close to the tail end of the aerator where the DO concentration is high and is higher in the middle of the aerator. Close to the head end the gain is small again, but then this analysis is not valid any longer. The reason is that the function $f(c_o)$ is getting important, see further section 2.3.

Some step responses of the DO concentration due to steps in the air flow are shown in figure 2.5. They demonstrate, that the "time constant" is independent of the operating level, but the gain is smaller closer to the saturation concentration.

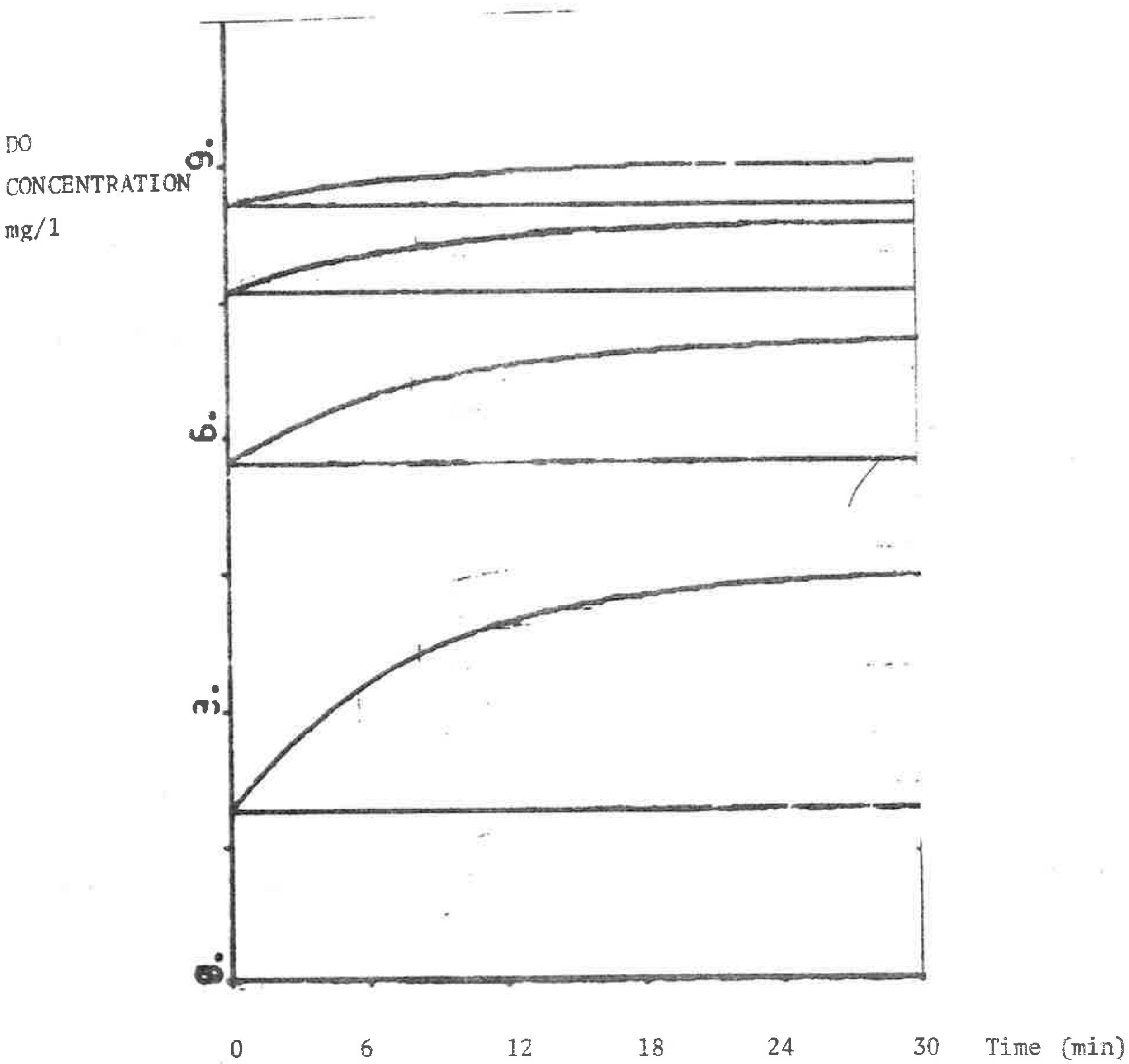

Fig. 2.5. Step responses of DO due to changes in air flow rate. The air flow rate in steady state is the same for all the cases, but the biological uptake rate is different. The air flow is increased 50 % over the steady state value. The time constants are the same for the different cases, about 8 minutes. The gain, however, is different

2.5. Nonlinearities in the wastewater influent flow

The DO dynamics is nonlinear also in the wastewater influent flow input Q. Let it suffice here to analyze the complete mix equation (2.1) to show the character of the nonlinearity.

The changes due to metabolism can be neglected, so s and c_x are constant in (2.1). Moreover, only DO concentrations larger than about 1 mg/l are considered, so the function $f(c_o)$ is assumed to be constant and one. Eq. (2.1) can therefore be rewritten as

$$\frac{dc_o}{dt} = a_1 Q + a_2 Q c_o + a_3 (c_{os} - c_o) + a_4$$

where $a_1, \dots a_4$ are constants.

Let c_o and Q vary around the steady state operating point,

$$Q = Q^\circ + \Delta Q$$

$$c_o = c_o^\circ + \Delta c_o$$

$$\frac{d(\Delta c_o)}{dt} = a_1 \Delta Q + a_2 \Delta Q\, c_o^\circ + a_2 Q^\circ \Delta c_o + a_2 \Delta Q \Delta c_o - a_3 \Delta c_o =$$

$$= [\, a_2 (Q^\circ + \Delta Q) - a_3 \,] \Delta c_o + (a_1 + a_2 c_o^\circ) \Delta Q$$

The "time constant" of the system thus is

$$T = [-a_2 (Q^\circ + \Delta Q) + a_3]^{-1}$$

In order to examine how much ΔQ will influence T let us look at the order of magnitude of a_2 and a_3.

$$a_2 = \frac{1+r}{V}$$

$$a_3 = k_L a \, u_{air}$$

Then $a_2(C)$ is of the order 0.1 - 0.2 for the actual plant, while a_3 is of the order 5. Therefore the amplitude of [illegible] is of minor importance for the "time constant".

The gain of the system is

$$G = \frac{a_1 + a_2 c_o^\circ}{a_3 - a_2(Q^\circ + 4Q)}$$

The constants

$$a_1 = \frac{c_{oi}}{V}$$

can be almost neglected compared to $a_2 c_o^\circ$, and therefore the gain is about proportional to the operating level of the DO concentration. Thus the gain ought to be somewhat larger in the tail end than in the middle part due to disturbances in the influent water flow.

2.6. Nonlinearities in the return sludge flow input

The analysis for the return sludge flow input nonlinearities can be performed completely analogous to section 2.5. Eq (2.1) is rewritten in the form

$$\frac{dc_o}{dt} = b_1 - D(1+r)c_o + b_2(c_{os} - c_o) + b_3$$

If the return sludge flow r is varied

$$r = r^\circ + \Delta r$$

then the equation is rewritten as

$$\frac{d(\Delta c_o)}{dt} = -D[\,(1+r)\Delta c_o + c_o^\circ \Delta r + \Delta r \Delta c_o\,] - b_2 \Delta c_o =$$

$$= [\,-D\,(1+r+\Delta r) - b_2\,]\Delta c_o \;-\; D\,c_o^\circ \Delta r$$

The constant b_2 is of the order 5 while the term $D\,(1+r+\Delta r)$ is of the order 0.1 - 0.2. Therefore the "time constant" is al   independent of the magnitude of the input Δr. As for the wastewater input the gain is negative and proportional to the DO concentration.

It should be emphasized that the influence that is discussed here is only the hydraulic influence from the return sludge flow rate. There is a secondary influence in a longer time scale. For a changing return sludge flow rate, the sludge concentration will change. Therefore the biological oxygen uptake will change. The first change can be seen within the order of hours, when sludge simply is moved from the settler to the aerator with an changing speed. In the order of days the metabolism will   influence the total sludge mass

3. EXPERIMENTS AND DATA HANDLING

A summary of the experimental conditions is made in this chapter. The different experiments are then described in detail in the chapters 5 - 11, where also the identification results are given. The summary is given in 3.1. The data handling procedure has been somewhat complicated and it is briefly described in 3.2.

3.1 Summary of the experiments

As mentioned in chapter 2 there are three interesting inputs to the DO concentration. The major input and manipulative variable is of course the air flow, here called V 21. The disturbances to the DO concentration mainly have to do with changes in flow rates of the wastewater or the return sludge flow rate, here called V 9 and V 52 respectively. It has been able to manipulate all these three variables in order to examine the cause-effect relationships for the DO. There are also other interesting variables which will disturb the DO concentration, such as the substrate and MLSS concentrations. It has not been possible to manipulated those variables, but the MLSS concentration has been registered at the tail end of the aerator.

Table 3.1 summarizes the experiments.

TABLE 3.1.

SUMMARY OF THE EXPERIMENTS

Experiment	Manipulated variables	Other relevant inputs	Sampling time (sec)	N	Total exp. time (h,min)
740626	21	-	10	1850	5.20
740627	9, 21	16,27,52	30	547	4.33
740702	52	9,27	30	780	6.30
740826	21	9	30	348	2.54
740827	21	27,52	30	760	6.20
740828	9	27,52	60	424	7.04
741126 A	21	-	10	899	2.30
B	21	-	20	405	2.15

Variables

V 9 = influent water flow to grit removal chamber 1 (to aerator 1+2)

V 16 = suspended solids of primary sedimentation effluent

V 21 = air flow rate to aerator 2

V 27 = suspended solids concentration in aerator 2

V 52 = total return sludge flow rate to aerator 2

DO oxygen outputs are called V173, V174 and V175.

Their locations vary from experiment to experiment

Some experimental design considerations have of course to be done. In order to get a high signal-to-noise ratio a large input amplitude is necessary. There is a natural lower and upper limit on all three input signals.
The air flow must not be too small. Then the mixing of the aerator is insufficient, and there is also a risk for clogging of the diffusers. Also the air tubes must be supplied with a minimum pressure in order to work properly. There is naturally a maximum limitation of the air flow. The primary limit has to do with the pressure in the air tubes. If the pressure gets too high, then a safety valve system gets into action.

The influent water can be varied between quite wide limits. The flow can be redirected between the grit chambers and a significant disturbance can therefore be achieved. The flow can also be kept constant during an experiment. Then the natural variations are lead into the other aerators.

For short times the return sludge flow rate can be varied quite significantly, and this possiblity was also used.

The nonlinearities of the DO concentration naturally limits the possible amplitudes for the inputs, see chapter 2.4-2.6, especially for the air flow input. There is a trade-off between the different constraints. Some of the limitations were poorly known in the first experiments. With better system and plant knowledge it has been possible to design better experiments.

It is desirable to excite the system with a persistently exciting input signal, such as a PRBS signal. This was possible to do for some experiments. For water inputs, however, the inputs mostly had to be made like step disturbances or a few rectangular pulses.

3.2. Data handling

The Siemens 304 computer at the plant is supplied with good data acquisition programs, which makes it easy to acquire the interesting data. Only the standard programs for data acquisition have been used.

During the experiment the variables are stored at the disk memory, and afterwards punched on paper tape, 10 characters/sec. The paper tape is only of 5 channel type and has therefore been converted to 8 channel paper tape. At the same time some unnecessary information at the primary tape was removed.

The 8 channel paper tape was in turn used to get the data in the PDP 15/30 computer at the Department of Automatic control, Lund Institute of Technology. The data was transferred into standard files on DEC-tape for further use by the identification program IDPAC, see chapter 4.

4. IDENTIFICATION METHOD

The Maximum Likelihood (ML) method has been used to estimate parameters in linear multi-input-single-output models for the DO concentration dynamics. The structure of the system is briefly described in 4.1. A more detailed description can be found elsewhere, e.g. Åström-Eykhoff (1971) or Eykhoff (1974). The identification program is mentioned in 4.2.

4.1 ML identification

The basic structure of the assumed system dynamics is linear with constant coefficients. The structure is given by the difference equation

$$(1 + a_1 q^{-1} + \dots + a_n q^{-n})\, y(t) = \sum_{i=1}^{p} (b_{i1} q^{-1} + \dots + b_{in} q^{-n})\, u_i(t) + \lambda (1 + c_1 q^{-1} + \dots + c_n q^{-n})\, e(t) \qquad (4.1)$$

where q^{-1} is the backward shift operator, and p the number of inputs.

Eq. (4.1) can be written in polynomial form

$$A(q^{-1})\, y(t) = \sum_{i=1}^{p} B_i(q^{-1})\, u_i(t) + \lambda C(q^{-1})\, e(t). \qquad (4.2)$$

The disturbances e(t) are assumed to be a sequence of independent gaussian random variables.

The problem to maximize the likelihood function is reduced to the problem to minimize the loss function V,

$$V = \frac{1}{2} \sum_{t=1}^{N} \varepsilon^2(t) \tag{4.3}$$

with respect to the unknown parameters. The residuals $\varepsilon(t)$ are defined by

$$\varepsilon(t) = [\ C(q^{-1})]^{-1}\ [A(q^{-1})y(t) - \sum_{i=1}^{p} B_i(q^{-1})u_i(t)\ ] \tag{4.4}$$

N is the number of samples and λ^2 is the covariance of the residuals. The parameter λ can actually be estimated independently of the parameters a_i, b_i and c_i and is

$$\hat{\lambda}^2 = \frac{2}{N} V(\hat{\Theta}) \tag{4.5}$$

where Θ is the parameter vector, consisting of a_i,b_i and c_i.
The parameter λ can be interpreted as the standard deviation of the one step prediction error.
In the identificationsnot only the estimates but also their standard deviation is given. The latter is calculated from the Cramer-Rao inequality.

The system order test has been performed with the well-known F-test, see Åström-Eykhoff (1971). The test quantity

$$F_{1,2} = \frac{V_{n1} - V_{n2}}{V_{n2}} \cdot \frac{N - n2}{n2 - n1} \qquad n2 > n1 \tag{4.6}$$

asymptotically has a F-distribution, where n1 and n2 are the numbers of system parameters and V_{n1} and V_{n2} corresponding loss functions respectively.

The residuals can also be tested for independence and normality.

Generally all models found are of low order, either one or two. In most cases there has been great difficulties to find second order models too. Therefore the statistical order tests have been used to a small extent.

4.2. Identification program

The data analysis and the identifications have been performed on the PDP 15/30 computer at the Department of Automatic Control, Lund Institute of Technology. The interactive identification program package IDPAC has been used extensively. It is described elsewhere, see Gustavsson et al (1973). Especially for a relatively poorly known system like the activated sludge system the interactive facility has been invaluable.

Not only the manipulated variables have varied during the experiment but also other variables which may influence the DO concentration. With the IDPAC program such cause-effect relationships have been examined to a great extent with a very reasonable effort.

5. EXPERIMENT 740626. AIR FLOW RATE DISTURBANCE

The main purpose of this experiment was to give a preliminary estimate of the dominating time constants for the dissolved oxygen (DO) transfer from the compressors. Of that reason the sampling time was chosen relatively short, only 10 seconds.

At the time for the experiment no analysis had been made of the DO profile sensitivity for air flow changes. Therefore, the three DO probes were located equally distributed along the tank.

5.1 Recorded variables

For the identification purposes the following variables are interesting

V021 - recorded air flow rate to aerator 2
V173 - DO concentration in the middle (65 m from inlet)
V174 - DO concentration at the tail end (94 m from inlet)
V175 - DO concentration at the head end (20 m from inlet)

Sampling interval = 10 sec
Number of samples = 1850
Experiment time = 5 hrs 20 min

Fig. 5.1 shows a plotting of the air flow rate, where the mean value has been subtracted. The shortest pulses of the input are about 2.5 minutes, while the longest pulse is 90 minutes. Some very fast oscillations of the air flow are registered. They have to do with pressure variations in the air tubes. With the present air flow control system those variations could not be avoided.

The DO concentration in the middle (V173) is registered in Fig. 5.2. Some characteristic features are observed. The response to the step changes of the input is very rapid, much more rapid than was expected. The air flow oscillations also are transferred to the DO concentration, and a high frequency noise is added to the DO concentration signal. On top of the fast response it is possible to see approximately a first order response to the DO signal.

The head end signal verified the qualitative theory, that the DO **variations** should be small. In fact the DO signal V175 had almost a constant mean value with a high noise level added on top of it despite the air flow disturbances.

The tail end DO signal V174 is quite different from V173, see Fig. 5.3. Both the noise amplitudes and the time responses are different.

5.2 Maximum likelihood identifications

Two different models will be discussed. The first one has V173 as output and the other one has V174 as output. The air flow is input in both models.

5.2.1 DO concentration V 173 (middle part)

The DO signal V173 is considered the output y and the air flow rate V 21 is the input u of the structure (4.2). The actual variables are the changes of the real signals. The DO concentration is measured in per cent of the saturation concentration (about 10 mg/l) while the air flow rate is measured in normal m^3/min. The average value of the input is 79.5 Nm^3/min and the average output is about 4 mg/l.

Model structures of order 1, 2 and 3 were tried. For the third order model a very poor convergence was achieved. In the minimum point calculated the gradient was too large. Several starting points were tried, but no better third order model could be achieved.

Table 5.1 summarizes the identification parameters. From the F test (4.6) the second order model should be accepted. Its parameters have an acceptable accuracy and the minimum point have a reasonable value of the maximum gradient value.

The time constant of the second order model verify the observations from Fig. 5.2. There is a fast time constant except the expected one of 11 minutes.

The fast time constant indicates, that the DO sensor is sensitive to gaseous oxygen and not only to dissolved oxygen. If this is the normal case or simply caused by a poor membrane was not well-known [11].

TABLE 5.1 Identification results of middle DO concentration (V173) as function of air flow input. (V021)

	1 order	2 order
N	1840	1840
a_1	-0.875 ± 0.014	-1.384 ± 0.051
a_2		0.393 ± 0.049
$b_1 \cdot 10^2$	0.848 ± 0.096	1.972 ± 0.143
$b_2 \cdot 10^2$		-1.896 ± 0.145
c_1	-0.219 ± 0.045	-0.749 ± 0.055
c_2		-0.142 ± 0.040
λ	0.241 ± 0.004	0.228 ± 0.004
V	53.64	47.80
F		75
abs. max grad	1.35 E-4	1.5 E-2
discrete poles	0.875	0.985, 0.399
Δt (s)	10	10
time const.	75 sec.	11.0 min, 10.9 sec.

TABLE 5.2 Identification results of tail end DO concentration V174 as function of air flow input V021.

Case	1	2	3
N	1840	Data 1-900	Data 900-1830
a_1	-0.995 ± 0.001	-0.994 ± 0.001	-0.999 ± 0.001
$b_1 \cdot 10^2$	0.595 ± 0.044	0.668 ± 0.096	0.610 ± 0.057
$c_1 \cdot 10$	-0.641 ± 0.330	-0.440 ± 0.417	0.048 ± 0.477
λ	0.206 ± 0.003	0.233 ± 0.005	0.182 ± 0.004
V	39.24	(24.34)	(15.49)
Abs max grad	2.0 E-4	8.0 E-3	3.4 E-4
Δt (s)	10	10	10
Time const.	33.2 min	27.7 min	166 min
Discrete poles	0.995	0.994	0.999

5.2.2. DO concentration V174 (tail end)

The identification results of the tail end DO concentration V174 as function of the air flow to aerator 2 are summarized in table 5.2. It was only possible to get convergence for first order model of the dynamics.

In table 5.2 three different first order models are shown. The first one is based on all available data, while the second and third ones are based on the first half and second half of the data set respectively.

The time constant of 33 min. found for V174 is significantly longer than the 11 minutes found for V173. The accuracy, however, of the 33 minutes time constant is relatively poor. The reason is the short sampling interval, which makes the discrete pole very close to 1. A small error in a_1 will therefore create a large variation in the value of the corresponding time constant.

In the model simulation, Fig. 5.4, a trend error can be seen. A new identification was attempted with the trends of the input and output removed. The parameters did not change much, and the loss function remained the same. The model error still has a trend in it, see Fig. 5.5, but in the other direction.

The residual independence has been tested, Fig. 5.6, for case 1.

Now consider the cases 2 and 3, table 5.2. Case 2 is based on the first half of the data set, while case 3 is based on the second one.

Figs. 5.1-5.3 show, that in the first half of the experiment there is a long rectangular disturbance, but in the last half only fast modes are excited. Therefore the determination of the long time constant should be more accurate in Case 2 compared to Case 3. If the time constants in Table 5.2 are compared it is noted a large difference between Case 1 and 2 on one hand and case 3 on the other. In case 3 the system is almost approximated simply by an integrator.

The model output from case 2 is plotted in Fig. 5.7.

6. EXPERIMENT 740627. DISTURBANCES IN INFLUENT WASTEWATER FLOW RATE AND AIR FLOW RATE.

The purpose of the experiment was to verify the relationship between the influent wastewater flow rate and the DO concentrations in different parts of the aerator. The air flow rate was also changed independently of the water flow rate.

There were practical limitations to change the water flow rate. They are considered more as a sequence of step changes than a persistently exciting signal. The dominating response time from the water flow is expected to be of the order one hour.

6.1 Recorded variables

The variables that were purposefully disturbed are not the only ones that are interesting for the identification. Some other variables are unpurposefully disturbed during the experiment, such as the suspended solids concentration in influent wastewater and in the aerator. Their relationship to the DO concentration will also be examined.
The interesting variables for the experiments are

- V 9 - influent water flow to grit removal chamber 1
- V 16 - suspended solids of primary effluent
- V 21 - air flow rate to aerator 2
- V 27 - suspended solids concentration in aerator 2
- V 52 - total return sludge flow rate for aerator 2
- V 173 - DO concentration at two thirds from the inlet (~65 m)

174 - DO concentration at the tail end (~95 m)

Sampling interval = 30 sec.
Number of samples = 547
Experiment time = 4 hrs. 33 min.

The influent water flow V 9 is the total flow to aerators 1 and 2. The influent water to aerator 2 is therefore half of V 9.

The variables are plotted in the Figures 6.1-6.7, where corrections for outliers and missing data points have been made. The step in the water flow rate (Fig. 6.1) is relatively large, ranging from 0.2 m^3/sec to 0.5 m^3/sec. The average flow for V 9 is about 0.45 m^3/sec, which corresponds to one third of the total plant input. In Fig. 6.2 the variations of the suspended solids of the primary sedimentation effluent are registered. There is a slow variation in the suspended solids concentration with about 2 hours from the minimum to the maximum, which apparently has to do with the diurnal variation. The air flow rate is plotted in Fig. 6.3.

There is only one step applied during the experiment.

The suspended solids concentration in aerator 2 shows only a slight variation, why there is probably a negligible influence from it in this experiment, Fig. 6.4. The total return sludge flow rate was coupled in this experiment to the influent flow rate by a ratio controller, Fig. 6.5. Because of this it is impossible to distinguish between the two signals V 9 and V 52 in the identifications. Consequently all influence from the return sludge flow is represented by the influent flow V 9.

The primary outputs are the DO concentrations V173 and V174. V173 is plotted in Fig. 6.6. There is a clear connection between the big flow rate step (Fig. 6.1) and the response in V173. As the air flow rate change is relatively small, its contribution in the DO change is of minor importance here. There is here- as in experiment 740626 - a relatively high noise level of the signal V173 and a significant difference between the responses of V173 and V174. The DO probe V173 was not changed from previous experiment.

6.2 Maximum likelihood identification

The identifications have been performed for the two different outputs V173 and V174. The influence of influent flow rate, air flow rate as well as the three inputs V 16, V 27 and V 52 has been examined. It has only been possible to achieve first order models.

The influence from the variables V 16 (suspended solids influent) V 27 (MLSS) and V 52 (return sludge flow rate) are shown to be negligible.

6.2.1 Tail end DO concentration V174

The tail end concentration V174 has been identified as function of all the variables V9, V16, V21, V27, V52. In table 6.1 parameter values are shown. Case 1 is the model with the two manipulated variables as inputs. Both of the b parameters have acceptable variances, even if the air flow influence is the clearest. This fact was also observed from the experimental data plot. The time constant is long, more than two hours. The accuracy is not very reliable, as the pole is close to the unit circle. It is, however, natural to expect, that this time constant should be bigger than the one in experiment 740626. The flow rate influence is of the order hours, so the model time constant will apparently find a value between the air flow time constant and the water flow time constant. No second order model converged.

Consider the deterministic model input, Fig. 6.8. It does not behave well, and because of the long time constant it looks like an integrator. The main error is due to a linear trend. In order to correct for this linear trends were removed from the V174. Corresponding model is listed as case 2 in table 6.1. It is true, that the loss function is smaller for case 2, but on the other hand the relative accuracy of the b parameters is poorer than in case 1. The influence from the water flow (b_{11}) is no longer significant. The model output is not satisfactory, Fig. 6.9. Therefore a better experiment has to be constructed.

As illustrated by case 3, the influence from the variable V27 (MLSS concentration variation) is negligible, compared to case 1. Moreover the MLSS 6 parameter accuracy is low. Even the sign is wrong. As a first approximation to a model case 1 is accepted.

6.2.2. Center DO concentration V173

As for the variable V174 there is only a significant influence on the DO concentration from the manipulated variables V 9 and V 21. The relative importance is, however, different here. This fact was discovered already in the plots, Fig. 6.6 and 6.7, Table 6.2

TABLE 6.1 Identification of the tail end DO concentration V174 as function of air and wastewater influent flow rates.

Case	1	2	3
N	541	541	541
a_1	-0.996 ± 0.002	-0.996 ± 0.003	-0.997 ± 0.002
b_{11}(V9)	-0.132 ± 0.107	-0.015 ± 0.060	-0.128 ± 0.107
$10 \cdot b_{21}$(V21)	0.124 ± 0.022	0.085 ± 0.016	0.134 ± 0.024
b_{31} (V27)			0.354 ± 0.266
c_1	-0.248 ± 0.046	-0.361 ± 0.048	-0.247 ± 0.046
λ	0.222 ± 0.007	0.214 ± 0.007	0.222 ± 0.007
V	13.28	12.37	13.28
Δt (s)	30	30	30
time const.	123 min.	136 min.	147 min.
		Trend removed	

TABLE 6.2 Identification of the DO concentration V173 as function of air and influent water flow rates.

Case	4	5	6
N	541	536	541
a_1	-0.937 ± 0.011	-0.912 ± 0.016	-0.907 ± 0.022
b_{11} (V9)	-0.304 ± 0.055	-0.420 ± 0.080	-0.286 ± 0.065
$10^2 \cdot b_{21}$(V21)	0.335 ± 0.064	0.461 ± 0.085	0.438 ± 0.098
$10 \cdot b_{31}$ (V27)			0.669 ± 0.999
$10 \cdot b_{41}$ (V52)			-0.408 ± 0.211
c_1	-0.745 ± 0.050	-0.711 ± 0.054	-0.689 ± 0.065
λ	0.179 ± 0.005	0.177 ± 0.005	0.178 ± 0.005
V	8.623	8.440	8.545
Δt (s)	30	30	30
time const.	7.7 min	5.4 min	5.1 min
		(b_{11} delayed 6 * 30 sec)	$F_{6,4} = 2.5$

case 4 shows a first order model. The parameter accuracy estimations are satisfactory. The time constant of 7.7 minutes is much smaller than that of V174, and is still larger than the one found in experiment 740626 (75 seconds). The model tries to make a compromise between the air flow time constant and the water flow time constant.

Case 6 shows the influence from the variables V27 and V52. They do not contribute significantly to decrease the loss function, which was expected. Their accuracy is also poor.

In case 5 it has been examined if a better model accuracy could be achieved, by describing the water flow input with a time delay. A slightly smaller loss function was found for a delay time of 6 sampling intervals (3 minutes). The system time constant was consequently smaller than for case 4.

As it was discovered that the sensor membrane was poor in the experiment the time constants for V173 are probably too small.

Fig. 6.10 shows a comparison between the model deterministic output and the experimental output of V173. The model is the one from case 4.

7. EXPERIMENT 740702. DISTURBANCE IN RETURN ACTIVATED SLUDGE FLOW RATE.

In this experiment the ratio control between the influent flow rate and the return sludge flow rate has been removed. A re ctangular pulse disturbance of the return sludge flow was made. The pulse amplitude was about 100% of the average flow value, i.e. from about 100 liters/sec to about 200 liters/sec. The pulse length is about 2 hrs 25 minutes.

The DO concentrations were measured in two points with the sensors V173 and V174. Because of electrical malfunctions only V173 data could be used for the evaluation.

7.1. Recorded variables

The main influence on the DO concentration comes from the return sludge flow rate V52. The suspended solids concentration of the aerator also varies a s a result of the disturbance, and may also influence the DO concentration. The influent water flow rate was changed unintentionally at the initial part of the experiment, and therefore also the water flow rate is exa-mined.

The relevant variables for the actual identification are

V 9 - influent water flow to grit removal chamber 1

V 27 - suspended solids in aerator 2

V 52 - total return sludge flow rate for aerator 2

V 173 - DO concentration at 2/3 from inlet

Sampling interval = 30 sec
Number of samples = 780
Experiment time = 6.5 hrs.

The signals are plotted in the figures 7.1 - 7.3, where corrections are outliers and missing data points are made. Fig. 7.1 shows the return sludge flow rate V52 as well as the DO response. It is possible to find quite a clear relationship between the variables. In fig. 7.2 the water flow is plotted. The large step in the beginning should be noted. There are also some rapid changes of the flow rate during the experiment. The MLSS of the aerator 2 varies about 5% of its total value during the experiment, Fig. 7.3.

7.2. Maximum likelihood identification.

ML identification has been made for the V173 output, excited by the three different inputs water flow (V9), suspended solids in aerator 2 (V27) as well as the return sludge flow rate (V52).

Only first order models have been found. The time constants of the dynamical models are of the order one hour.

Case 1 of table 7.1 shows the results with only return sludge input for the model. The accuracy of the b_1 parameter is not satisfactory. The time constant of the corresponding model is 71 minutes. Compare this value with the time constants of table 6.2. The influence of suspended solids concentration is negligible here. The influent water influence is not either significant. In order to try to improve the accuracy, the data set was cut, and only the data 41-780 were identified. This resulted in the model of case 2, table 7.1. There is only a minor improvement. If the loss functions are normalized to the same number of samples, case 2 corresponds to V = 5.123 (alternatively the values of λ can be compared).

The model output of case 1 is compared with the real output in fig. 7.4. For the case 2 there is only a slight change in the model output. Also by including the MLSS (V27) there is only a negligible model output change.

The residual independence test is shown in fig. 7.5. The residuals are not satisfactorily independent.

TABLE 7.1 Identification of the center DO concentration V173 as function of the return sludge flow rate.

Case	1	2
N	783	740 (41-780)
a_1	-0.993 ± 0.004	-0.994 ± 0.004
100 * b_1	-0.534 ± 0.330	-0.452 ± 0.329
c_1	-0.762 ± 0.035	-0.774 ± 0.038
λ	0.114 ± 0.003	0.114 ± 0.003
V	5.130	4.842
Δt (sec)	30	30
time const. (min)	71	89

8. EXPERIMENT 740826. DISTURBANCE IN AIR FLOW RATE.

In order to compare different sensors two identical DO sensors were placed close to each other at about 2/3 from the inlet in the aerator. The air flow rate was disturbed by a simple rectangular pulse with about 45 minutes duration.

The water flow rate was not constant during the experiment, and therefore, the models found were of first order with a significant input influence from both air and water flows.

8.1. Recorded variables.

For the identification the following recorded variables are interesting

- V 9 - influent water flow
- V 21 - air flow
- V 173 - DO concentration
- V 174 - DO concentration

Sampling interval = 30 sec
Number of samples = 348
Experiment time = 2 hrs. 54 min

As the DO sensors were located close to each other they should show almost identical signals.

Fig. 8.1 shows the water flow, which is not purposefully disturbed during the experiment. The air flow pulse is plotted in Fig. 8.2. The two DO signals are drawn in Fig. 8.3. It is shown that the variations but not the absolute values of the signals are similar.

8.2. Maximum likelihood identification

As the DO sensors show practicly the same variation it is only interesting to identify one of them, V173.
Table 8.1 shows the result for two cases, one with only the air flow as input and one with two inputs. The value of the loss functions are tested against each other, and the case 2 is significantly better. Also the model output is better for case 2. fig 8 .4. The autocovariance of the residuals for case 2 is shown in fig 8 .5.
The V173 curve has actually still a fast mode, which is shown clearly in fig 8.3. This fast mode makes the overall time constant for the model relatively small, only between 4 and 8 minutes.

TABLE 8.1 Identification of the DO concentration V173, excited by the air flow and influent water flow rates.

Case	1	2
N	348	348
a_1	-0.938 ± 0.018	-0.878 ± 0.029
b_{11} (V9)	---	0.487 ± 0.151
1000 * b_{21} (V21)	0.401 ± 0.111	0.843 ± 0.192
c_1	-0.525 ± 0.067	-0.502 ± 0.073
10 * λ	0.260 ± 0.010	0.255 ± 0.010
V	0.1170	0.1135
Δt (sec)	30	30
time const. (min.)	7.8	3.8 $T_{2,1}$ = 12.7

9. EXPERIMENT 740827. DISTURBANCE IN AIR FLOW RATE.

In order to check earlier results from 740626 the air flow rate was disturbed with a PRBS type signal. The locations of the DO sensors were now different from previous experiments, and the three sensors were placed 6 meters apart around about 2/3 from the inlet of the aerator.

Only the air flow rates and the DO concentrations were recorded at every sampling interval (30 seconds), but a few other interesting variables were recorded at every 5 minutes for check-up purposes.

9.1. Recorded variables

For the identification there are three interesting variables

V 21 - air flow to aerator 2

V 173 - DO concentration 66 m from inlet (=66%)

V 174 - DO concentration 72 m from inlet (=72%)

Sampling interval = 30 sec
Number of samples = 760
Experiment time = 6 hr. 20 min

The DO sensor V175 was placed at 60 m from the inlet, but it did not function properly during the experiment. For check-up purposes some variables were recorded each 5 minutes. The relevant signals here are

V 27 - MLSS in aerator 2

V 52 - return sludge flow rate for aerator 2

Number of samples = 76

The air flow rate disturbance is shown in Fig. 9.1. The longest pulse is 2 hours, and the shortest one is 2.5 minutes. The DO responses are shown in figures 9.2 and 9.3. In both the DO variables there are trends which cannot be explained by the air flow rate changes. Instead the trends are related to an unintended change of the return sludge flow rate, fig 9.4, during the experiment. The MLSS of aerator 2 is not affected significantly by the return sludge flow change, so the response in the DO signals from the return sludge flow is because of the hydraulic changes in the aerator. The MLSS is plotted in fig. 9 .5.

9.2. Maximum likelihood identification

As for most of the experiments only first order models have been found . Due to the trend caused by the change in the return sludge flow the results are quite poor.

9.2.1. DO concentration V173

The DO concentration was first identified with only the air input, see case 1 table 9 .1 . The diagram 9 .6 gives a clear indication, that the trend is significant and must be taken into account. Before the error was related to the return sludge flow an attempt was made to just remove a linear trend from the output, as the response to the return flow ought to be very slow compared to the response to the air flow. The DO signal with the trend removed is shown in fig 9 .7, and corresponding model is the case 2, table 9.1. There are two major differences to case 1. Firstly the time constant is now only 2.5 minutes, as the slow variations are not dominant any longer. Secondly, the static gain from the air flow is now only about $8.1\ 10^{-3}$ compared to about $20.8\ 10^{-3}$ for case 1. From the plotting fig 9.8 it is demonstrated, that the fast variations can be reasonably well

TABLE 9.1 Identification of the DO concentration V173 as function of air flow rate and of return sludge flow rate.

Case	1	2	3
N	760	760	74
a_1	-0.984 ± 0.004	-0.818 ± 0.015	-0.958 ± 0.025
$10^3 \cdot b_{11}$(V21)	0.332 ± 0.065	1.477 ± 0.119	0.692 ± 0.416
$10^3 \cdot b_{21}$(V52)			0.009 ± 0.406
$10 \cdot c_1$	-0.880 ± 0.356	-0.936± 0.393	-0.541± 0.183
$10 \cdot \lambda$	0.270 ± 0.007	0.246 ± 0.006	0.923 ± 0.076
V	0.277	0.229	0.316
Δt(sec)	30	30	5 min
time const.	32.0 min.	2.5 min. Linear trend removed	115 min.

TABLE 9.2. Identification of the DO concentration V174 as function of air flow rate and of return sludge flow rate.

Case	4	5	6
N	760	760	74
a_1	-0.982 ± 0.004	-0.905 ± 0.010	-0.842± 0.052
$10^2 \cdot b_{11}$(V21)	0.114 ± 0.017	0.247 ± 0.022	0.543 ± 0.184
$10^2 \cdot b_{21}$(V52)			-0.260 ± 0.195
c_1	-0.383 ± 0.030	-0.411 ± 0.031	-0.085 ± 0.122
λ	0.102 ± 0.003	0.097 ± 0.002	0.256 ± 0.021
V	3.952	3.550	2.416
Δt(sec)	30	30	5 min.
time const.	27.3 min.	5.0 min. linear trend removed	29.1 min.

explained. There is however a somewhat longer time constant in the system, which is not included in the model. This is seen at the beginning of the longest air flow pulse, fig 9.8. By inspection of the curves it is estimated to be of the order 12 minutes.
In order to estimate the influence from the unintended change of the return sludge flow, the signal values were picked for a 5 minutes sampling interval. Thus only 74 samples were achieved. In case 3, table 9.1 the result is shown were the DO signal is assumed to be excited of both air and return flow. As expected there is no fast time constant because of the long sampling interval. Instead the dominating time constant is 115 minutes. The quality of the parameters is very poor. The b parameter corresponding to the air flow has become quite inaccurate. One reason is the small number of data. Another reason is that the input signal, fig 9.9., is not represented accurately any longer. Also the return sludge b parameter is small and inaccurate The model output does not describe the fast variations of the DO. It only gives a rough average variation, fig. 9.10.
It should be observed that the parameter values of cases 1,2 and 3 rêspectively are not directly comparable because of the different sampling intervals.

9.2.2. DO concentration V174

The behaviour of the V174 signal is quite similar to the V173 signal. Figure 9.11 and case 4, table 9.2 show a model with only the air input and no trend correction. If a linear trend is removed, fig, 9.12, the resulting model behaves quite satisfactorily, case 5. The time constant found is 5 minutes, which is shorter than in experiment 740626. The location of the sensor is however different. Fig. 9.13 shows the model output and the real output.

The model with the return sludge flow as input, case 6, is poor as for the other DO signal. The parameter accuracy is not satisfactory and also the model output, fig. 9.14 does not follow the experimental output.

10. EXPERIMENT 740828. DISTURBANCE OF INFLUENT WASTEWATER FLOW RATE

The water flow rate has been disturbed in a more sophisticated manner than in the previous experiment 740627 (Ch. 6). The DO sensors were located somewhat differently now, separated 6 meters about 2/3 from the inlet of the aerator.

10.1 Recorded variables.

During the experiment 12 variables were recorded. For the identification there are only 5 interesting signals

V 9 - influent wastewater

V 27 - MLSS of aerator 2

V 52 - return sludge flow rate

V 173 - DO concentration 66 m from inlet (= 66%)

V 174 - DO concentration 72 m from inlet (= 72%)

Sampling time	=	60 seconds
Number of samples	=	424
Experiment time	=	7 hrs, 4 min

The values from the DO sensor V 175 were not usable for the identification.

The influent flow rate V 9 is plotted in Fig. 10.1. There are two large spikes in the flow data, starting at about 150 and 260 samples respectively. It is doubtful if the real flow is the same. It might be only transient flows in the Parshall flumes with no resemblance in the plant flow. The plotted values, however, have been used in the identification. The MLSS concentration V27, Fig. 10.2, has a relatively significant variation and may influence the DO concentration. The total return sludge flow rate varied unintentionally during the experiment, Fig. 10.3.

Especially during the last phase of the experiment the flow rate increases quite significantly. The resulting DO concentrations are displayed in Fig. 10.4 and 10.5. Their maximum and minima occur almost at the same times.

10.2. Maximum likelihood identification

Only first order models have been found for the dynamic models. The second order model structures did never converge to a reasonable minimum.

The major influence on the DO concentration naturally comes from the influent water flow in this case. There is also minor influences from the MLSS of aerator 2 and from the return sludge flow rate. It is however difficult to judge from identifications only which one is the relevant one. Rather physical judgement may decide which signal to accept.

10.2.1. DO concentration V173

The DO concentration is first identified as function of only the water flow V9, and the result is shown in table 10 .1, case 1. As the plot in fig 10 .6 shows there is an unsatisfactory model error in the last half of the experiment. Different time delays for the water flow input were tried. It was found, that a 1 minute time delay could improve the loss function, but no visual improvement could be seen in the model output. The residuals for case 1 are satisfactory, fig. 10.7.

TABLE 10.1. Identification of the DO concentration V173 when the water flow is excited (V9).

Case	1	2	3
N	424	424	424
a_1	-0.969 ± 0.005	-0.967 ± 0.005	-0.964 ± 0.005
$10 \cdot b_{11}$(V9)	-0.344 ± 0.031	-0.349 ± 0.030	-0.379 ± 0.031
$10 \cdot b_{21}$(V27)		-0.101 ± 0.046	
$10 \cdot b_{31}$(V52)			0.549 ± 0.175
c_1	-0.453 ± 0.042	-0.469 ± 0.042	-0.476 ± 0.042
$10 \cdot \lambda$	0.113 ± 0.004	0.112 ± 0.004	0.112 ± 0.004
V	2.704 E-2	2.675 E-2	2.644 E-2
		$F_{2,1} = 4.6$	$F_{3,1} = 9.6$
Δt(sec)	60	60	60
time const	32.1 min	30.0 min	27.2 min

TABLE 10.2. Identification of the DO concentration V174 when the water flow is excited (V9).

Case	4	5	6
N	424	424	424
a_1	-0.978 ± 0.010	-0.975 ± 0.010	-0.958 ± 0.011
$10 \cdot b_{11}$(V9)	-0.699 ± 0.199	-0.724 ± 0.200	-1.011 ± 0.222
$10 \cdot b_{21}$(V27)		-0.335 ± 0.329	
$10^2 \cdot b_{31}$(V52)			0.411 ± 0.139
c_1	-0.214 ± 0.056	-0.213 ± 0.056	-0.226 ± 0.057
$10 \cdot \lambda$	0.542 ± 0.019	0.541 ± 0.019	0.536 ± 0.018
V	0.622	0.620	0.609
		$F_{5,4} = 1.4$	$F_{6,4} = 8.8$
Δt(sec)	60	60	60
time const	45.6 min	39.1 min	23.5 min

There is a slightly positive trend in the DO concentration data. If the trend is removed the model output behaves like figure10.8, which is somewhat unsatisfactory too.

As the MLSS fig.10.2 and return sludge flow fig 10.3 show variations during the experiment their influence is examined. If the MLSS (V27) is assumed to excite the DO there is an improvement in the model, case 2, table 10.1. Also the model output, fig 10.9 is better, and the maxima at about t=200 and 250 are better explained

If the return sludge flow rate is tried instead as the second input the result is also better, case 3, table 10.1. The model output is changed slightly, fig 10.10, and the maxima at 190 and 250 are not so well predicted. On the other hand the values towards the end of the experiment are better predicted. The b_{31} parameter in case 3 is, however, false. Of physical reasons it must be negative, and therefore the positive value is caused by other effects. The model in case 3 is therefore not accepted.

10.2.2 DO concentration V174

The same types of inputs as for V173 are examined. In case 4, table 10.2 the model for only the water flow input is shown (cf case 1). The time constant for case 4 is significantly longer than for case 1. The b_{11} parameter in case 1 is somrewhat more accurate than corresponding b_{11} in case 4. If the MLSS (V27) is added as an extra input, case 5, the improvement is negligible, unlike case 2. The b_{21} parameter is also very inaccurate. There is, however, a much larger improvement, if the return sludge flow rate (V52) is assumed to be an input, case 6. Not only the loss function is better, but also the last part of the deterministic output of the model is improved, fig. 10.11 (cf. fig. 10.10). As for the V 173 case this model, however, cannot be accepted because of the positive sign of b_{31}.

10.3 A note on analog versus digital multiplication.

If the return sludge flow rate V52 is multiplied with the return sludge concentration V58 the total solids of the return flow results. This signal is achieved by an analog device at Kappala, called V70. The signal V70 is shown in fig 10 .12. If corresponding signal is shown in a digital way, by multiplying V52 and V58 in the computer the result is displayed in Fig 10 .13. There is a notable difference in the noise levels.

11. EXPERIMENT 741126. DISTURBANCE IN AIR FLOW RATE

The air flow rate was disturbed in a similar manner but with different input sequences as in previous experiments 740827 (Ch. 9) and 740626 (Ch. 5). The locations of the sensors were also somewhat different. The membrane of the V173 probe was replaced since previous experiments and some differences here could be noted. The fast mode which was discovered previously did not occur. Therefore it could be concluded that the poor membrane caused the fast mode.

11.1 Recorded variables

There are four recorded variables of interest here

- V 21 - air flow rate for aerator 2
- V 173 - DO sensor located at 60 m (=60%)
- V 175 - DO sensor located close to V 173
- V 174 - DO sensor located at 84 m (=84%)

The sensors V 173 and V 175 were located close to each other in order to check up both calibrations and noise properties.

The experiment was made in two parts, A and B. defined in the table.

Part	A	B
Sampling time (sec)	10	20
Number of samples	899	405
Experiment time	2 hr 30 min	2 hr 15 min

The variables of experiment A are plotted in figures 11.1 - 11.3.

Note that the V173 and V175 signals are not identical. Later the models will be compared. The signal V174 has a different noise character and a different signal amplitude. Note the large difference in absolute DO concentration from 60 to 84 meters along the tank. This is the steepest part of the DO concentration profile. Corresponding signals from the part B of the experiment are plotted in the figures 11.9 - 11.11.

11.2. Maximum likelihood identifications

In no case it has been possible to achieve a reasonable model of second order. In some case second order models have been found with one of the poles on the real negative axis.

11.2.1. DO concentrations V173 and V175

The results of the ML identifications of V173 and V175 are summarized in table 11.1. The V173 model for part A is listed as case 1 and the V175 model as case 4. Theyhave similar time constants, about 26 minutes. The static gains are slightly different, which was observed already from the plotting in figure 11.2. The model output for V173 (case 1) is shown in fig 11.4 and its residial covariance is plotted in fig 11.5. The residuals are not completely acceptable, but no better model could be found. The V175 model output is shown in fig 11.6. In both fig 114 and 11 .6 it can be observed, that the maxima of the DO concentration cannot be predicted very well. The reason can be either a varying sludge concentration in the actual

TABLE 11.1. Identification of the DO concentrations V173 and V175 when the air flow is excited (V21).

Case	1 (V173) (A)	2 (V173) (B)	3(B) [½(V173+V175)]
N	899	405	405
a_1	0.994 ± 0.001	-0.979 ± 0.003	-0.978 ± 0.003
$10^2 \cdot b_1$(V21)	0.308 ± 0.048	0.985 ± 0.095	1.122 ± 0.093
c_1	-0.576 ± 0.035	-0.564 ± 0.036	-0.518 ± 0.035
λ	0.341 ± 0.008	0.383 ± 0.013	0.335 ± 0.012
V	52.352	29.669	22.730
Δt(sec)	10	20	20
time const.	26.1 min	15.4 min	14.7 min

Case	4(A)(V175)	5(B)(V175)
N	899	405
a_1	-0.994 ± 0.002	-0.977 ± 0.003
$10^2 \cdot b_1$(V21)	0.409 ± 0.066	1.272 ± 0.104
c_1	-0.427 ± 0.047	-0.527 ± 0.036
λ	0.349 ± 0.008	0.380 ± 0.013
V	54.790	29.247
Δt(sec)	10	20
time const	26.0 min	14.0 min

part of the aerator (where the suspended solids concentration were not measured) or a varying substrate concentration (BOD or COD). The latter could not either be measured.

The results from part B are listed as cases 2 and 5 in table 11.1. The most notable difference is the time constant. It is only 14-15 minutes here. Part B has a longer sampling time, which would favour a better accuracy of the time constant. Then the input in part B seems to excite the system better than that of part A.

In case 3, table 11.1 the mean value of the signals V173 and V175 has been defined as an output. The resulting model has a time constant between the cases 2 and 5. Also note, that the loss function is significantly better than any of the cases 2 and 5.

The model outputs from the cases 2 and 5 are shown in the figures 11.12 and 11.14 and corresponding residual autocovariances are shown in figs. 11.13 and 11.15. Especially the V175 residuals are not good and a clear oscillation is shown with a period time of the order 40 seconds. Those oscillations can probably be related to the input air flow oscillations. They are discussed earlier in experiment 740626 (Ch. 5). With the average signal of V173 and V175 the residual autocovariances could not be improved, see fig. 11.17.

Now consider the c_1 parameters of the models for V173 and V175. In part B (cases 2, 3 and 5) the parameters are quite similar. In part A (cases 1 and 4) they differ somewhat more.

11.2.2. DO concentration V174

The identifications results with V174 as output are summarized in table 11 .2. The cases 6 - 8 are from part A and case 9 from part B.
Case 6 shows a first order model with a relatively long time constant. The precision might be poor, as the pole is very close to the unit circle. Fig 11.7 shows the model output compared to experimental data. It is clear, that a trend has to be removed from the data. This is done for the case 7, when a linear trend of V174 was subtracted. The resulting output from the model is shown in fig 11 .8, which is significantly better than 11.7. Also note that the time constant is smaller. This is quite natural; with the trend removal an integrator (pole at one) was removed, and therefore the pole of the system was moved away from the unit circle.

Due to the short sampling time it was tried to estimate the time constant better with a longer sampling interval. Therefore each third value was picked from the data, case 8. The resulting time constant does not differ very much from the one in case 7. The linear trend of V174 was removed also here.

In part B (Case 9) the model time constant is quite similar to the one from part A.

TABLE 11.2. Identification of the DO concentration V174 when the air flow (V21) is excited.

Case	6(A)	7(A)	8(A)	9(B)
N	899	899	300	405
a_1	-0.996 ± 0.001	-0.994 ± 0.001	-0.984 ± 0.002	-0.988 ± 0.002
$10^2 \cdot b_1(V21)$	0.425 ± 0.042	0.540 ± 0.046	1.621 ± 0.087	1.017 ± 0.086
c_1	0.029 ± 0.042	0.010 ± 0.044	-0.308 ± 0.052	-0.244 ± 0.046
λ	0.136 ± 0.003	0.135 ± 0.003	0.216 ± 0.009	0.256 ± 0.009
V	8.348	8.240	6.983	13.311
Δt( )	10	10	30	20
time const	38.0 min	29.7	30.3	28.7 min
		Trend in V174 removed	Trend in V174 removed	

The plotting of the model output is shown in fig. 11.18 and its corresponding residual autocovariances in fig. 11.19. The c_1 parameter is very small in the cases 6 and 7. This means that the noise is almost white for the 10 second interval. It is, however, not white for the 30 second sampling time, case 8, as the corresponding c_1 parameter is significantly larger. The same conclusion is made for the case 9 for the 20 seconds sampling interval.

12. AIR FLOW RATE INFLUENCE ON THE DO CONCENTRATION

In the identifications it has been verified, that the air flow is the dominating input to the DO concentration. It is also the input that gives the fastest response time.

In 2.2 it was demonstrated, that the DO sensitivity to air flow changes is strongly varying along the tank. This fact was demonstrated in the early experiments. No influence whatsoever from air flow to the head end concentration of DO could be noted.

A failing membrane of the sensor V173 caused confusion in the beginning but resulted in a spin-off conclusion. The consequence of the poor membrane was, that an unreasonably fast time constant was found (Chs. 5,8,9)

It is hardly possible to detect on-line by any static methods, that a membrane has a poor quality. The results from the dynamical responses show one easy method to on- line test the sensor for the membrane quality.

A reasonable time constant was found in the experiment 741126 (B)(ch.11) where the sensors V173 and V175 gave similar results, about 14-15 minutes.

In all the experiments the time constant for the V174 sensor has been considerably higher than for V173 or V175. In experiment 740626 it was 27 - 33 minutes and in 741126 (B) (Ch. 11) about 28 minutes. In all cases this sensor has been placed towards the tail end of the reactor.

The time constants found are approximately the inverse of the overall oxygen transfer coefficient, see eq. (2.8). Therefore the long time constant would indicate a oxygen transfer coefficient towards the tail end of the reactor.

The oxygen transfer rate can actually vary along the reactor due to different concentrations of COD and MLSS, see [2], ch. 7. Usually, however, the oxygen transfer coefficient will increase along the tank due to this reason. Between the probe locations this variation is probably quite small, and it certainly does not explain the difference in time constants.

The only explanation for the long time constant towards the tail end must be less mixing, probably caused by a smaller air flow rate. The decreased air flow rate may be caused by clogging of the diffusers.

Differences in membranes of the probes cannot explain the time constant differences. Usually the instrument time constant is of the order one minute.

Some static calculations can verify the identification results. Typically the air flow rate in Käppala is about

$$u_{air} = 50 \text{ N m}^3/\text{min and aerator}$$

For six aerator this means

$$u_{air} = 18000 \text{ Nm}^3/\text{hour}$$

With respect to the known efficiency of the plant aeration the oxygen transfer is 30 g oxygen/m^3 * hour, or

$$k_L a \, u_{air} \, (c_{os} - c_o) = 30$$

With $c_o = 2.5$ mg/l and $c_{os} = 10$ mg/l

we get

$$k_L a \, u_{air} = 4$$

which corresponds to a time constant of about 15 minutes.

Typical values of the oxygen transfer rate coefficient found in the literature [2] vary from 3.5 to 6 depending on the degree of mixing.

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$$k_L a \; u_{air} \; (c_{os} - c_o) = 30$$

With $c_o = 2.5$ mg/1 and $c_{os} = 10$ mg/1

we get

$$k_L a \; u_{air} = 4$$

which corresponds to a time constant of about 15 minutes.

Typical values of the oxygen transfer rate coefficient found in the literature [2] vary from 3.5 to 6 depending on the degree of mixing.

13. INFLUENT WASTEWATER FLOW RATE INFLUENCE ON THE DO CONCENTRATION

Changes in the influent flow rate is an important external disturbance to the DO concentration. The influent flow rate and its substrate concentration make the loading to the plant. Naturally the gain from the influent flow rate changes to the DO concentration must be negative.

13.1 Identification results.

Identification results (Ch. 6-7) have verified that the gain is negative. The time constant is about 30 minutes for the probe V173 (case 1, ch. 10) and 45 minutes for the probe V174 (case 4, Ch. 10) further downstream. The cases 2, 3 and 5, 6 respectively are further discussed in chap. 14 and are not considered pertinent here.

In Chapter 6 both the water flow and the air flow rates have been disturbed. It would be natural to expect two time constants for this case, but no second order model could converge. Therefore the achieved time constant is a combination of the two dynamical transfer functions from water and air flow respectively. For the sensor with the poor membrane (V173) table 6.2 shows a time constant which is a combination of the very fast response of the sensor, the oxygen transfer and the water influence. For the sensor V174 table 6.1 shows relatively poor accuracy. This was discussed in chapter 6. No conclusion of the time constant due to water flow disturbances can therefore be drawn from expt 740627 in Ch. 6.

In expt. 740826 (Ch. 8) it was discussed that the water flow may have influenced the result. The sign of the parameter b_{11} in table 8.1 is, however, positive. This is not physically reasonable. The accuracy is too poor and therefore the result can not be accepted. The reason is, that the flow was not manipulated and had an insignificant amplitude variation, fig. 8.1.

13.2. Reasons for different time constants.

In the preliminary analysis in 2.5 it was assumed that the aerator was a complete mix reactor. It was then demonstrated that the time constant was determined almost exclusively by the time constant for the oxygen transfer. This means, that the time constant should be of the order 15 minutes instead of the achieved results 30 or 45 minutes.

The aerators in Käppala are not at all complete mix reactors, and therefore we will discuss if the flow type makes any difference for the time constants for water disturbances. Of that reason we consider an aerator which can be described by n subreactors in series.

The mass balance equation for subreactor k for the dissolved oxygen concentration will now be derived. It is analogous to eq (2.1) but the hydraulic flow is shown in figure 13.1.

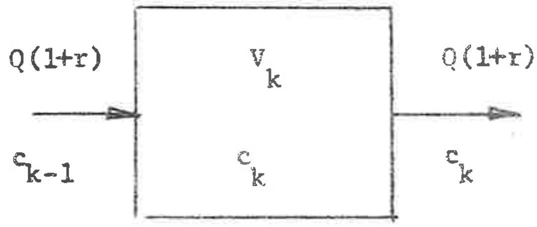

Fig. 13.1 Schematic diagram of subreactor k with corresponding flows and DO concentrations.

Then the mass balance is

$$\frac{dc_k}{dt} = \frac{Q(1+r)}{V_k}(c_{k-1} - c_k) + u\,(c_s - c_k) - g_k(s_k, c_{xk}, c_k) \qquad (13.1)$$

The first term is simply DO mass in minus DO mass out. The second term is the production of DO from the compressors and

$$u = k_L a\, u_{air}$$

At the moment we assume that u is constant in the whole tank, i.e. independent of k.

The last term corresponds to the biological DO uptake in reactor k. We also assume, that g_k is independent of c_k. This means, that the DO concentration is high enough so the synthesis is not DO limited, i.e. the function $f(c_o)$ in eq (2.3) is one.

Eq (13.1) is now linearized around a steady state operating point. Consider small disturbances in Q,

$$Q = Q^{\circ} + Q$$
$$c_k = c_k^{\circ} + \Delta c_k \qquad (13.2)$$

During the interesting time interval we assume, that the substrate and microorganism concentrations do not change. Therefore the function g_k is constant due to changes in Q.

Straightforward linearization gives

$$\frac{d\,\Delta c_k}{dt} = \frac{1+r}{V_k}(c_{k-1}^{\circ} - c_k^{\circ})\,\Delta Q + \frac{Q^{\circ}(1+r)}{V_k}(\Delta c_{k-1} - \Delta c_k) - \qquad (13.3)$$

$$- u\,\Delta c_k$$

Call

$$D_k = \frac{Q^{\circ}(1+r)}{V_k}$$

$$\delta c_k = c_{k-1}^{\circ} - c_k^{\circ}$$

Then (13.3) can be written in the form

$$\frac{d\,\Delta c_k}{dt} = -(D_k + u)\,\Delta c_k + D_k\,\Delta c_{k-1} + \frac{D_k}{Q}\,\delta c_k\,\Delta Q \qquad (13.4)$$

or in Laplace form

$$C_k(s) = \frac{D_k}{s + (D_k + u)} C_{k-1}(s) + \frac{D_k \delta c_k}{Q\,(s + (D_k + u))} Q(s) \qquad (13.5)$$

The first subreactor has a slightly different equation, as it have the hydrualic flows as in figure 2.1. The Laplace transform expression correponding to (13.5) is

$$C_1(s) = \frac{c_i - (1+r)\, c_1^{\circ}}{V_k\,(s + (D_1 + u))} Q(s) \qquad (13.6)$$

Now consider eq (13.5). It shows that the change in DO concentration caused by a change in the flow rate has two

Assume there is a flow disturbance in the head end. As the tank has a constant liquid volume the hydraulic change is distributed to all parts of the tank simultaneously. This corresponds to the last term in (13.5). There is then a concentration propagation trough the series of subreactors, corresponding to the first term in (13.5).

The concentration change in the first subreactor is negative. As the first transfer function in (13.5) always has a positive gain, the concentration propagation causes a negative gain. The sign of δc_k in (13.5) is usually negative. Therefore also the contribution from the last term in (13.5) has a negative gain.

The time constant for both the transfer functions in (13.5) is the same. For a complete mix reactor D_k can be neglected compared to u, which makes the time constant about 15 minutes. If the reactor is described by a large number of subreactors (almost a plug flow) than D_k is large compared to u. On the other hand the gain of the last transfer function is small, as δc_k gets small. Therefore the response time is primarily determined by the first term in (13.5). For the plug flow case this corresponds to a pure time delay.

Now assume for the moment that the aerator in the Käppala plant has a plug flow pattern in the actual locations for the DO measurements. Then the water velocity is about 0.4 m/min. The DO sensors en expt. 740828 (Ch. 10) are separated in space by 6 m, which corresponds to a flow transport time of about 15 minutes. This transport time can explain the differences in time constants between the two sensors.

14. RETURN SLUDGE FLOW INFLUENCE ON THE DO CONCENTRATION

When the return sludge flow is changed there are two effects. The first one is due to the hydraulic change and is analogous to a change in the influent wastewater flow rate. The second one is due to transportation of MLSS. An increase in return sludge flow rate will change the MLSS concentration in the aerator, which in turn will change the biological uptake rate of DO.

14.1 Return sludge flow identification results

The main result due to changes in return sludge flow comes from expt 740702 (chap. 7). The time constant is found to be 70-90 minutes, i.e. longer than that of the influent wastewater flow changes. The gain is negative as expected.

It is found that the accuracy of the influent wastewater parameters (table 10.1) are much more accurate than those of the return sludge flow (table 7.1). The reason is the amplitude of the input disturbances. The changes in the influent water flow caused significantly larger flow changes in the tank than the return sludge flow rate changes.

In order to examine the time constant the mass balance for the DO concentration is derived similarly as in chapter 13.2. For a disturbance in r instead of Q the expression (13.5) is slightly changed in the last term to

$$C_k(s) = \frac{D_k}{s + (D_k+u)} \; C_{k-1}(s) \; + \; \frac{D_k \, \delta c_k}{(1+r^\circ)[s + (D_k+u)]} \; R(s) \qquad (14.1)$$

where r° is the stationary value of r and R(s) is the Laplace transform of the change in r.

The fact that the return sludge flow input gives a larger time constant than the influent water is again due to the hydraulics. The influent return sludge enters the aerator at the head end. The transportation time for the return sludge to the DO sensor therefore is longer than that of the influent water.

If the aerator would be plug flow everywhere, then the transport time from the head end to the DO sensor would be 4-6 hours. The time constant of a little more than one hour shows, that the aerator could not be purely plug flow, see (14.1). Instead it seems to be a high degree of mixing in the first part of the reactor. Then it is reasonable to describe the first part of the aerator with a few complete mix subreactors in series. Eq (14.1) then suggests that the response time to flow disturbances is reduced considerably compared to plug flow.

14.2 Influence of the MLSS concentration

In the experiments it has not been possible to directly manipulate the MLSS concentration. Only by return sludge flow changes the MLSS concentration has been gradually changed to some extent. It has also been unintentionally changed by natural disturbances during some experiments.
The influence of the MLSS concentration has been taken into consideration in the experiments 740627 (chap 6, case 3 and 6) and in 740828 (chap 10, cases 2 and 5).

The accuracy of the MLSS parameters is poor and therefore no conclusions about the MLSS influence will be made. The sign of b in ch. 6 is even wrong compared to physical models.

15. CONCLUSIONS AND RECOMMENDATIONS

The DO probes are among the few reliable activated sludge instruments. As long as it is properly maintained and calibrated it is therefore a most useful signal and is easy to work with.

The identification resultsconfirm, that the air flow input is the most important input signal to the DO concentration. It has a time constant of about 15 minutes. Two important byproducts of the air flow experiments were achieved

* it is possible to on-line detect a poor membrane
* clogging or insufficient mixing can be detected

It is not feasible to measure DO in the upper part of the tank, as the DO concentration is too low to be measured assurately. It is also very little affected by the air flow changes, due to the large biological uptake rate.

The most important external disturbance is the influent wastewater flow rate and probably also the substrate concentration. The latter has not been possible to test in any experiment. The typical time constant for disturbances in flow rate is longer than 30 minutes for DO sensors located in the later half of the tank. One important byproduct of the water flow identifications has been detected,

* hydraulic flow pattern can probably be identified

By locating DO sensors at different places the different time delays can be measured. By such a method it is not necessary to induce any trace material in the tank in order to get a flow pattern. The statement is only true as long as the DO concentration can be measured fairly accurately. Therefore the method cannot be feasible in the head end of the reactor, where the DO concentrations are too small.

Some recommendations for future experiments will be made.

(i) It is desirable to make a more thorough test with air flow changes. Then DO sensors should be located at many points along the tank in order to test mixing and clogging conditions. It should be remarked, that the present model is accurate enough for the purpose of DO control.

(ii) DO sensors should be placed along the tank in many space points (or alternatively many experiments) for flow rate changes in the influent wastewater. Then the hydraulics can be tested more thoroughly.

(iii) The influence of MLSS and substrate concentrations is poorly known. In order to make use of the DO concentration to estimate the process conditions and the non-measurable variables, it is highly desirable to establish a better model relating DO to MLSS and substrate concentrations.

16. REFERENCES

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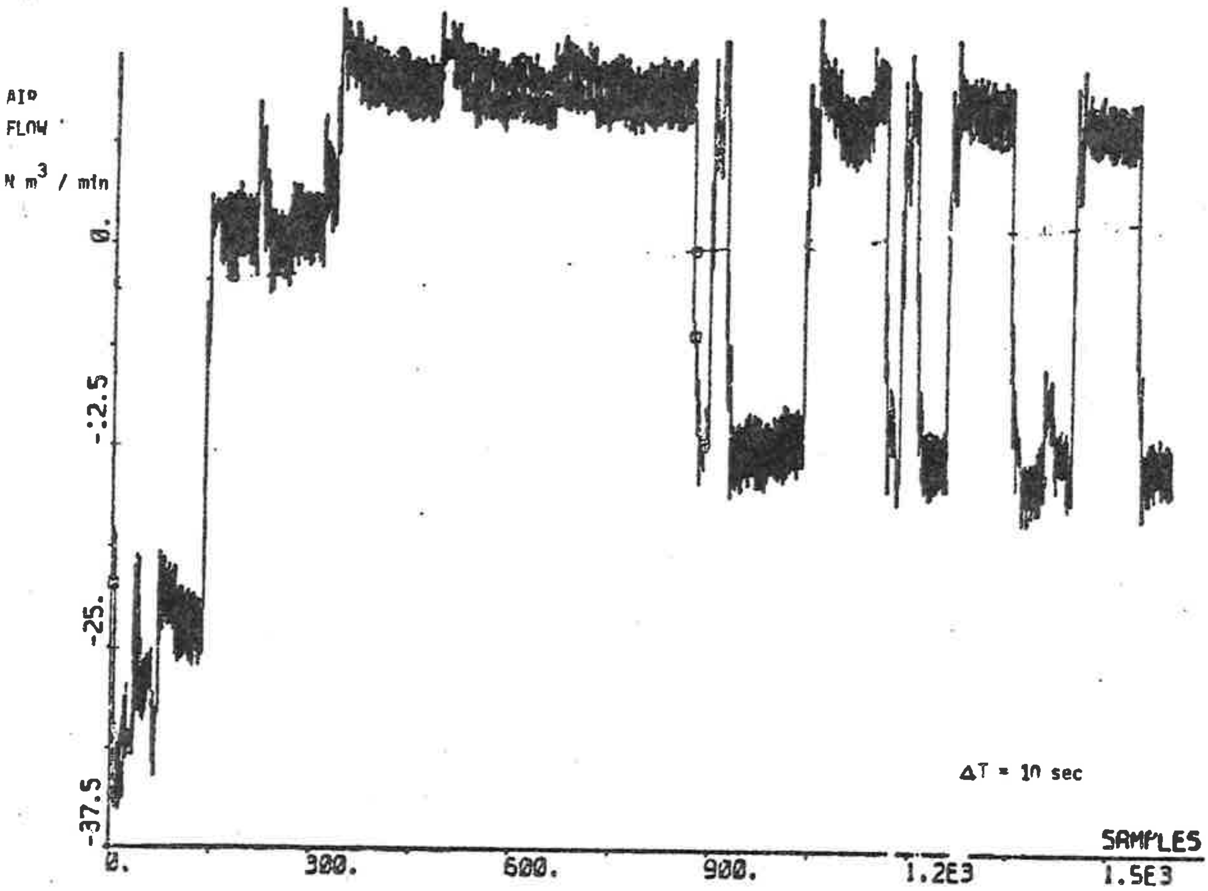

Fig. 5. 1. Experiment 740626. Air flow variations.

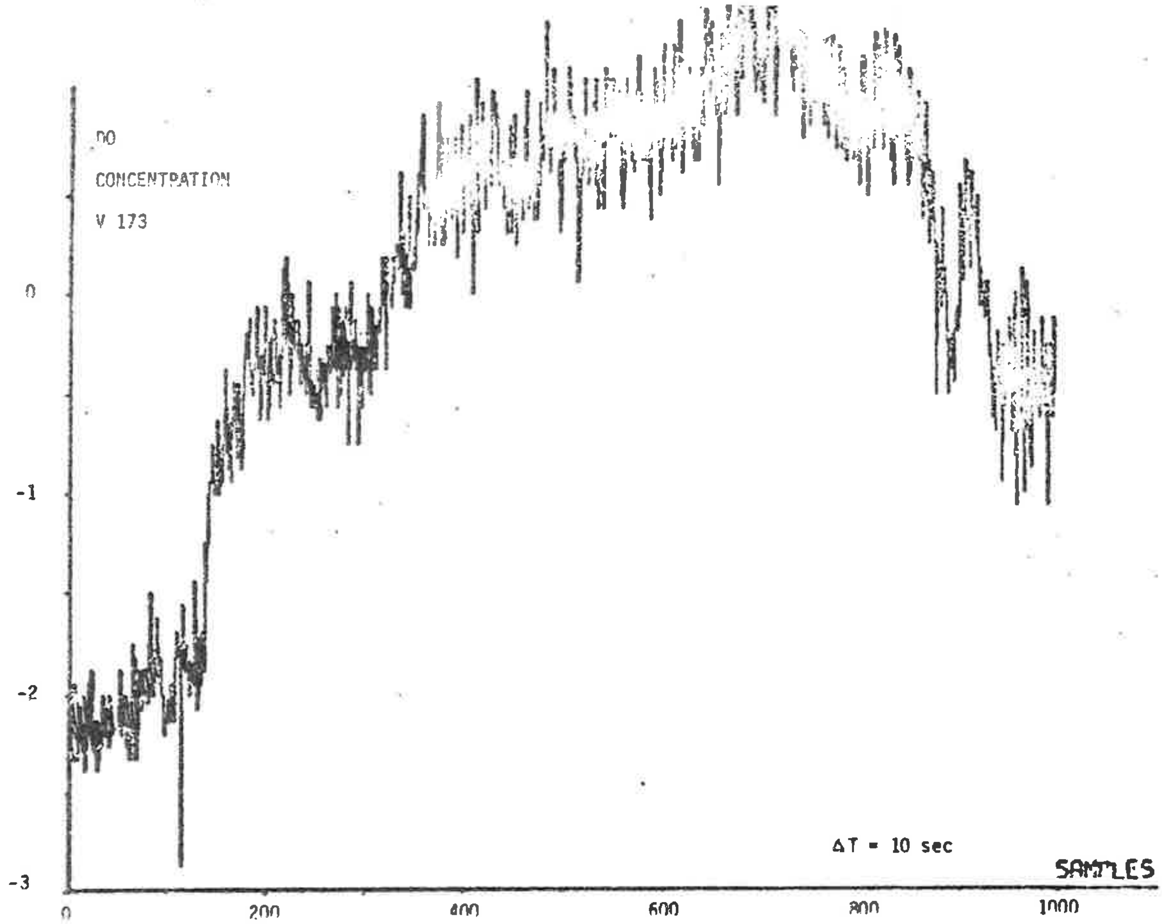

Fig 5.2A. Experiment 740626. DO concentration V173 changes, first part.

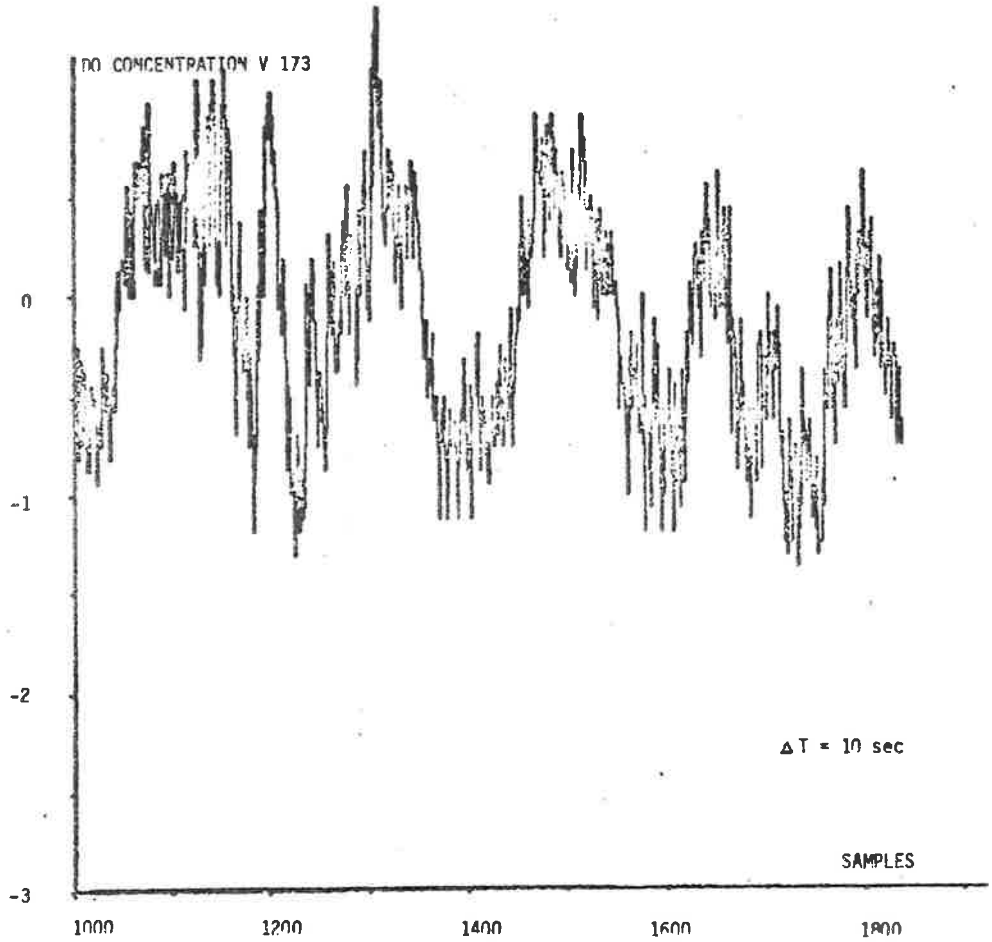

Fig. 5.2B. Experiment 740626. DO concentration V173, second part.

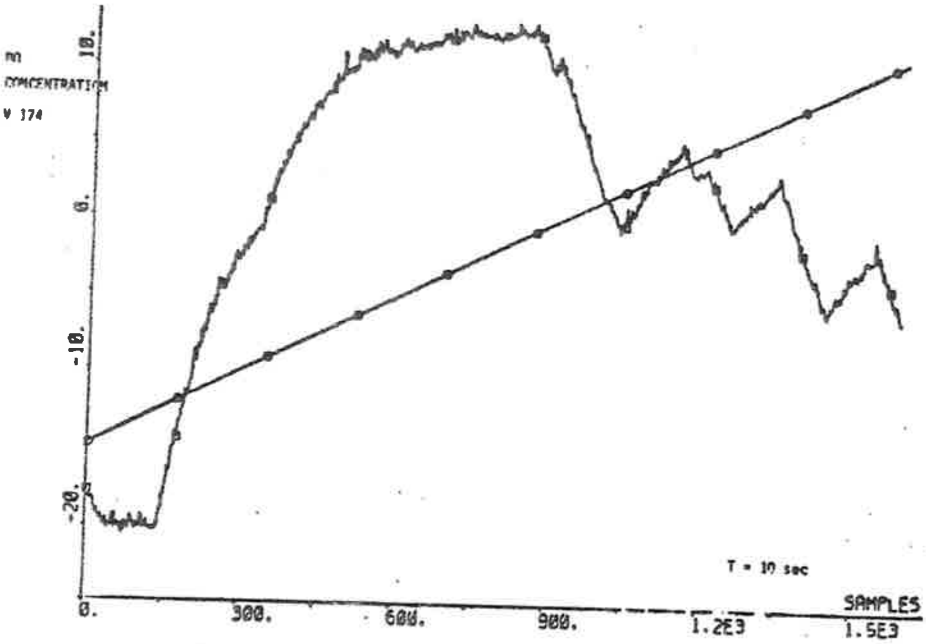

Fig 5.3. Experiment 740626. DO concentration V174 changes. A linear trend is removed from the data. The trend is also displayed.

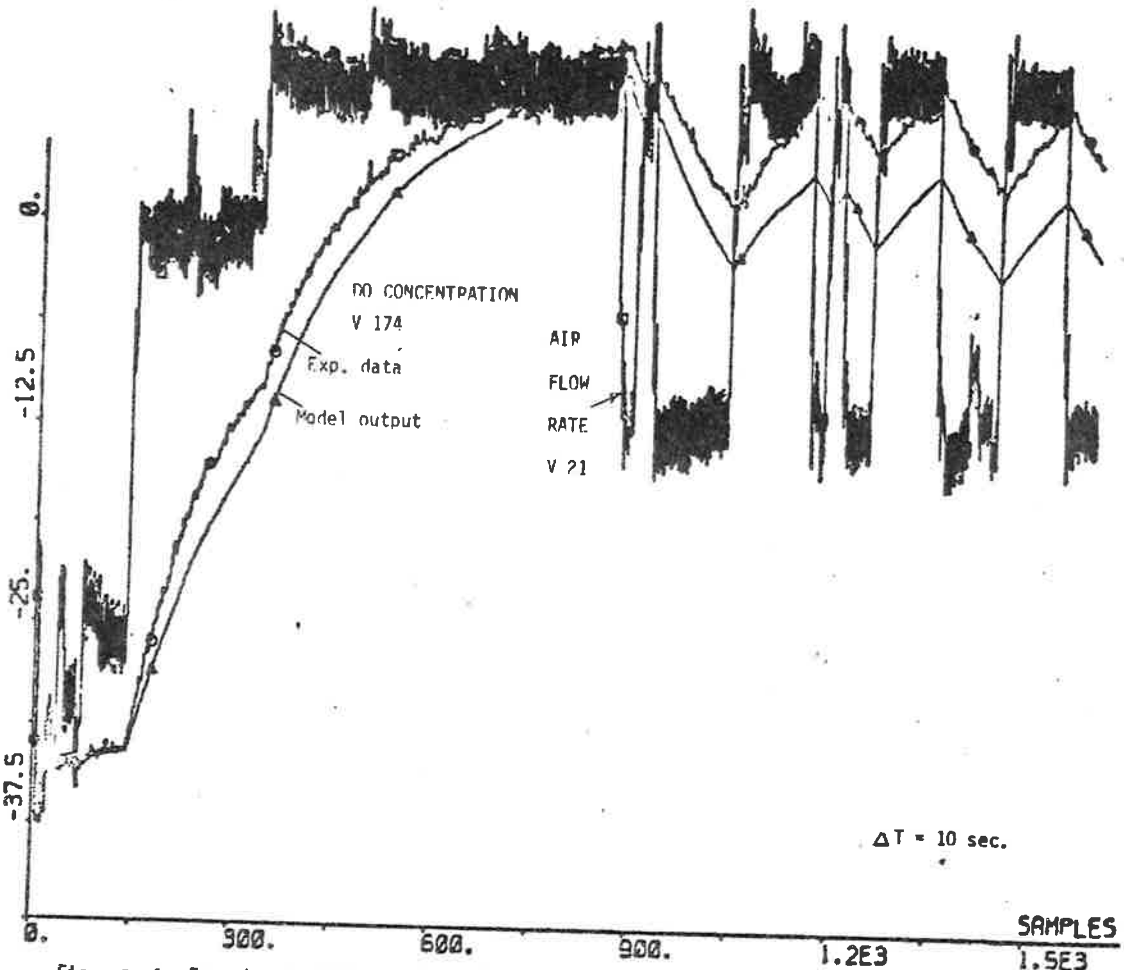

Fig. 5.4. Experiment 740626. Recordings of air flow rate V 21 and DO concentration V 174 together with model output.

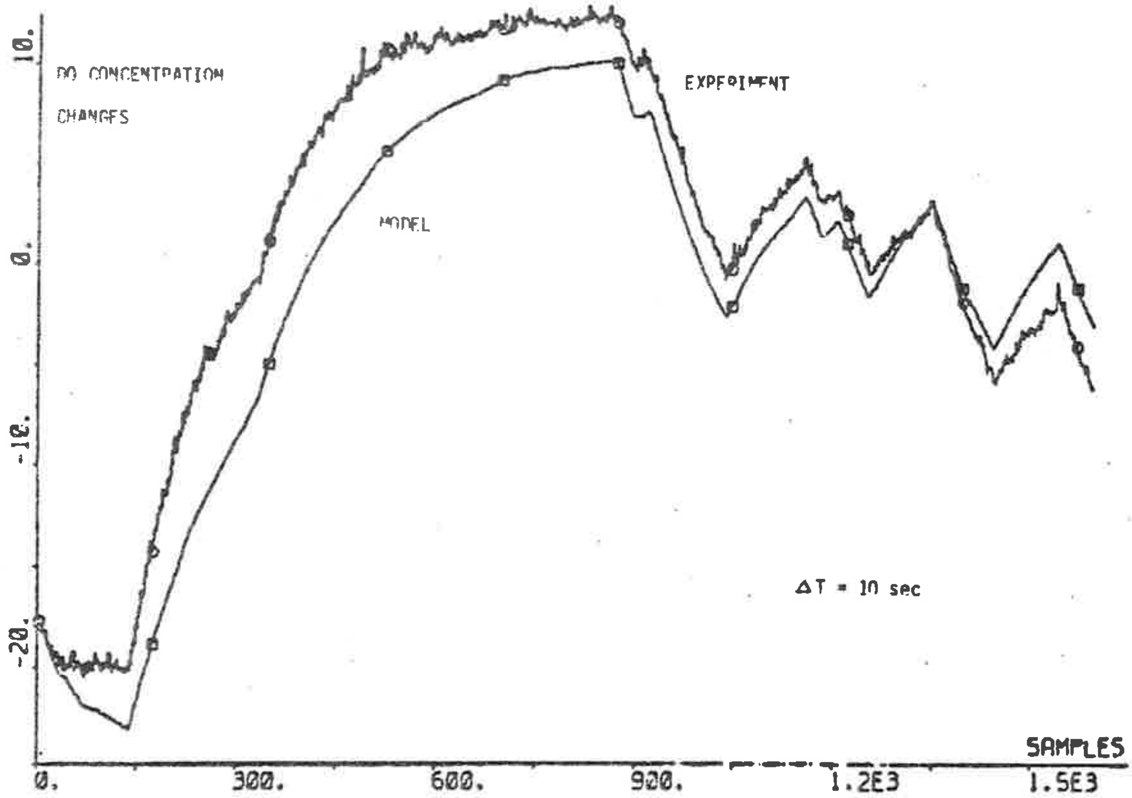

Fig. 5.5. Experiment 740626. Comparison between the experimental and model outputs of the DO concentration V 174. The model is of first order. A linear trend is removed.

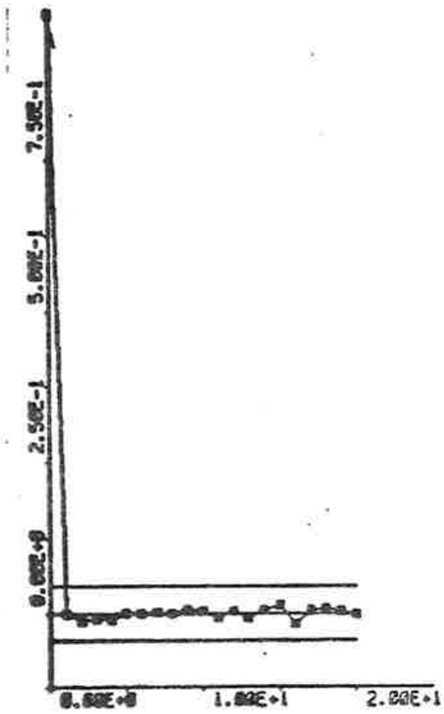

Fig. 5.6. Experiment 740626. Autocovariance of the residuals of the first order model of the DO concentration V174

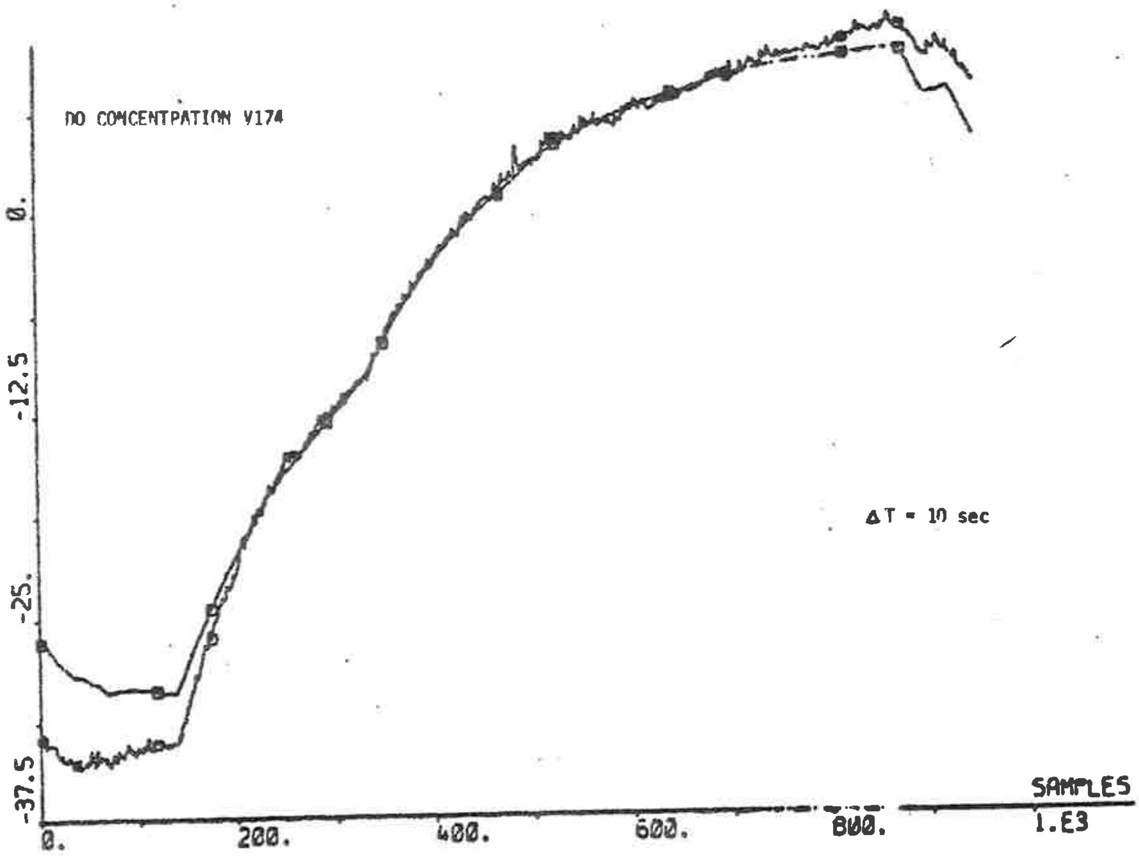

Fig. 5 .7. Experiment 740626. Comparison between the experimental and model outputs of the DO concentration V 174. The model is of first order and is based on data 1 - 900.

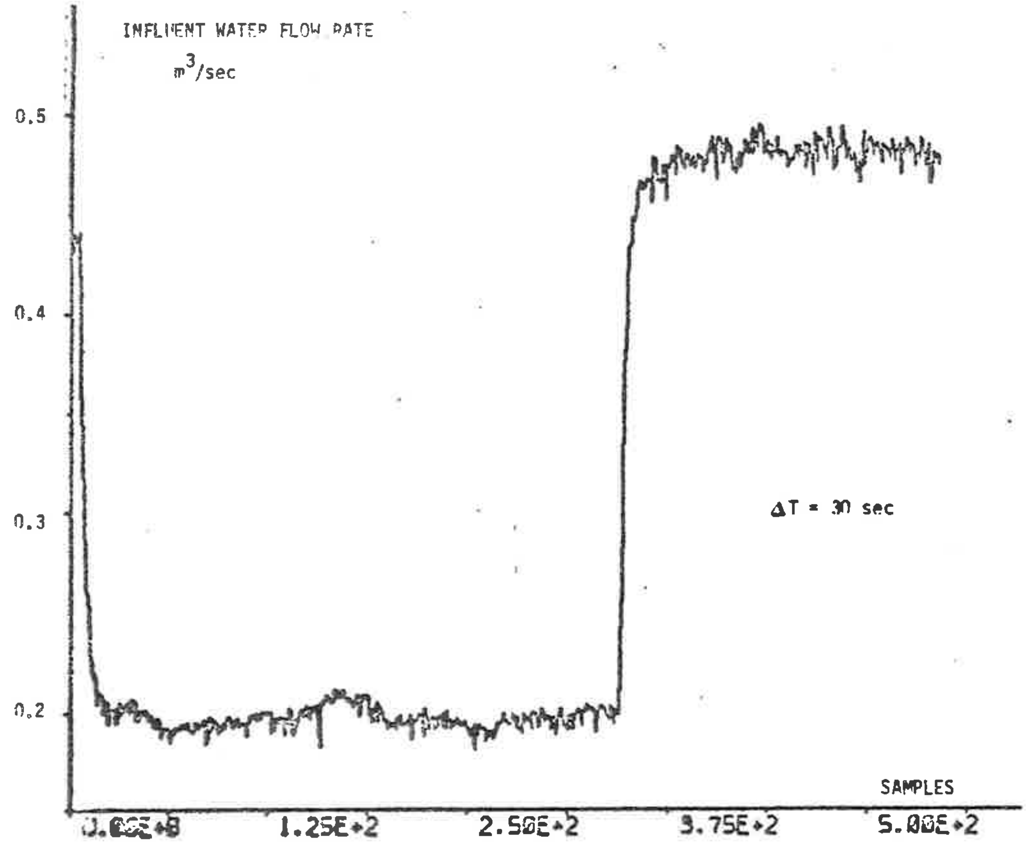

Fig 6.1. Experiment 740627. Input disturbance, influent water flow rate V9.

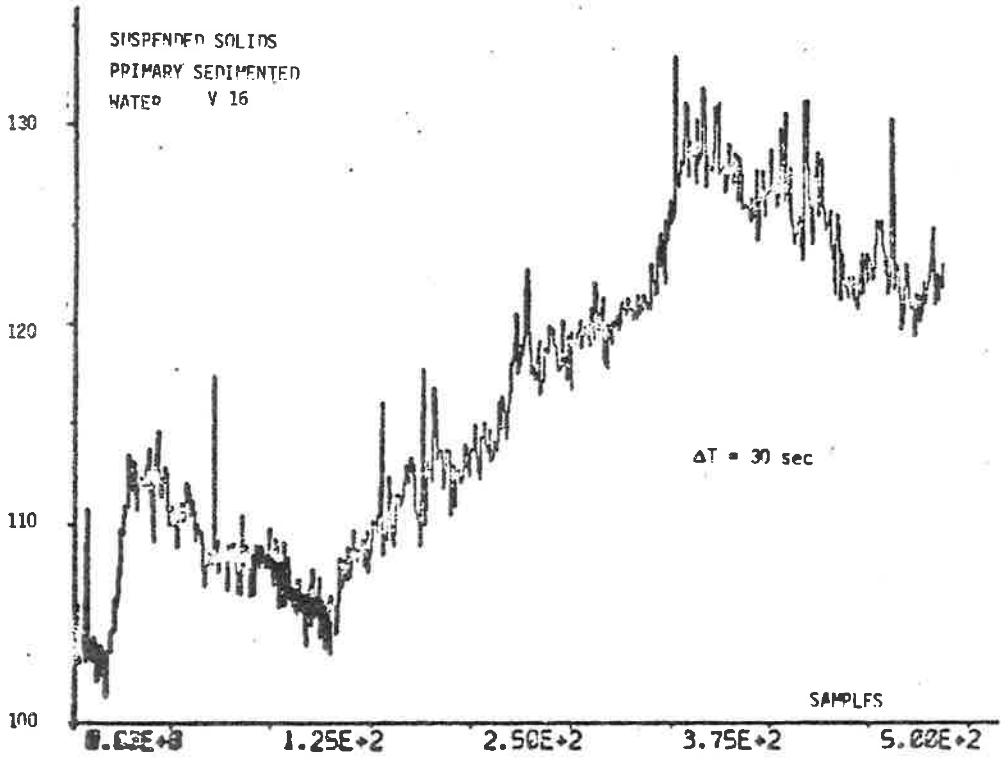

Fig 6.2. Experiment 740627. External disturbance from the primary sedimented water suspended solids.

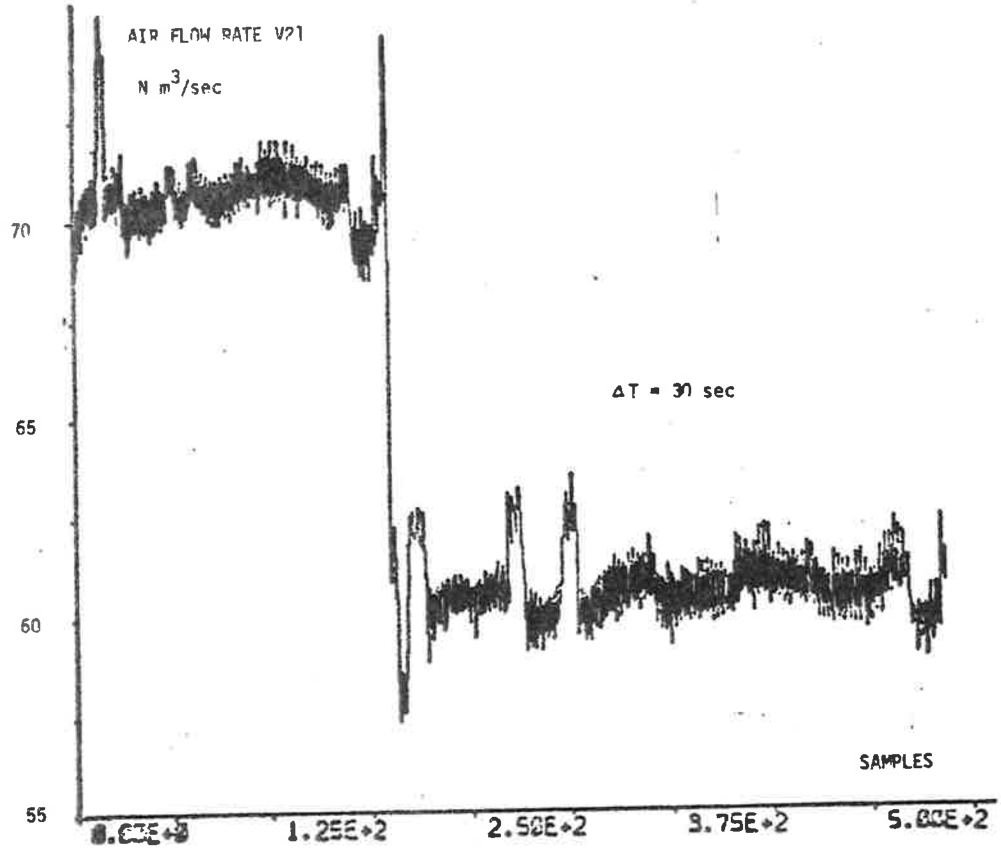

Fig 6.3. Experiment 740627. Input disturbance, air flow rate V21

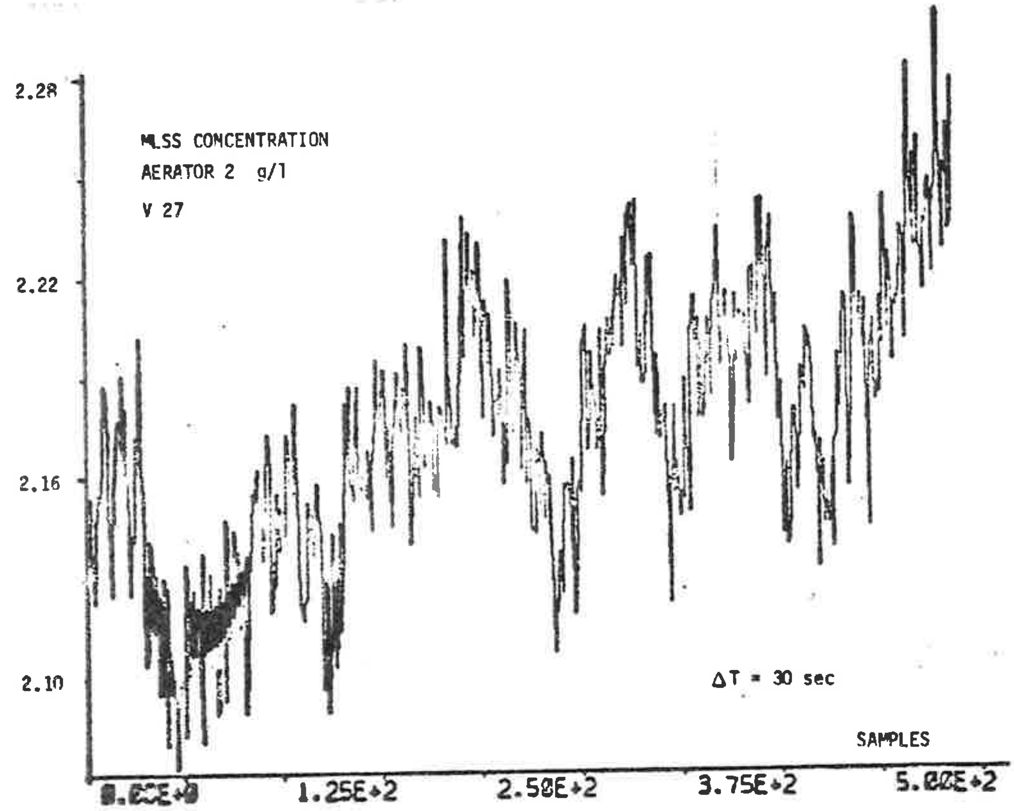

Fig 6.4. Experiment 740627. MLSS concentration in aerator 2 during the experiment.

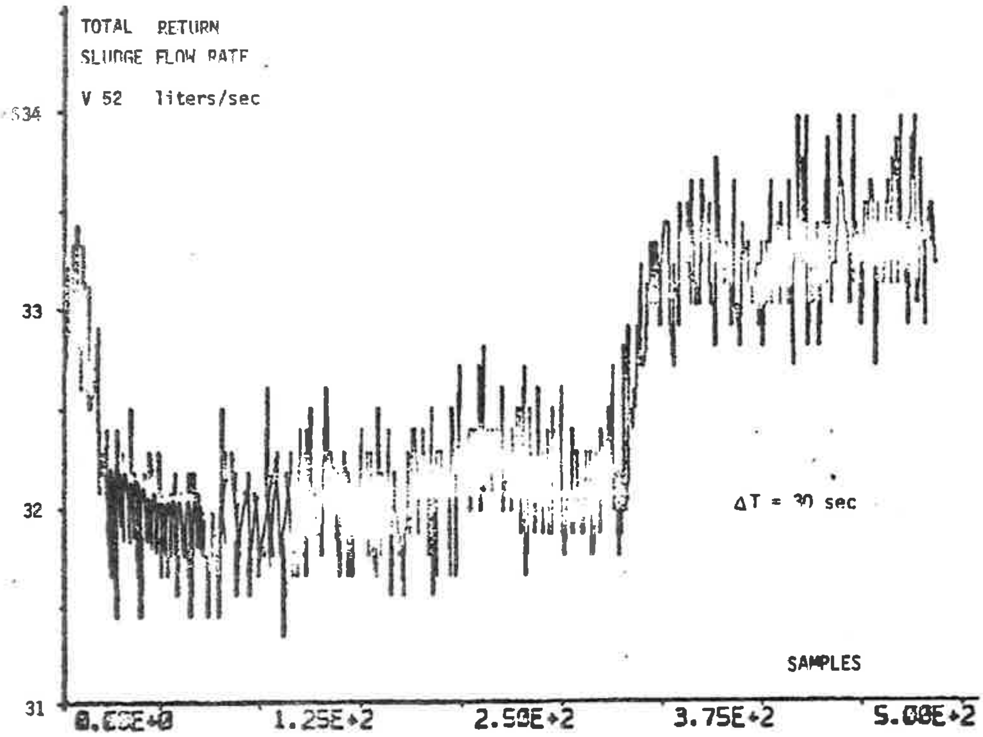

Fig 6.5. Experiment 740627. Variation of total return sludge flow rate during the experiment.

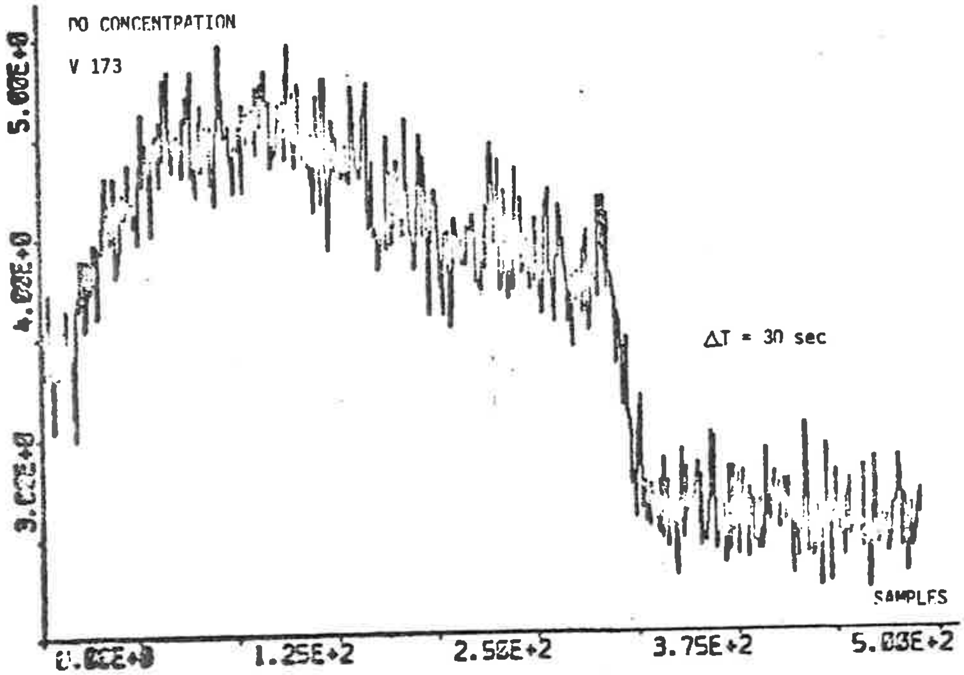

Fig. 6.6. Experiment 740627. DO concentration V 173 as a result of purposeful excitation of water and air flow rates.

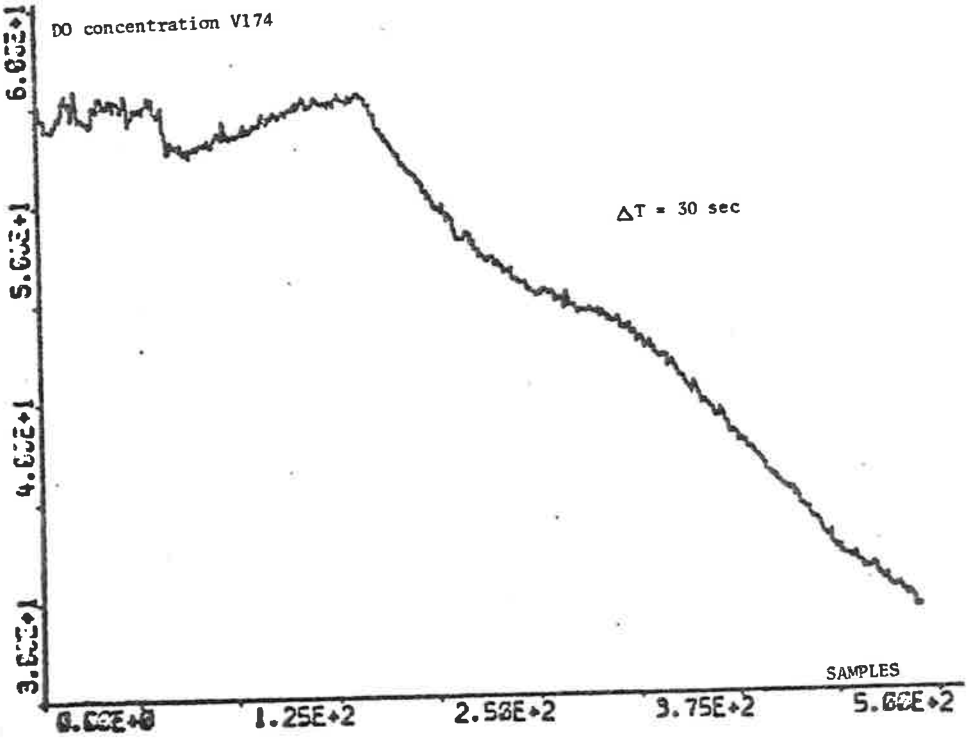

Fig. 6.7. Experiment 740627. DO concentration V 174 as a result of purposeful excitation of water and air flow rates.

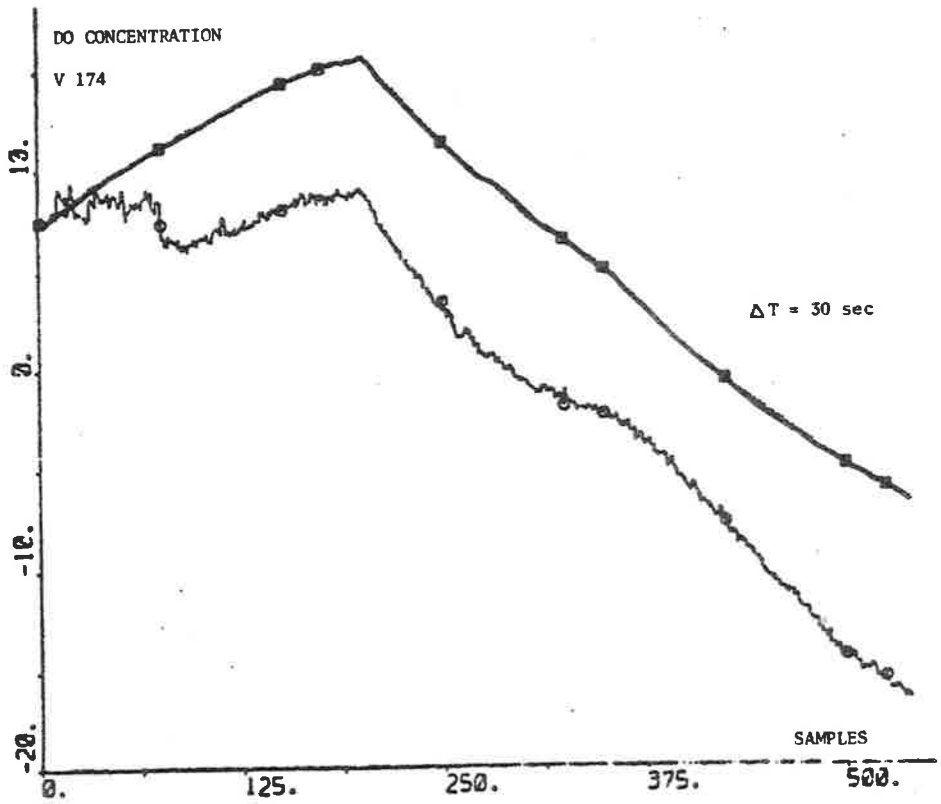

Fig. 6.8. Experiment 740627. Comparison between model output and experimental data for the DO concentration V 174. The model is of first order, assuming water flow and air flow as inputs.

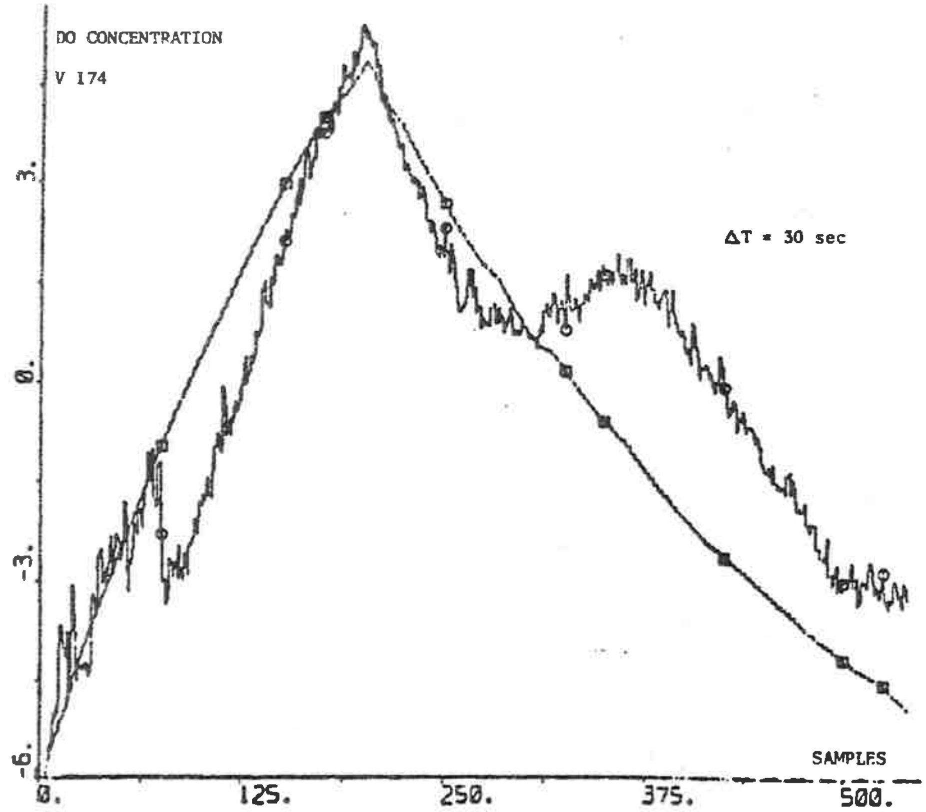

Fig. 6.9. Experiment 740627. Comparison between model output and experimental data for the DO concentration V 174. The model is of first order, assuming water and air flows as inputs. A first order trend is removed from the DO data.

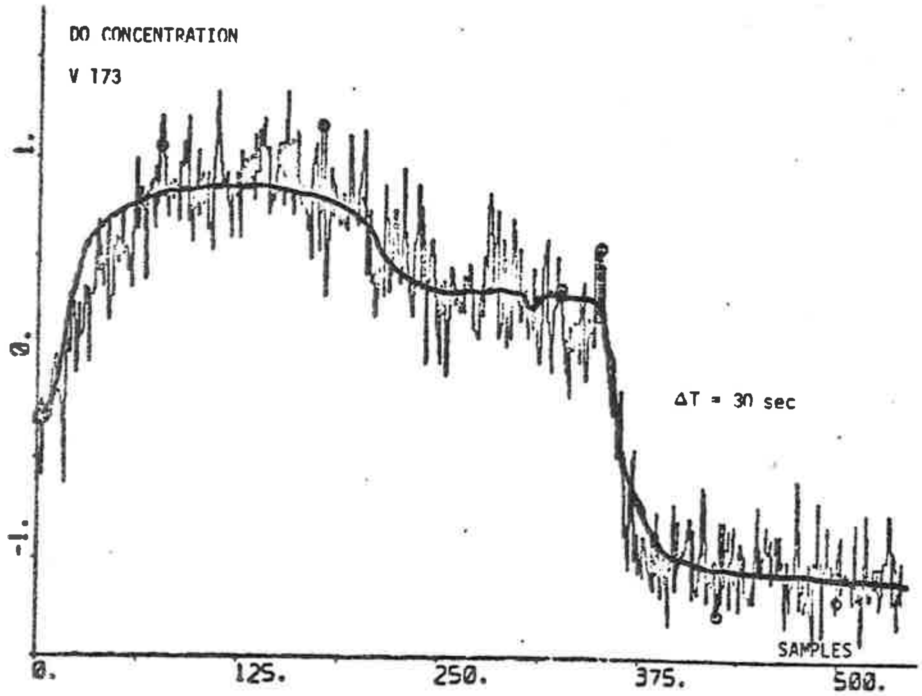

Fig. 6.10. Experiment 740627. Comparison between model output and experimental data for the DO concentration V 173. The model is of first order, assuming water flow V 9 and air flow V 21 as inputs.

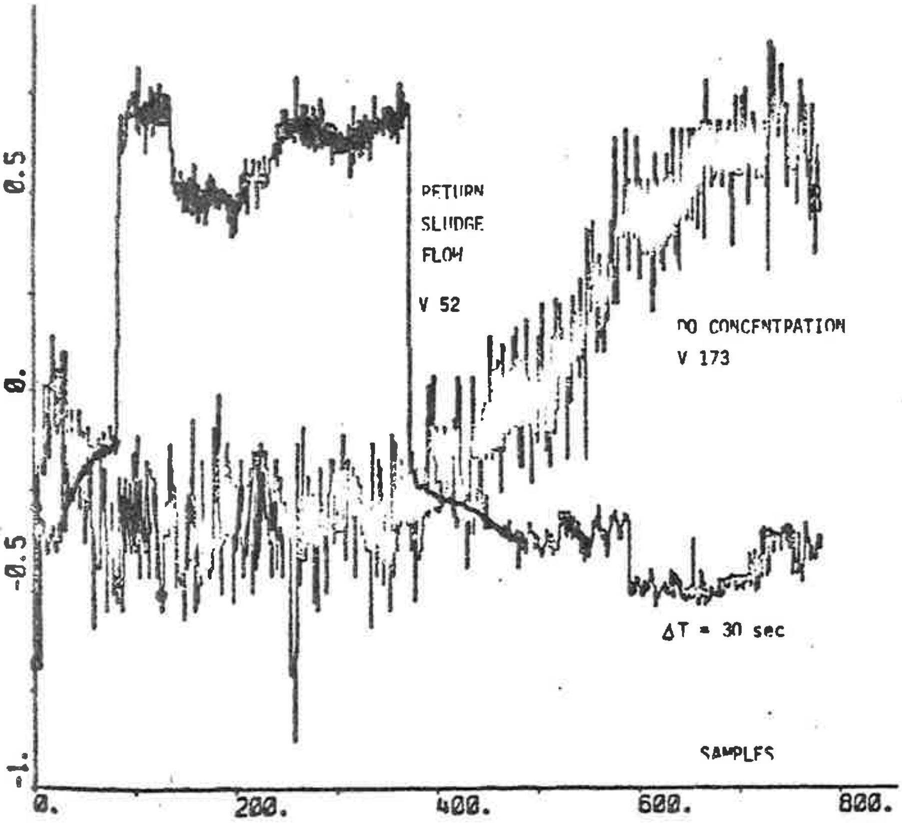

Fig. 7.1. Experiment 740702. Input (return sludge flow rate) and output (DO concentration V 173) recordings.

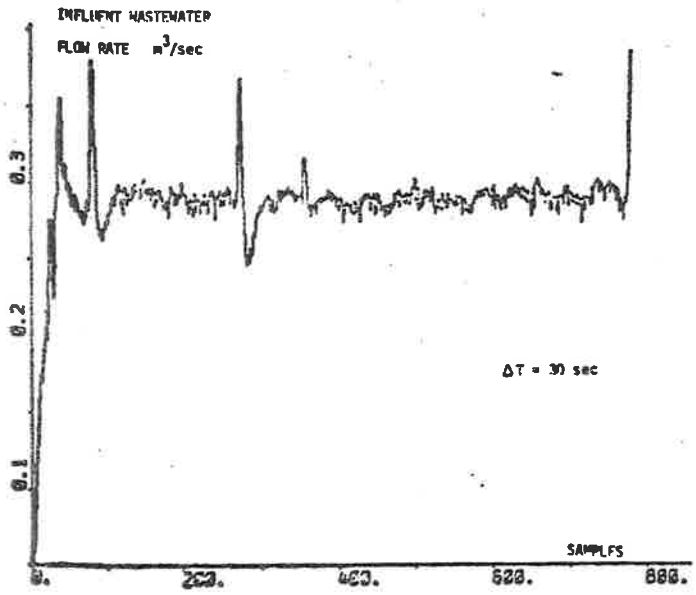

Fig 7.2. Experiment 740702. Recordings of influent wastewater flow rate V 9.

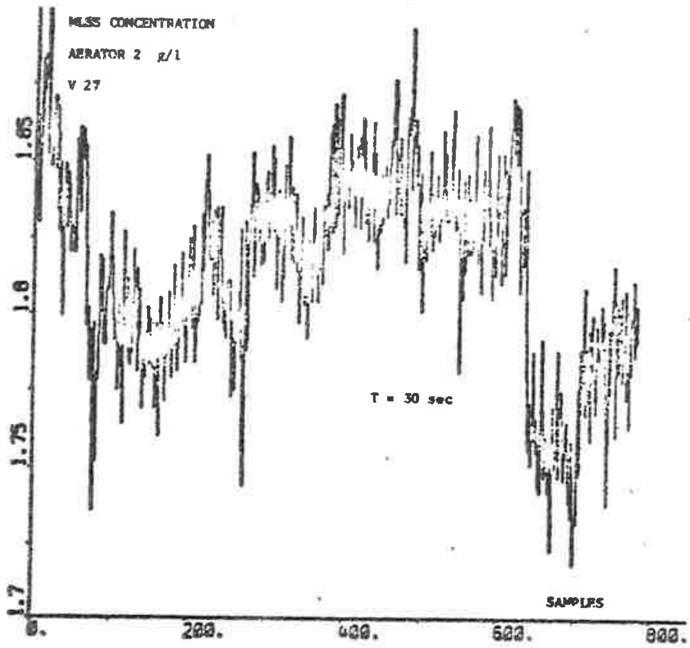

Fig. 7.3. Experiment 740702. Recording of the MLSS concentration.

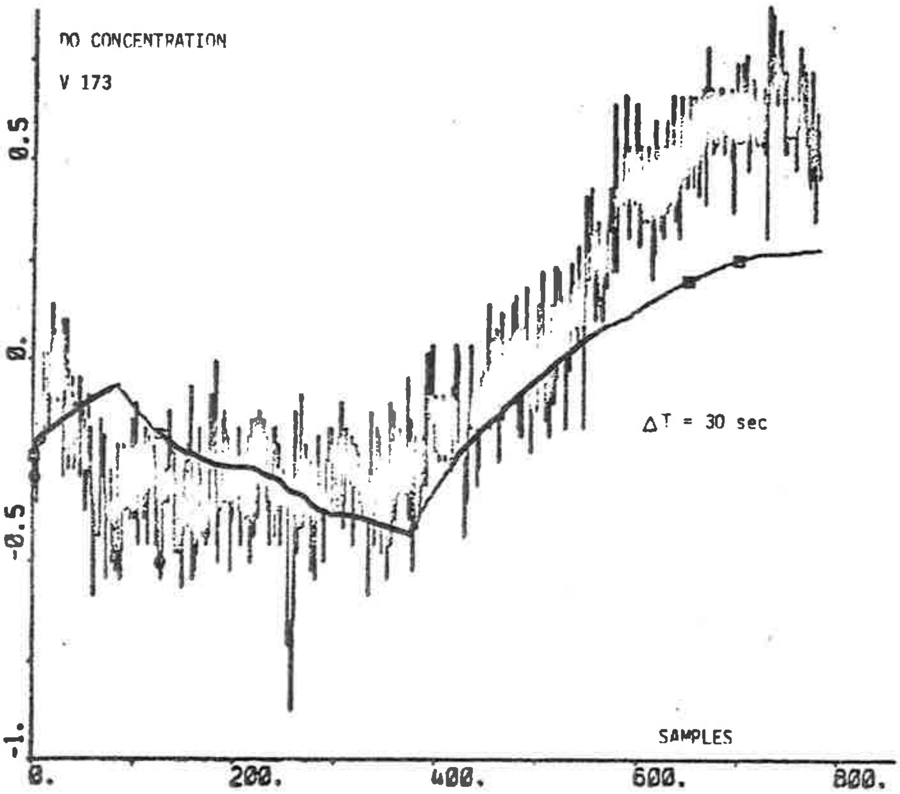

Fig. 7.4. Experiment 740702. Comparison of model output and experimental data for the DO concentration V 173. The model is of first order with a return sludge flow rate V 52 as input.

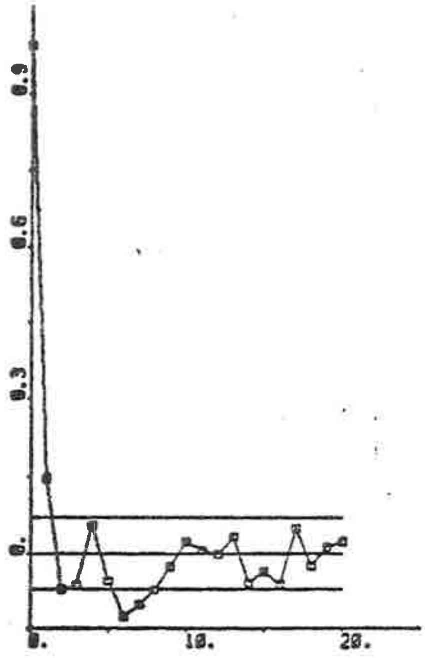

Fig. 7.5. Experiment 740702. Autocovariance of the residuals of the first order model of V 173 with the return sludge flow rate V 52 as input. The straight lines are the confidence limits for 5 %.

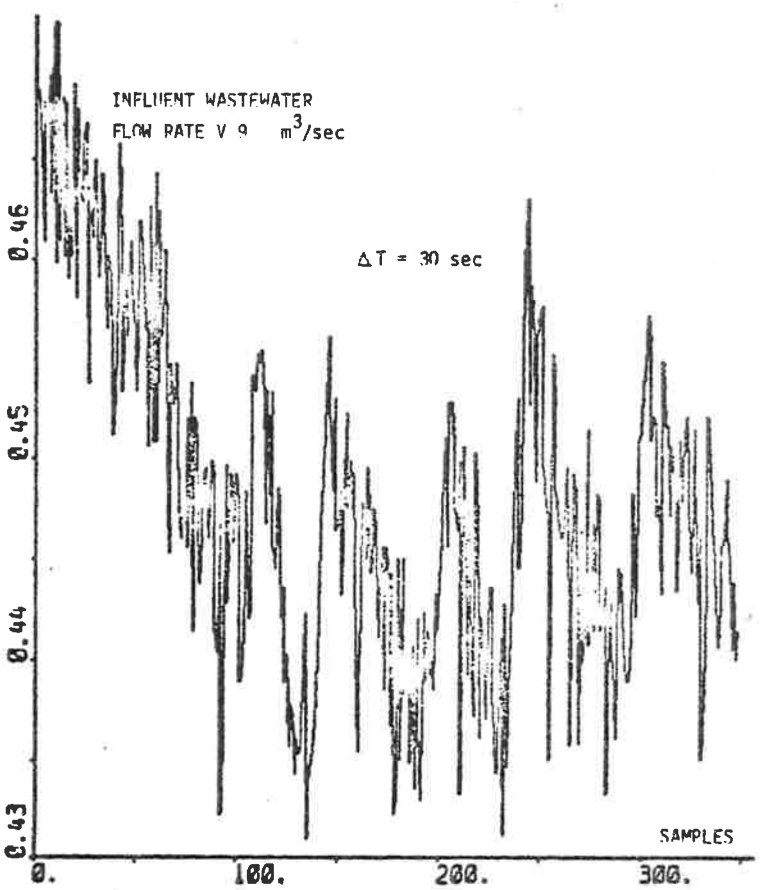

Fig. 8.1. Experiment 740826. Registration of the influent wastewater flow rate V 9.

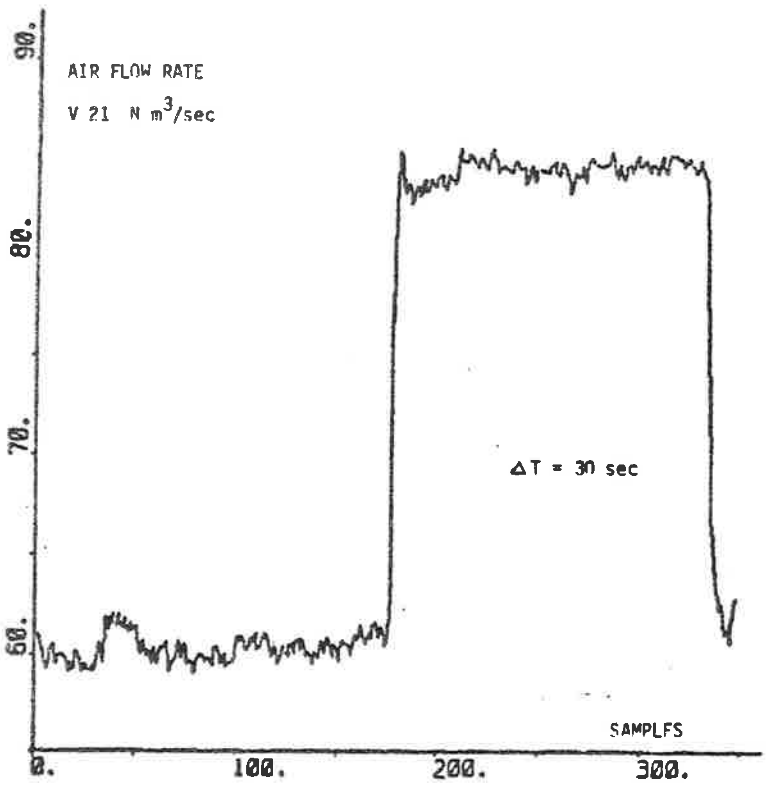

Fig. 8.2. Experiment 740826. Registration of the manipulated disturbance of the air flow rate V 21

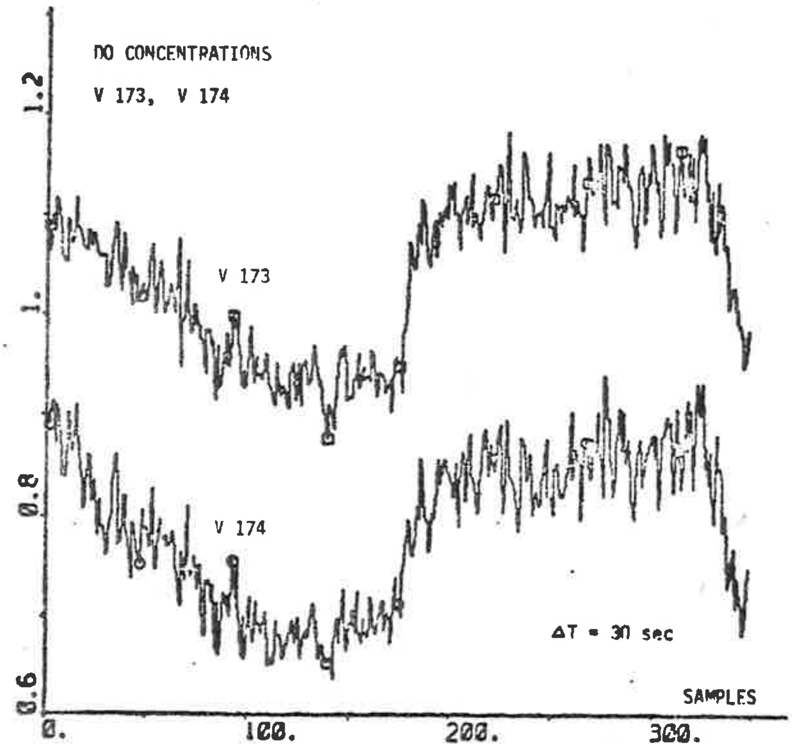

Fig 8.3. Experiment 740826. Registration of the DO concentrations V 173 and V 174.

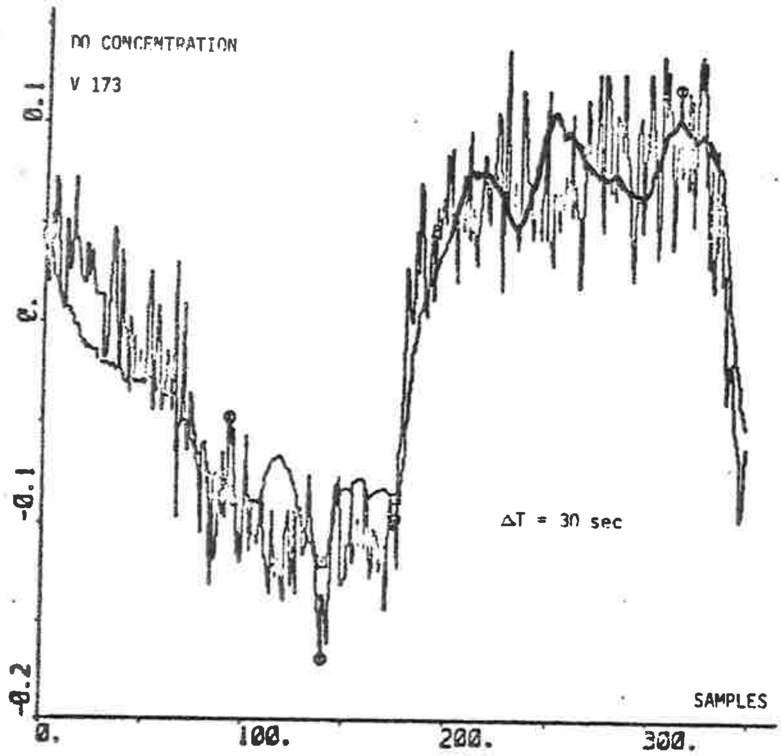

Fig. 8 .4. Experiment 740826. Comparison between model output and experimental data of the DO concentration V 173. The model is of first order, assuming air flow V21 and water flow V9 as inputs.

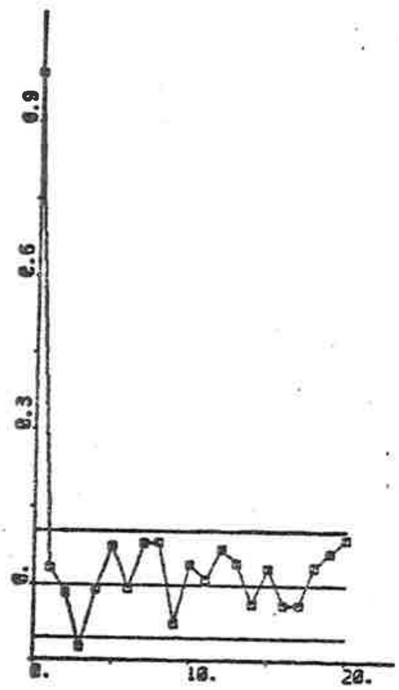

Fig. 8.5. Experiment 740826. Autocovariance of the residuals of the first order model of V173 with the influent flow rate V9 and the air flow rate V21 as inputs. The straight lines are the 5 % confidence limits.

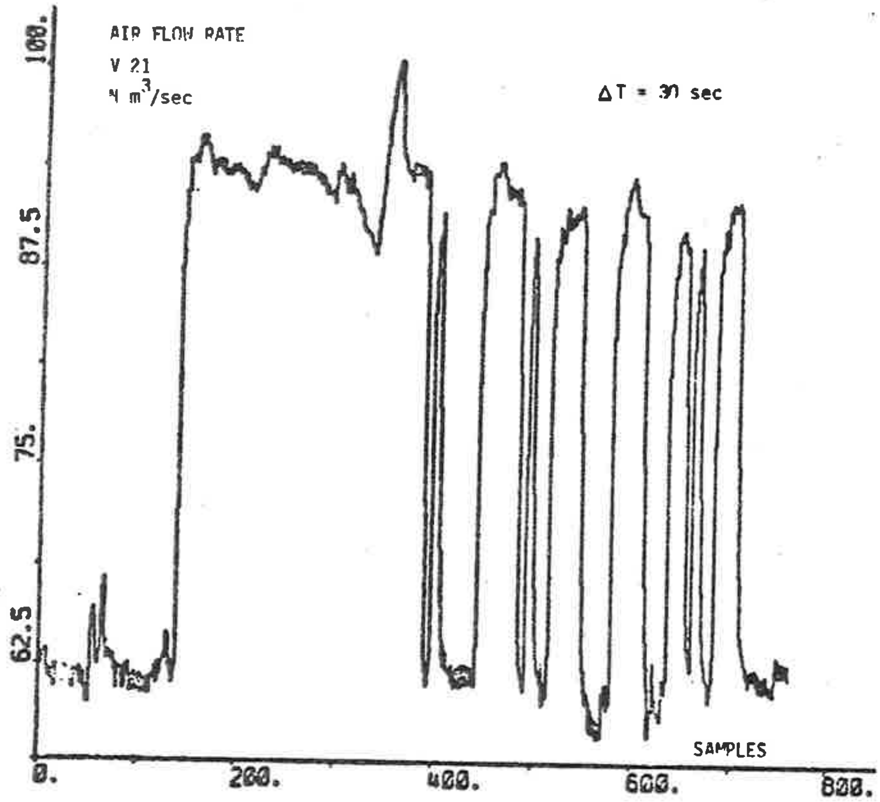

Fig. 9.1. Experiment 740827. Recording of the air flow rate input V21

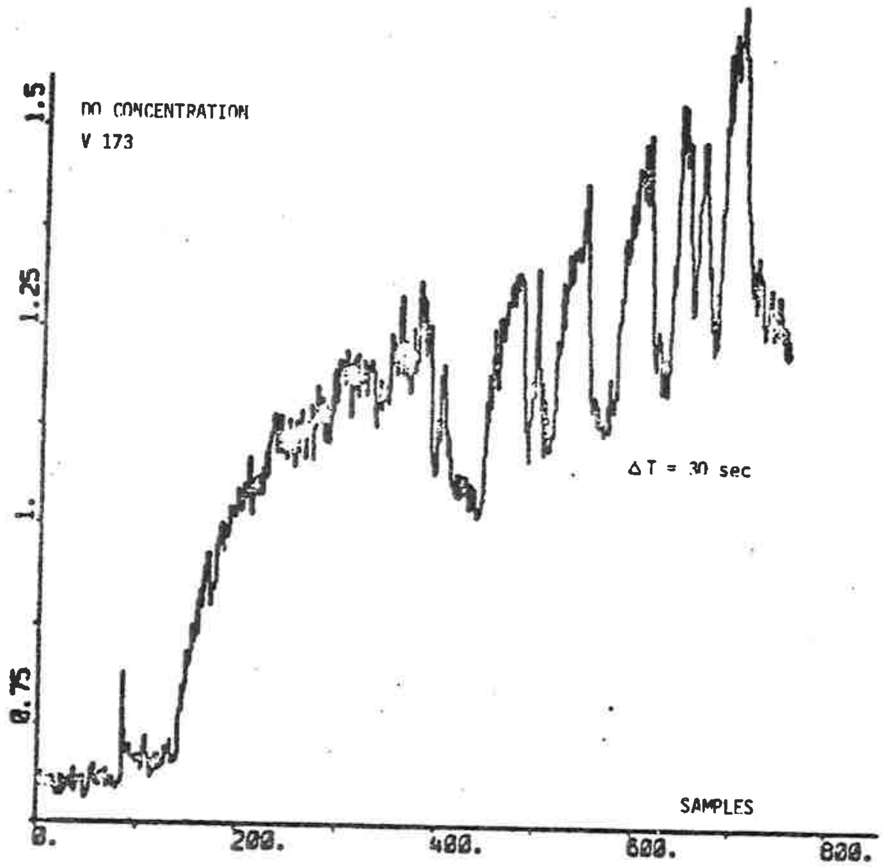

Fig. 9.2. Experiment 740827. Recording of the DO concentration V 173.

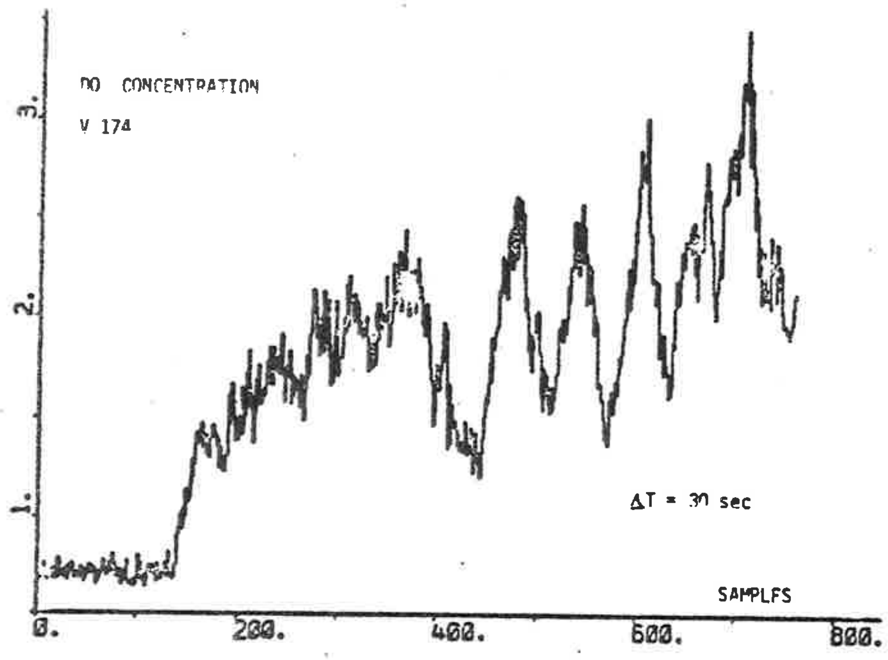

Fig. 9.3. Experiment 740827. Recording of the DO concentration V 174.

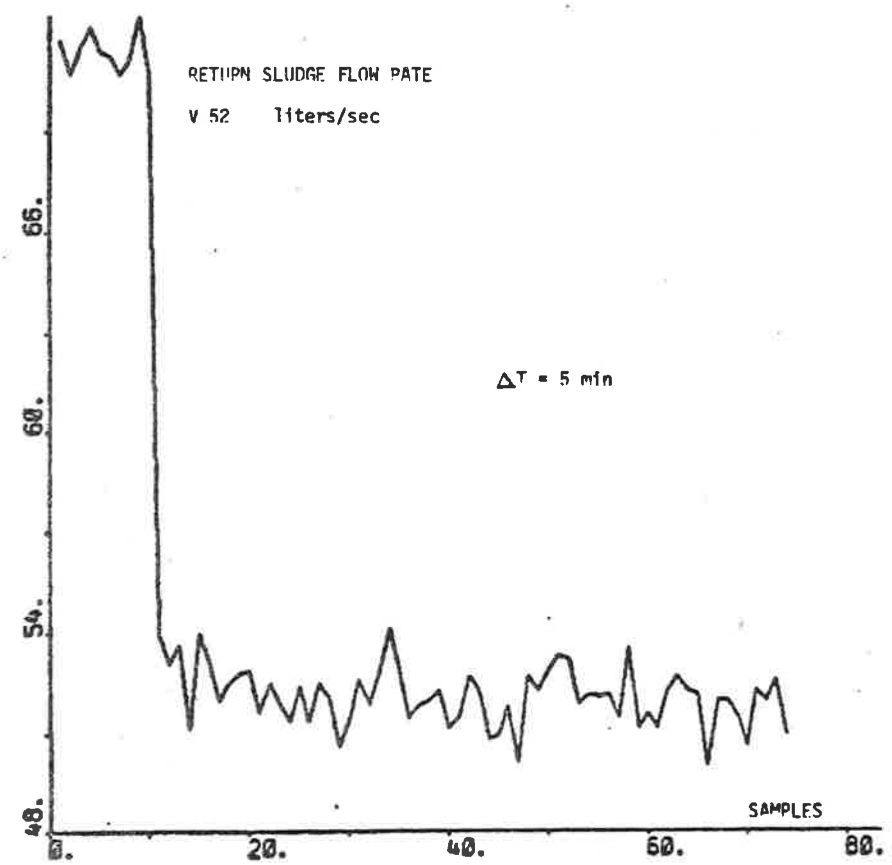

Fig. 9.4. Experiment 740827. Recording of the return sludge flow rate
unpusposefully disturbed.

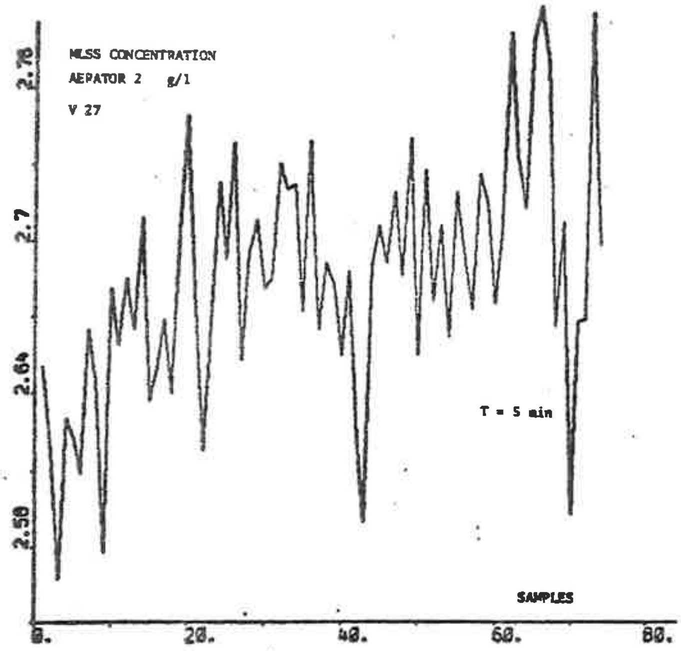

Fig. 9.5. Experiment 740827. Recording of the MLSS of aerator 2.

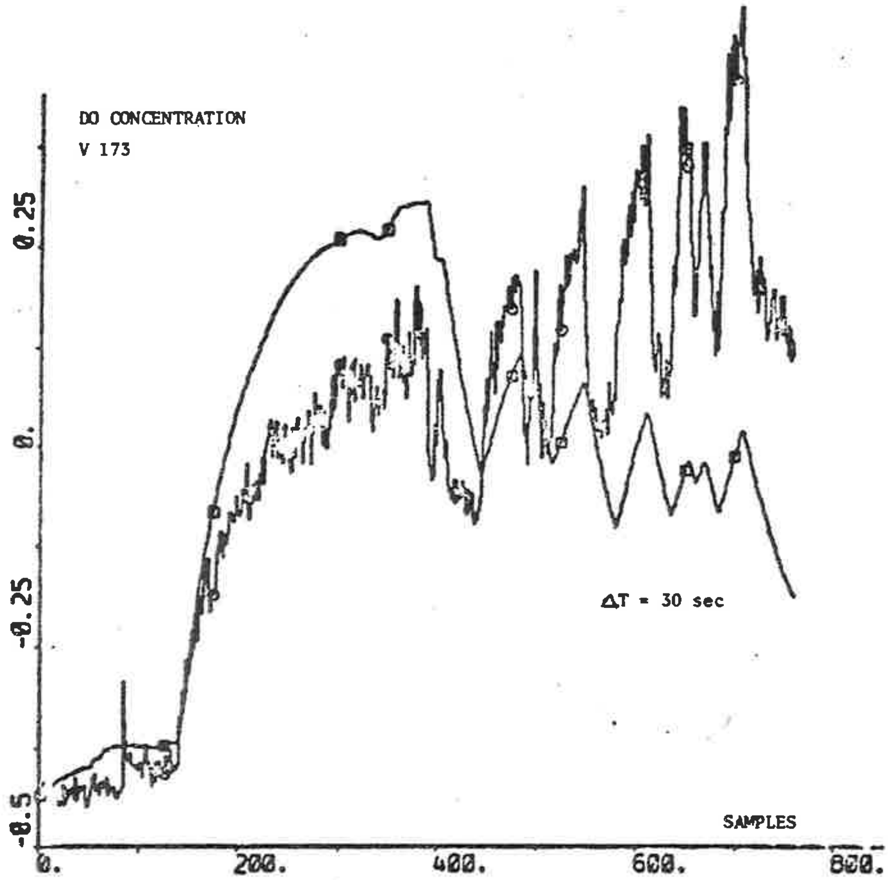

Fig. 9.6. Experiment 740827. Comparison between model output and experimental data of the DO concentration V 173. The model is of first order, assuming only air input V 21 as input. No trend in data is removed. The trend error is probably caused by the unpurposefully disturbed return sludge flow rate V 52.

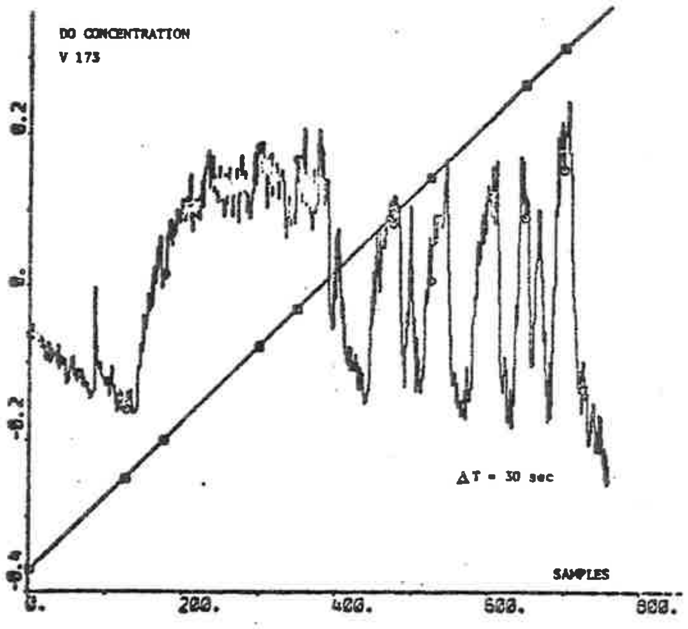

Fig. 9.7. Experiment 740827. DO concentration V 173 when a first order trend has been removed from the experimental data. The trend is shown in the figure.

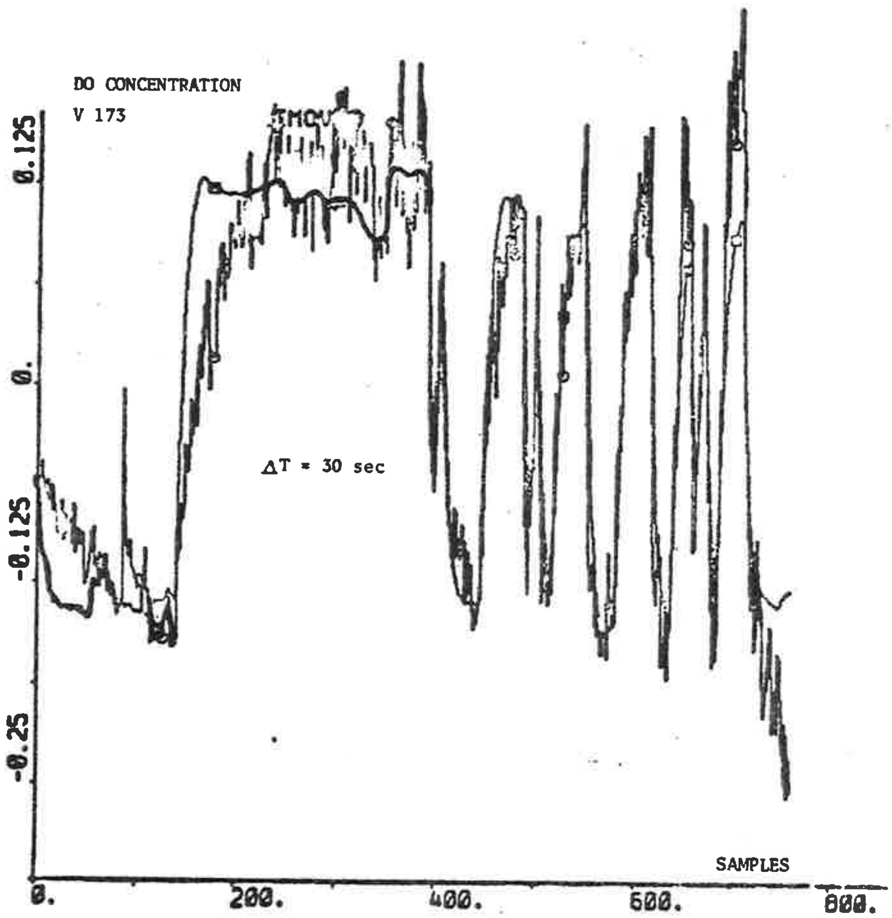

Fig. 9.8. Experiment 740827. Comparison between model output and experimental data of the DO concentration V 173. The model is of first order assuming only air flow V 21 as input. A linear trend is removed from the V 173 data. Compare fig. 9.6.

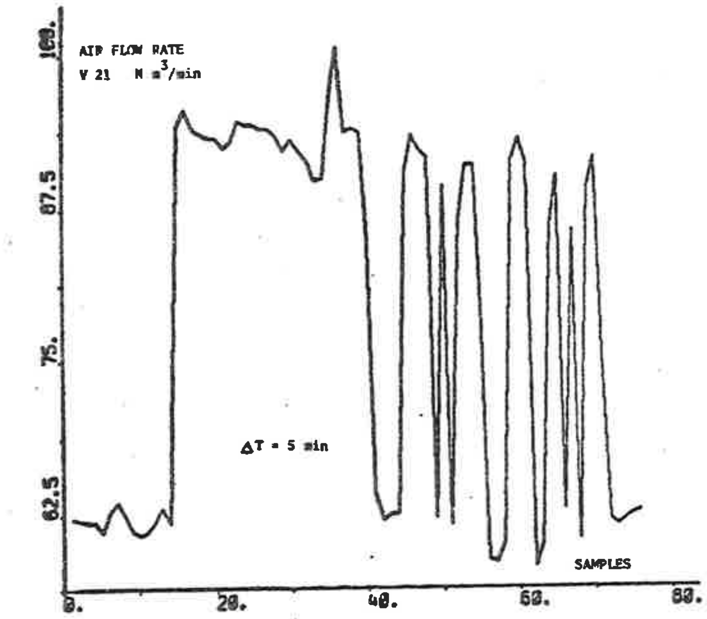

Fig. 9.9. Experiment 740827. Recording of the air flow rate input V 21. The data are identical to those of fig. 9.1, but only every 10 samples are plotted.

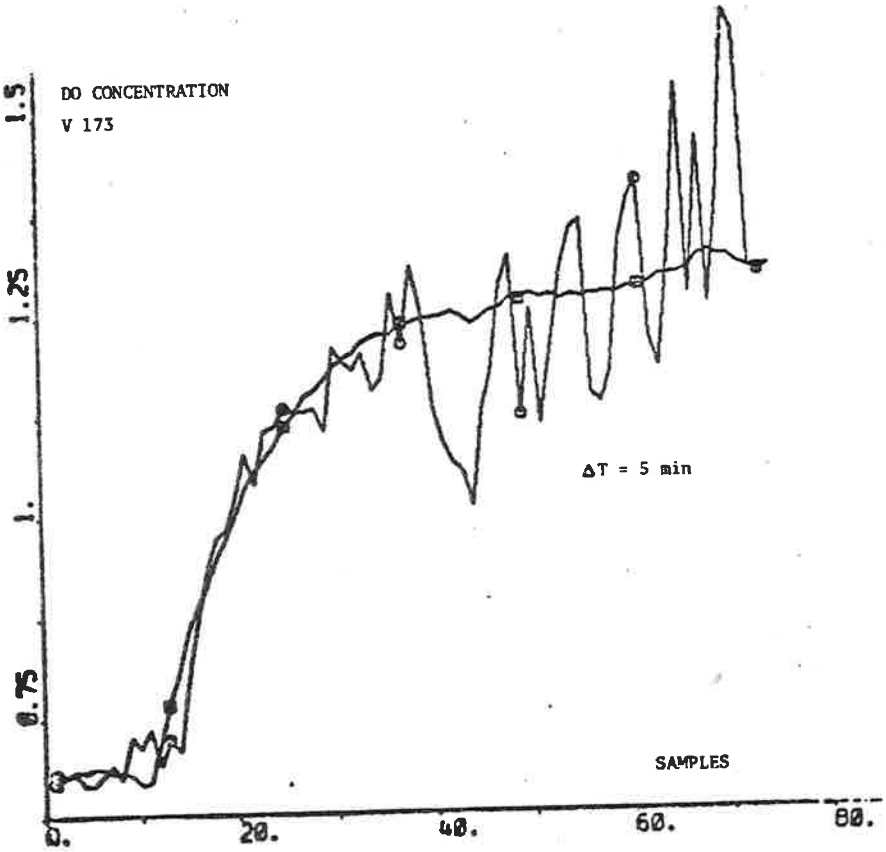

Fig. 9.10. Experiment 740827. Comparison between model output and experimental data for the DO concentration V 173. The model is of first order assuming air flow V 21 and return sludge flow rate V 52 as inputs. Only every 10 data point is picked from the experiment. Compare with figs. 9.6 and 9.8.

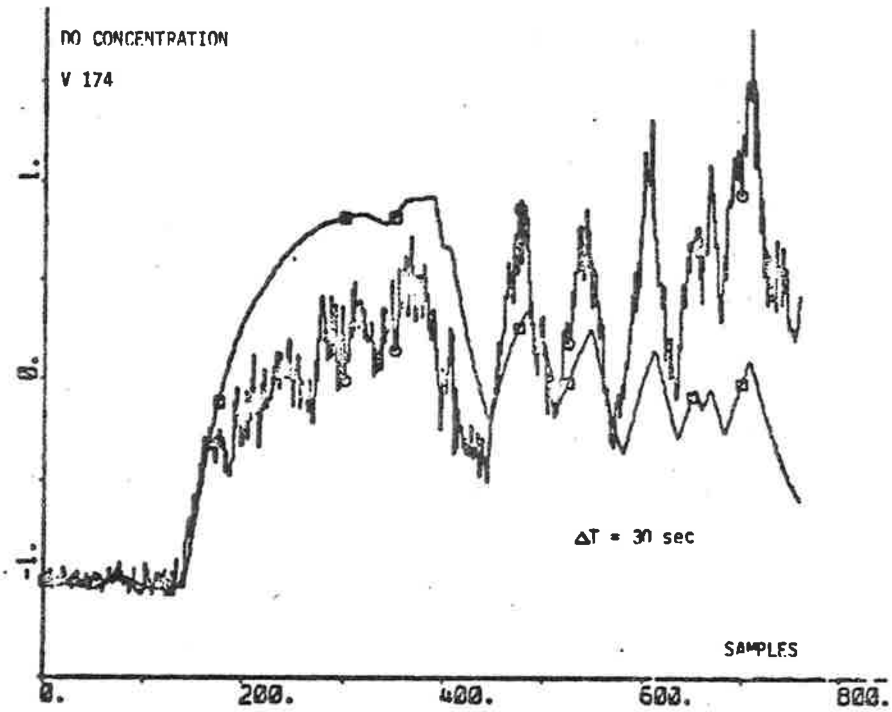

Fig. 9.11. Experiment 740827. Comparison between model output and experimental data for the DO concentration V 174. The model is of first order with only air flow rate V 21 as input. The trend error is probably caused by the unpurposefully disturbed return sludge flow rate V 52.

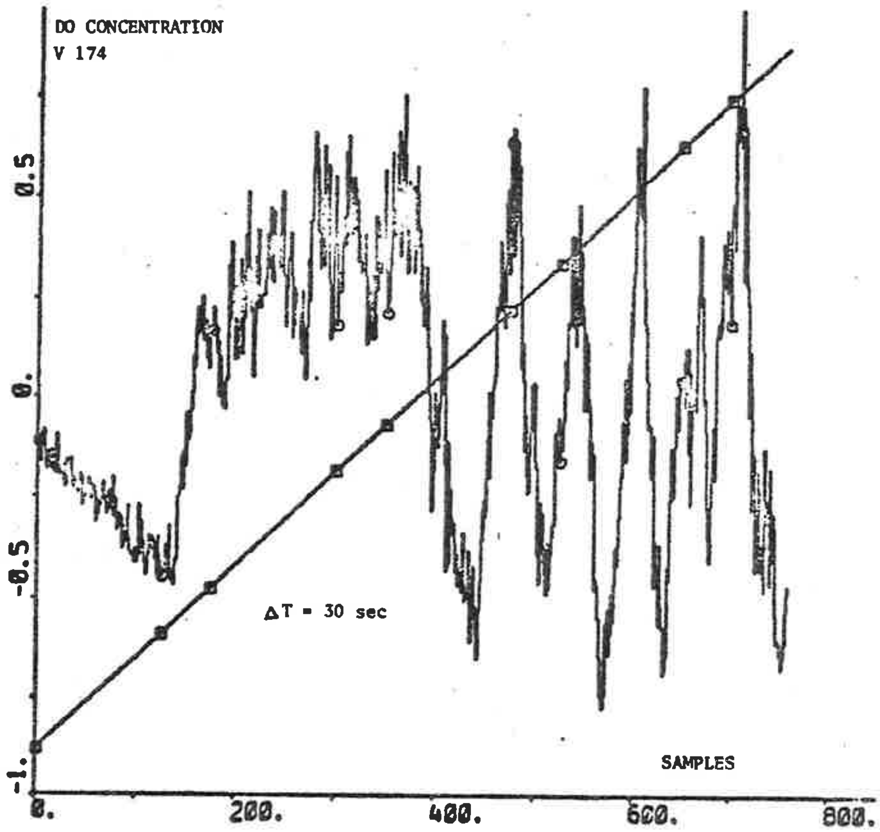

Fig. 9.12. Experiment 740827. DO concentration V 174 with a first order trend removed from the experimental data. The trend is shown in the figure.

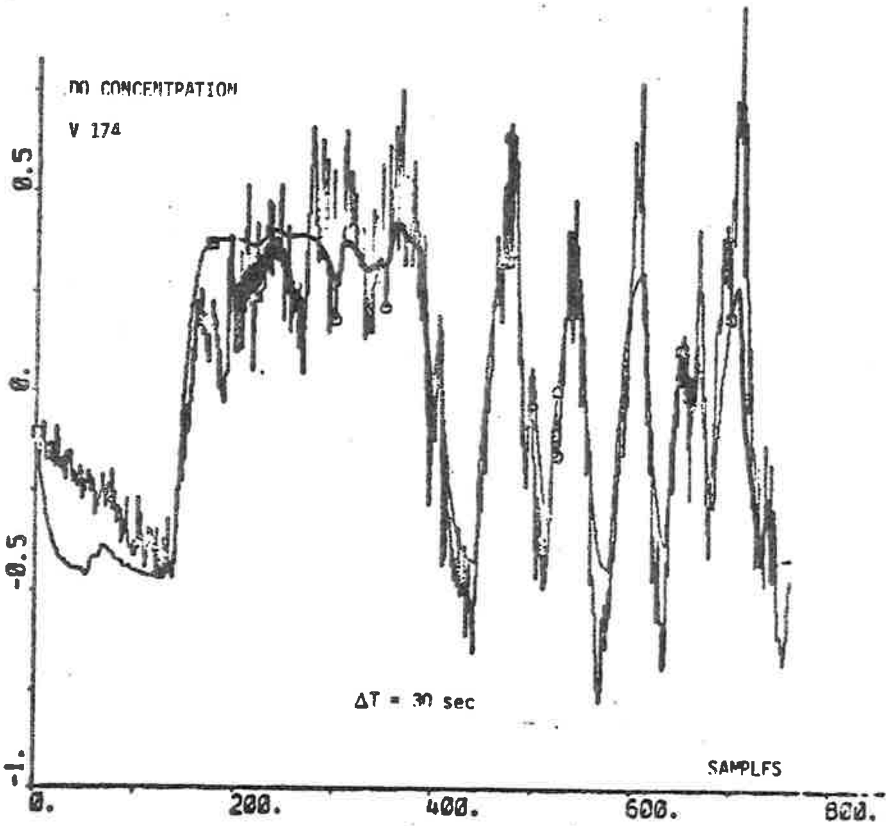

Fig. 9.13. Experiment 740827. Comparison between model output and experimental data of the DO concentration V 174. The model is of first order with only air flow V 21 as input. A linear trend in V 174 is removed.

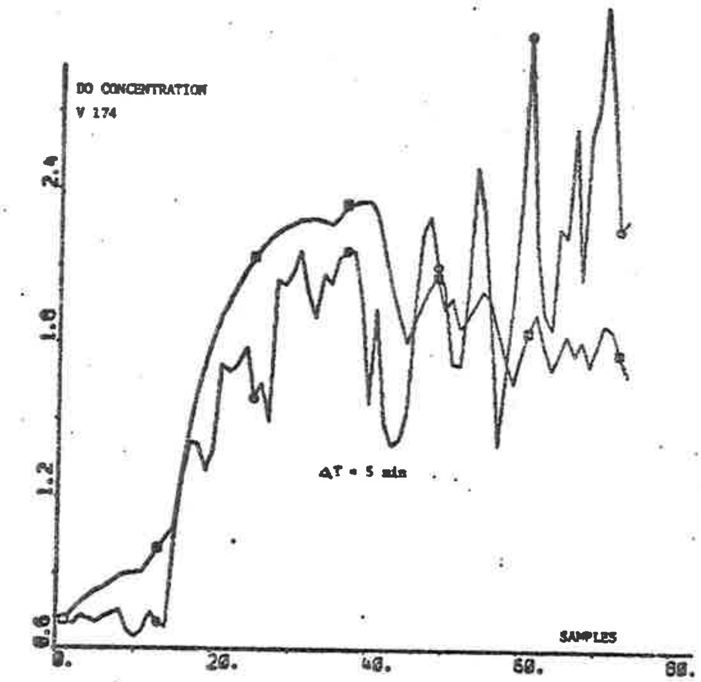

Fig. 9.14. Experiment 740827. Comparison between model output and experimental data for the DO concentration V 174. The model is of first order, assuming air flow V 21 and return sludge flow rate V 52 as inputs. Only every 10 data point is picked from the experiment. Compare with figs. 9.11 and 9.13.

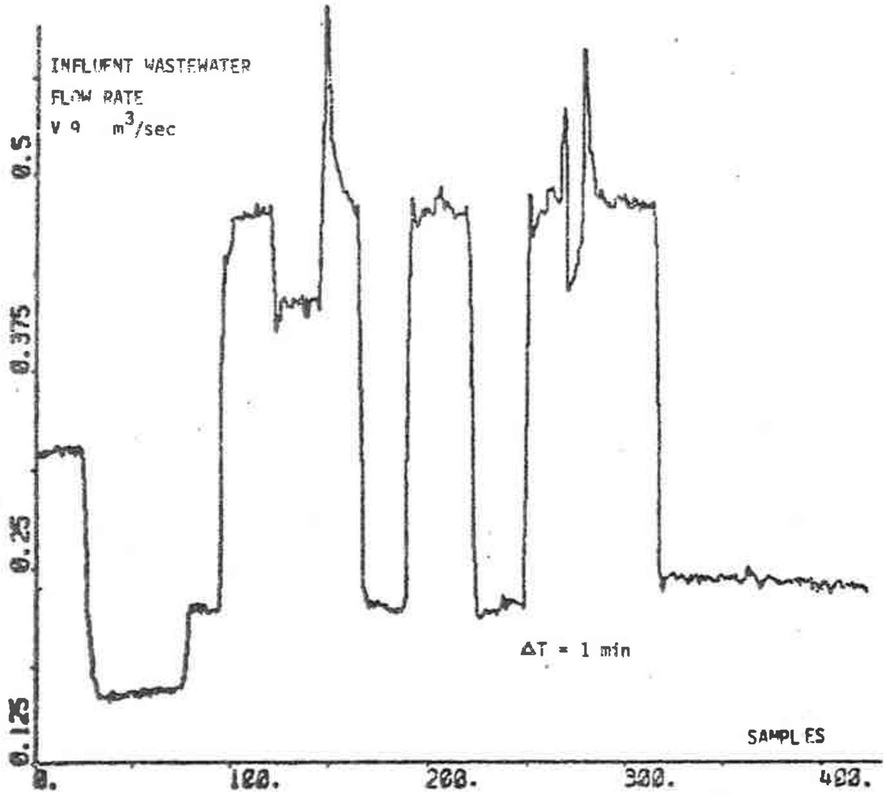

Fig. 10 .1. Experiment 740828. Recording of the input signal influent flow rate V 9.

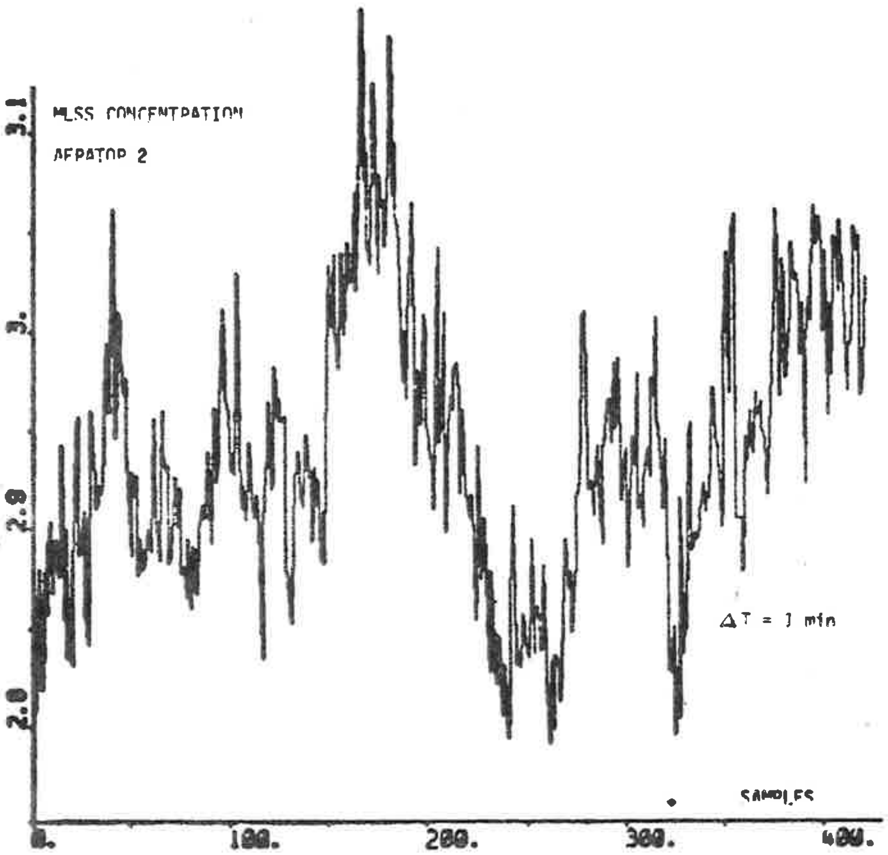

Fig. 10 .2. Experiment 740828. Recording of the MLSS concentration of aerator 2.

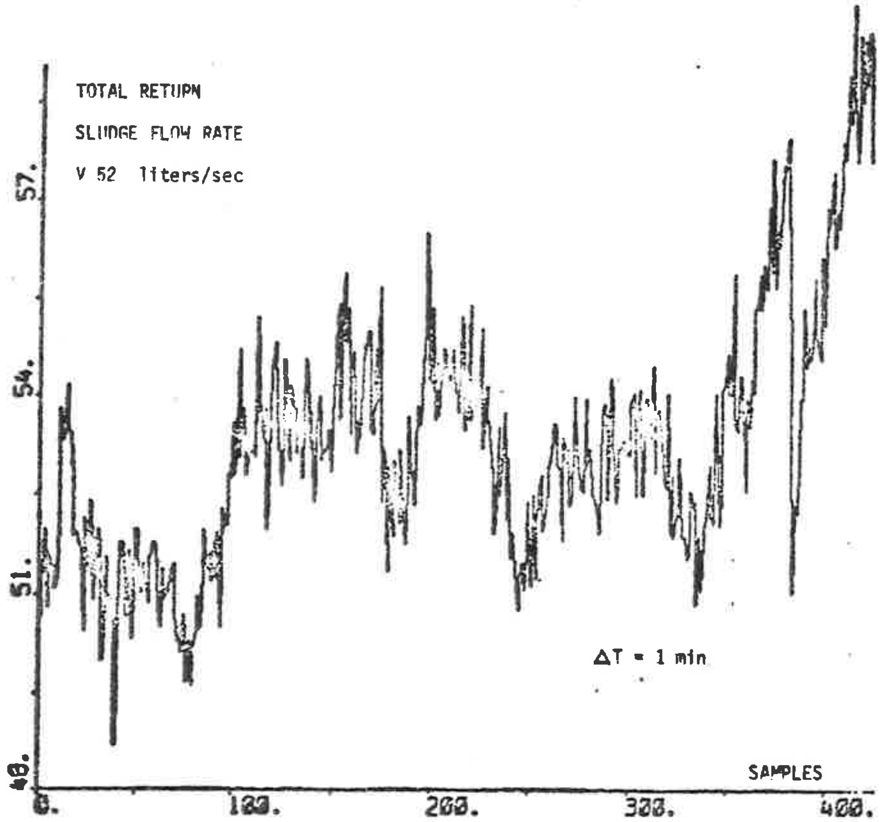

Fig. 10 .3. Experiment 740828. Recording of the total return sludge flow rate V 52.

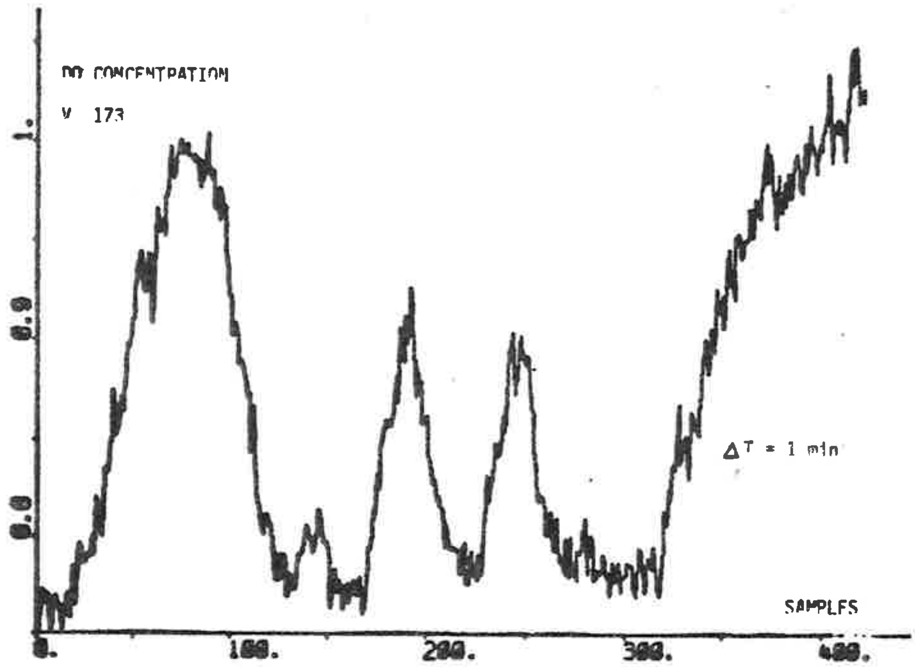

Fig. 10 .4. Experiment 740828. Recording of the DO concentration V 173.

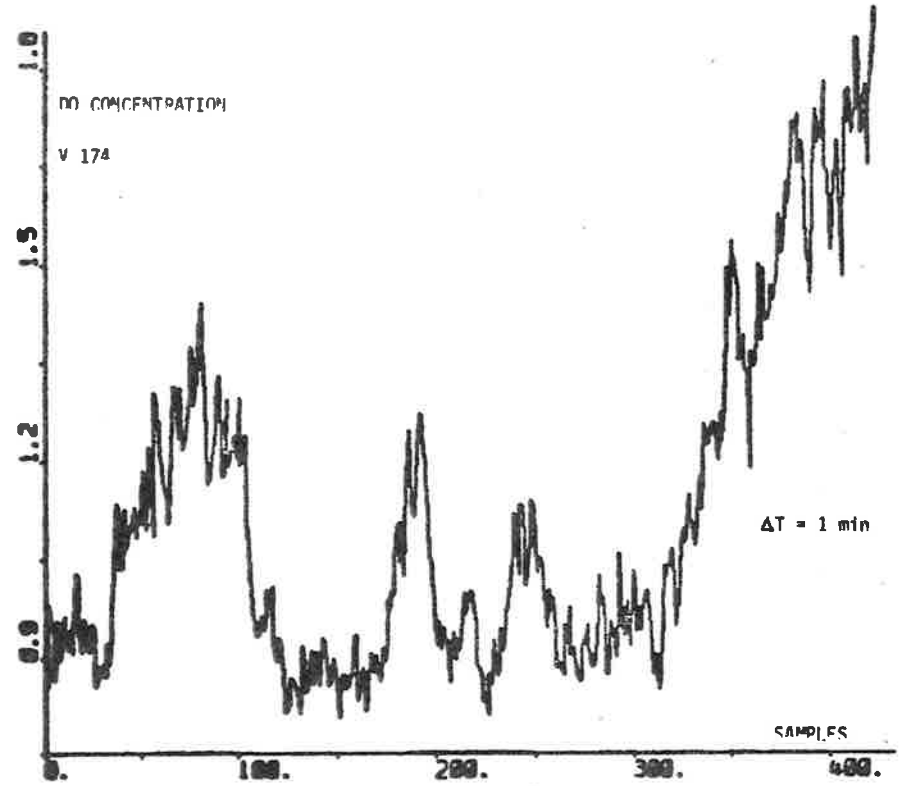

Fig. 10.5. Experiment 740828. Recording of the DO concentration V 174.

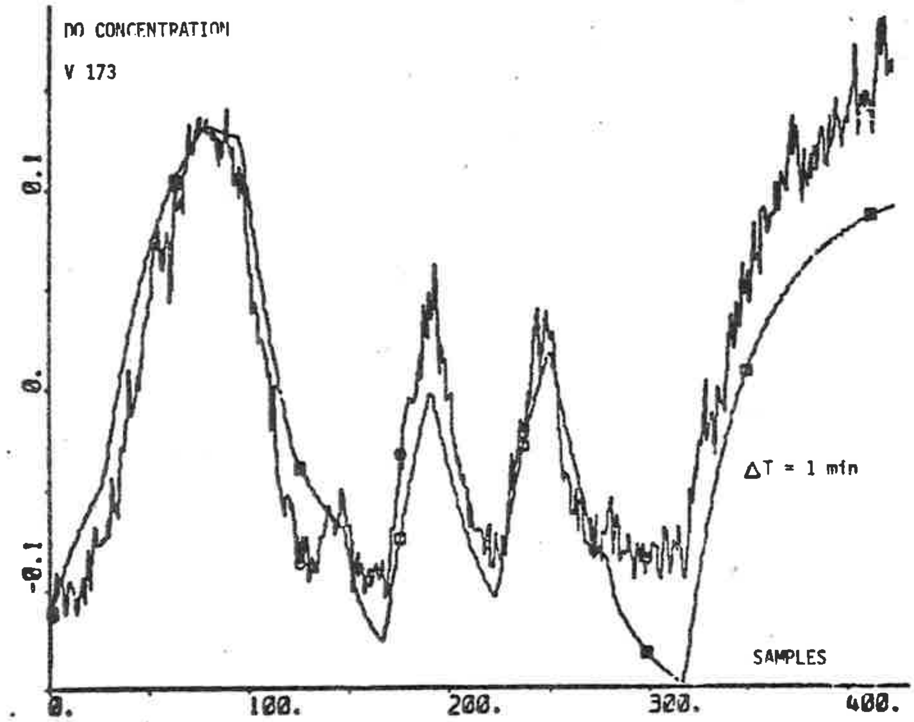

Fig. 10.6. Experiment 740828. Comparison of the model output and the experimental data of the DO concentration V 173. The model is of first order with the water flow rate V 9 as input. No trend correction is made.

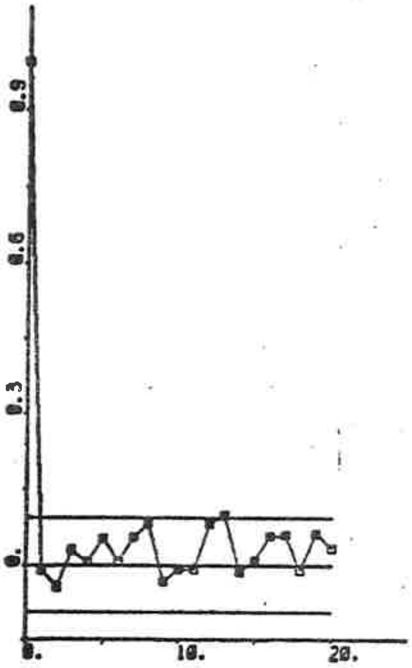

Fig. 10.7. Experiment 740828. Autocovariance of the residuals of the first order model of V173 with the influent water flow rate V9 as input. The straight lines are the 5 % confidence limits.

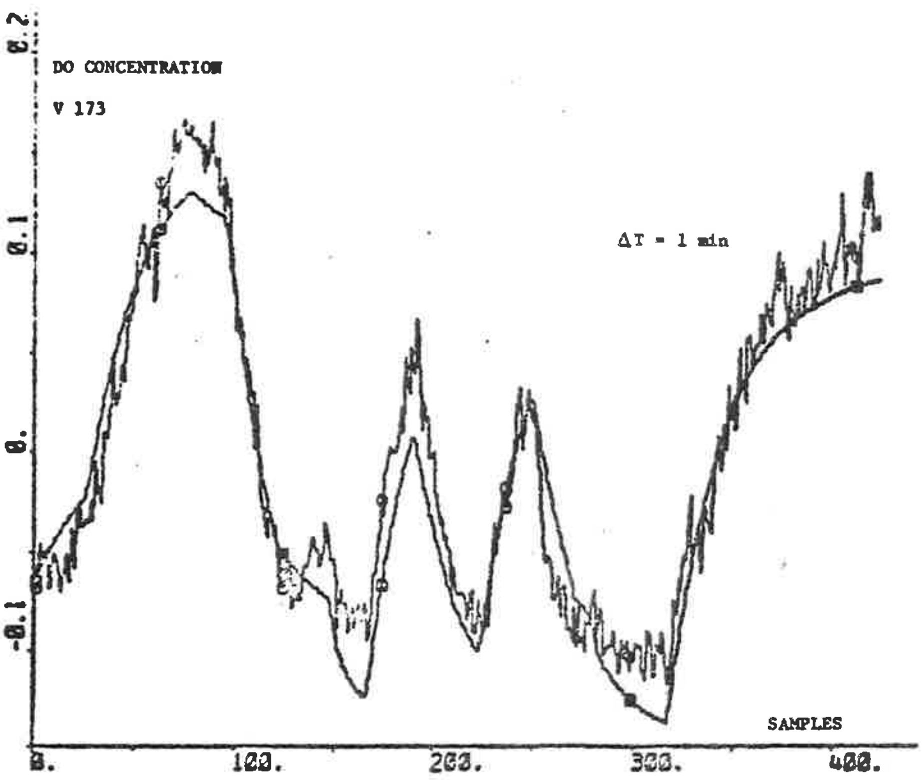

Fig. 10.8. Experiment 740828. Comparison of the model output and the experimental data of the DO concentration V 173. The model is of first order with the influent water flow as input (V9). A linear trend in the DO concentration has been removed.

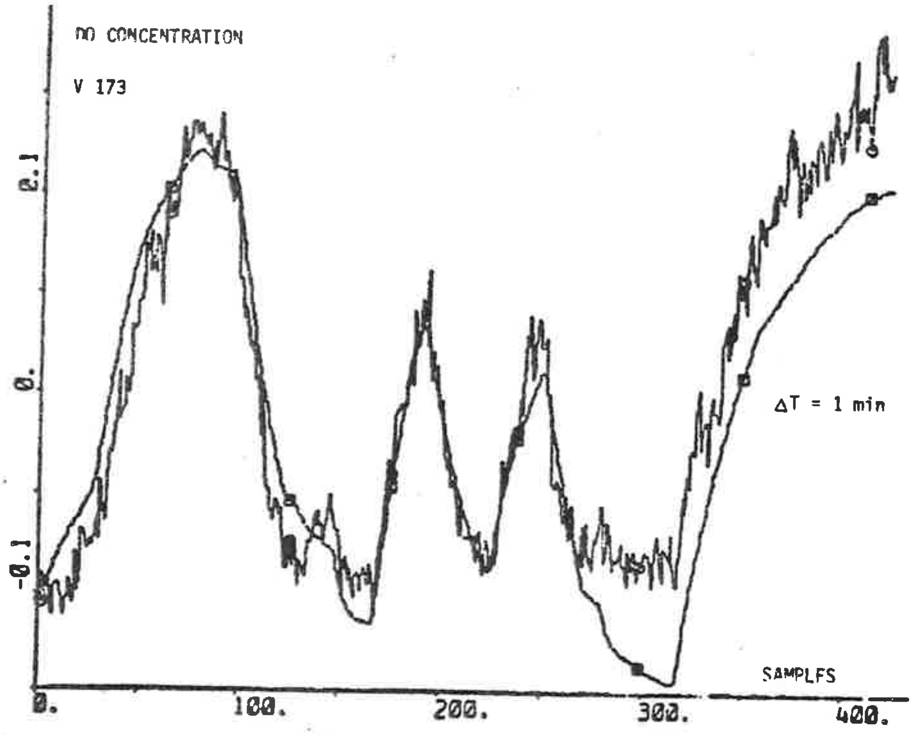

Fig. 10.9. Experiment 740828. Comparison of the model output and experimental data of the DO concentration V 173. The model is of first order with two inputs, the water flow rate V 9 and the MLSS concentration V 27. No trend correction is made.

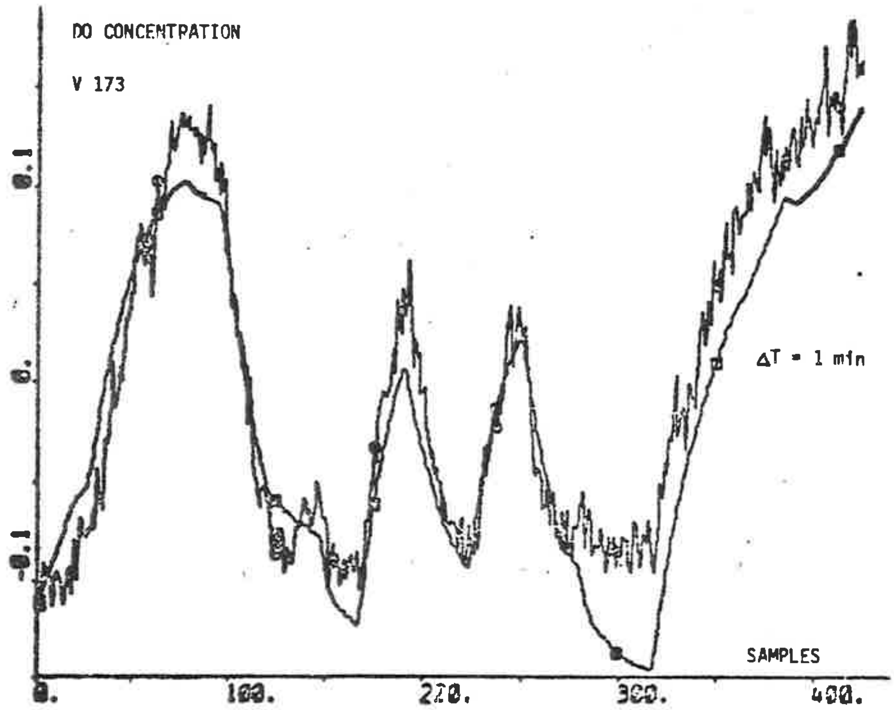

Fig. 10.10. Experiment 740828. Comparison of the model output and experimental data of the DO concentration V 173. The model is of first order with two inputs, the water flow V 9 and the return sludge flow rate V 52. No trend correction is made.

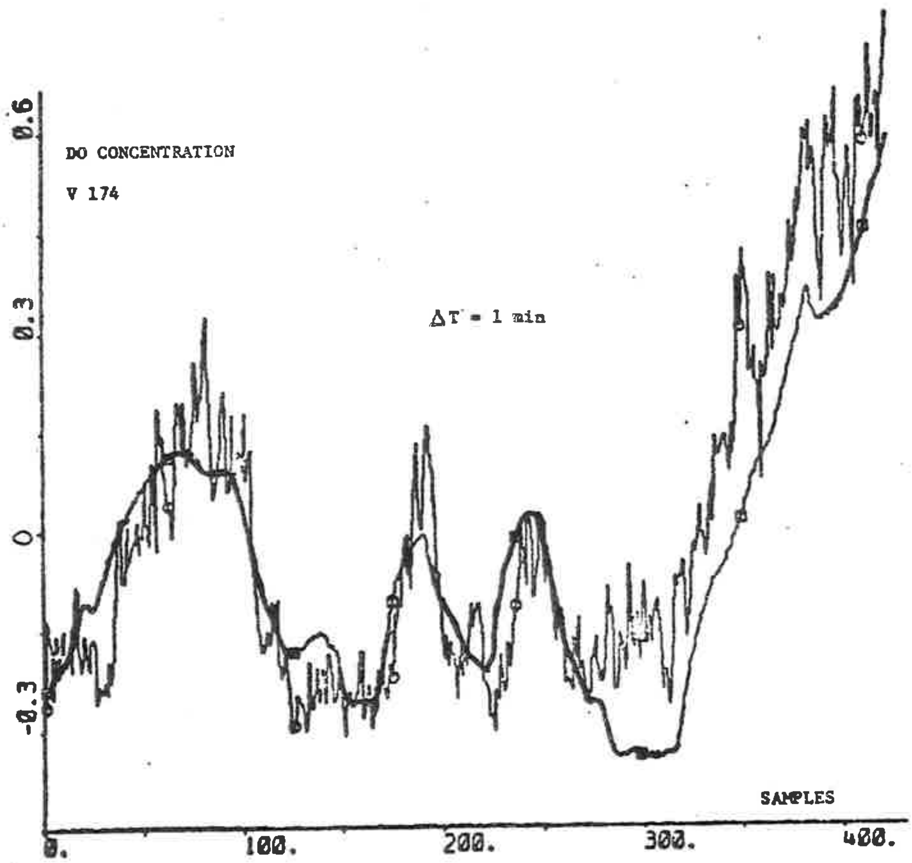

Fig. 10.11. Experiment 740828. Comparison of the model output and experimental data of the DO concentration V 174. The model is of first order with two inputs, the influent water flow V 9 and the return sludge flow rate V 52. No trend correction is made

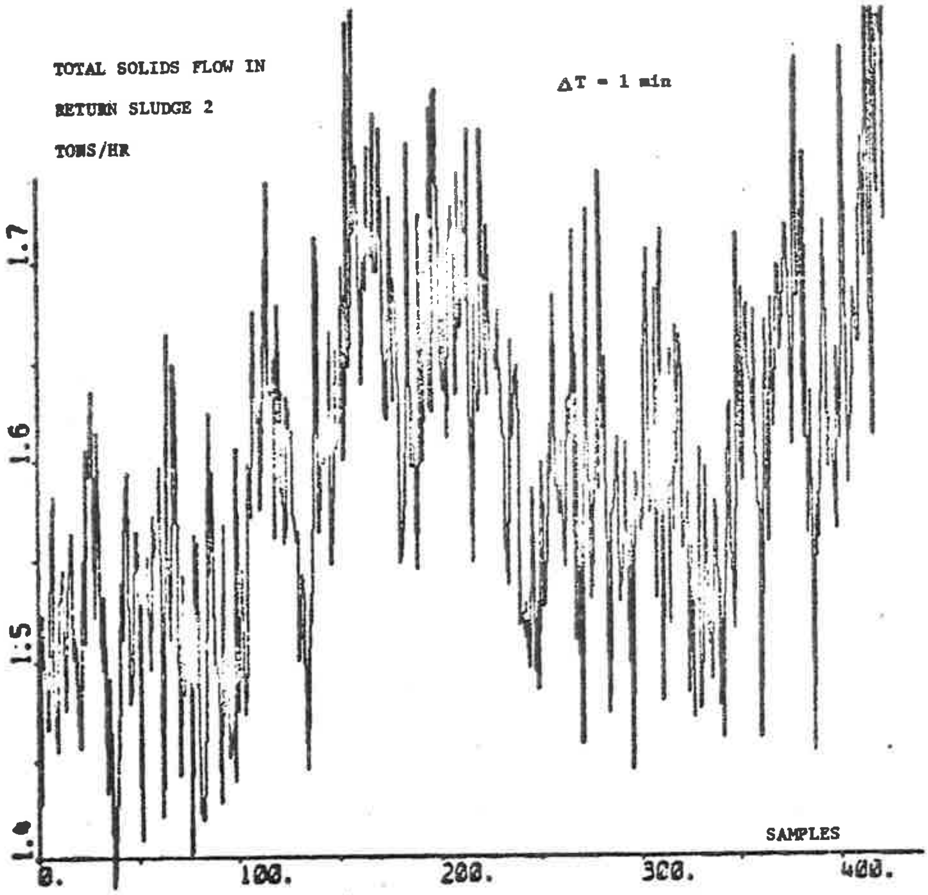

Fig. 10.12. Experiment 740828. Recording of the analog output of the total flux of solids in the return flow to the aerator 2, V 70. The signal is the output of an analog multiplier of the signals V52 (return sludge flow rate) and V58 (return sludge concentration). Compare with fig. 10.13.

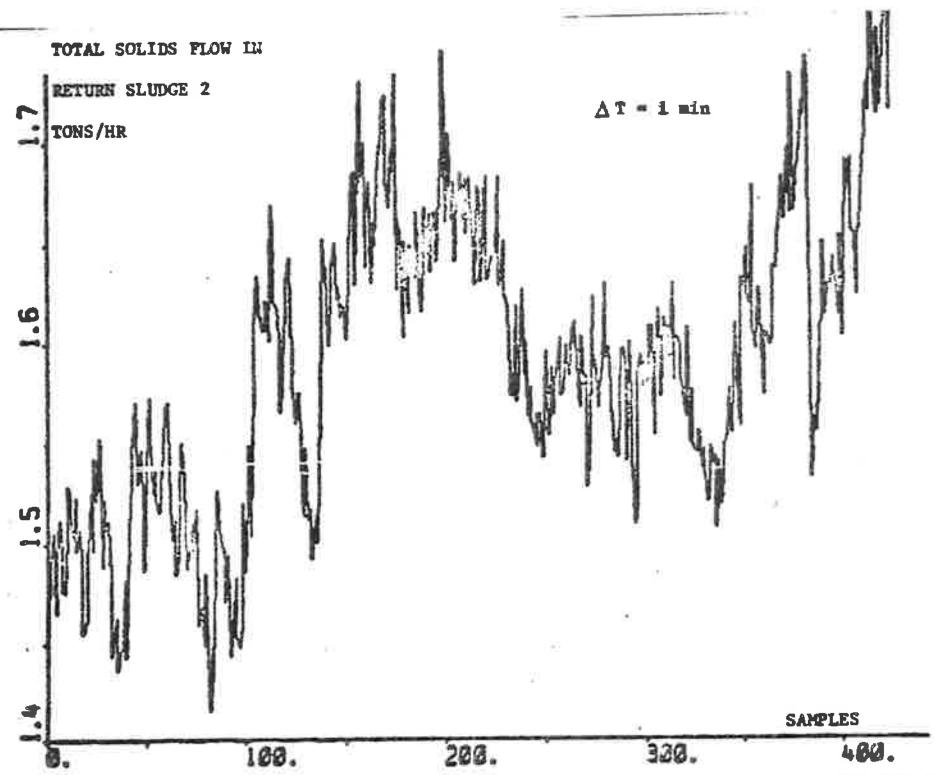

Fig. 10.13. Experiment 740828. Estimation of the signal V 70. The signal is achieved by multiplying the signals V52 (return sludge flow rate) and V 58 (return sludge concentration) digitally in the computer. Compare with fig. 10.12.

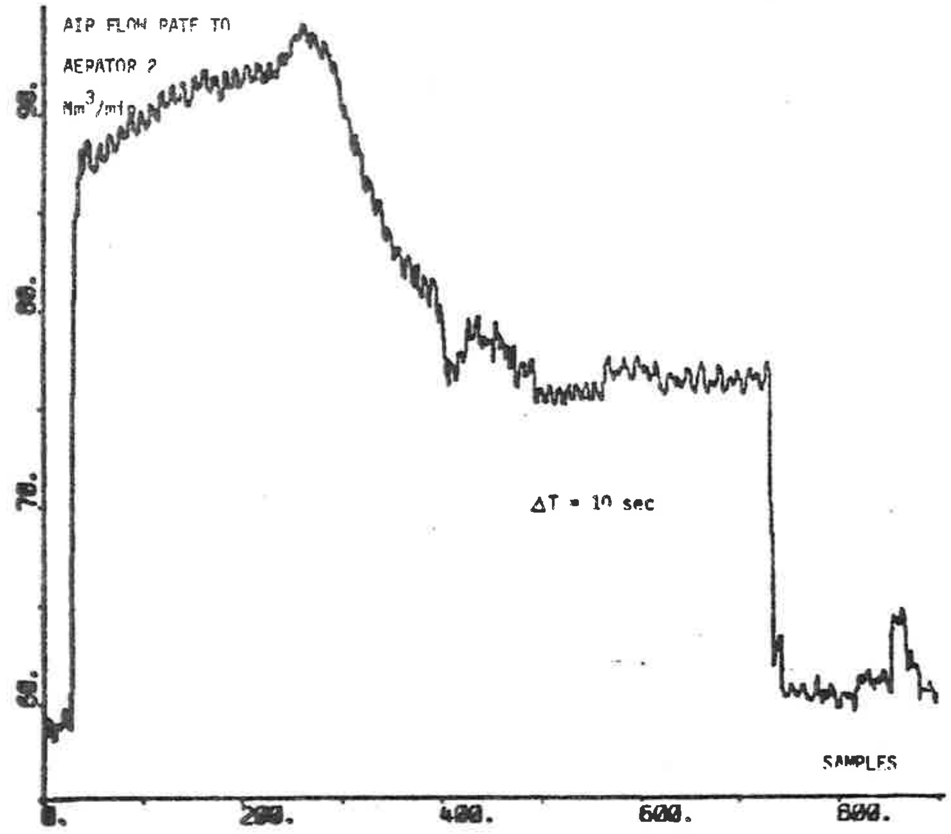

Fig. 11 .1. Experiment 741126, part A. Recording of the air flow rate V 21 to aerator 2.

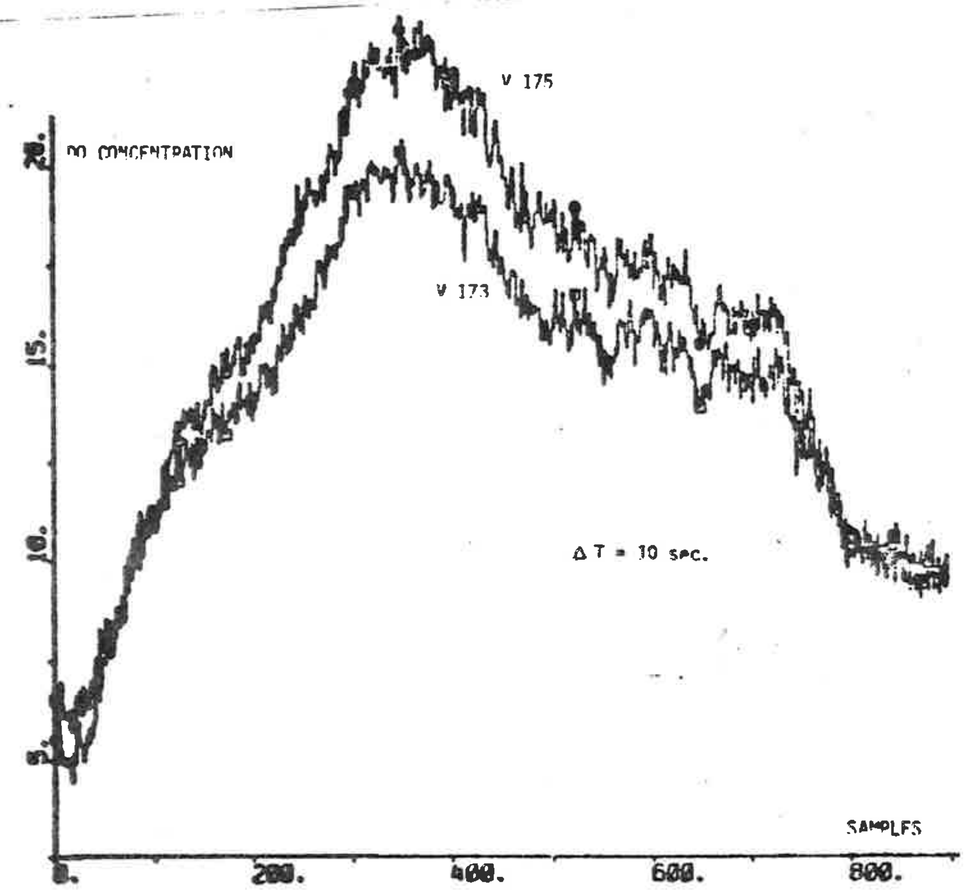

Fig. 11.2. Experiment 741126, part A. Recordings of the DO concentrations V 173 and V 175.

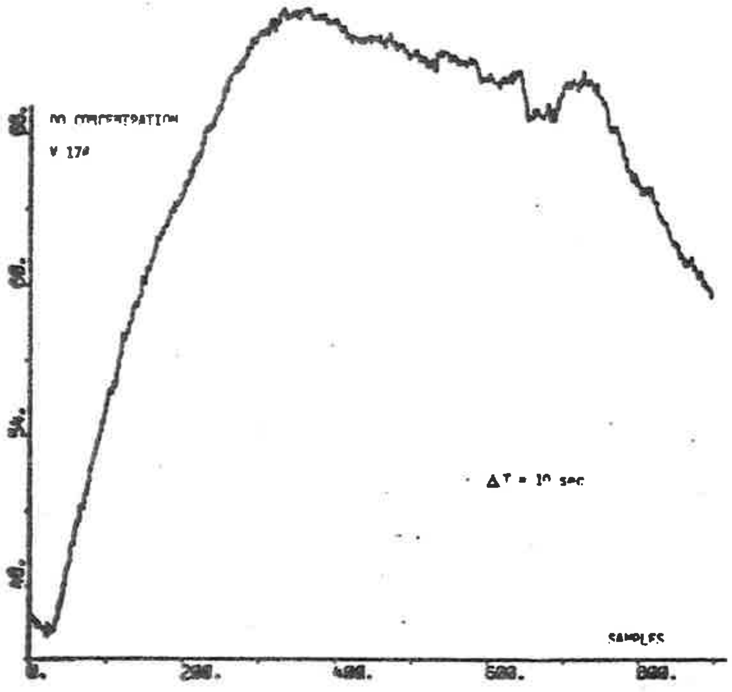

Fig. 11.3. Experiment 741126, part A. Recording of the DO concentration V 174.

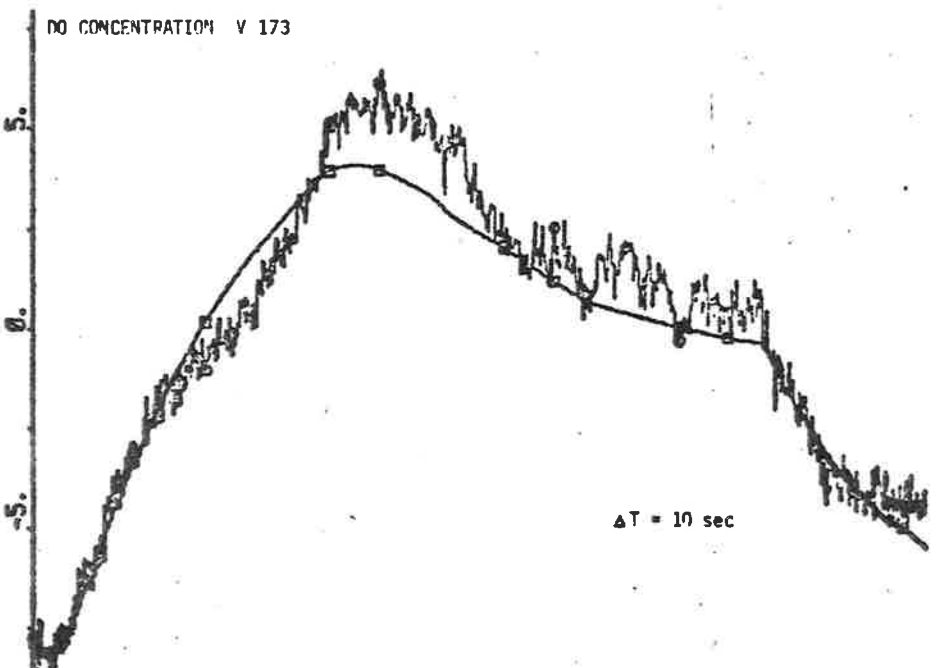

Fig. 11.4. Experiment 741126, part A. Comparison between the model output and experimental data of the DO concentration V 173. The model is of first order with one input, the air flow rate V 21.

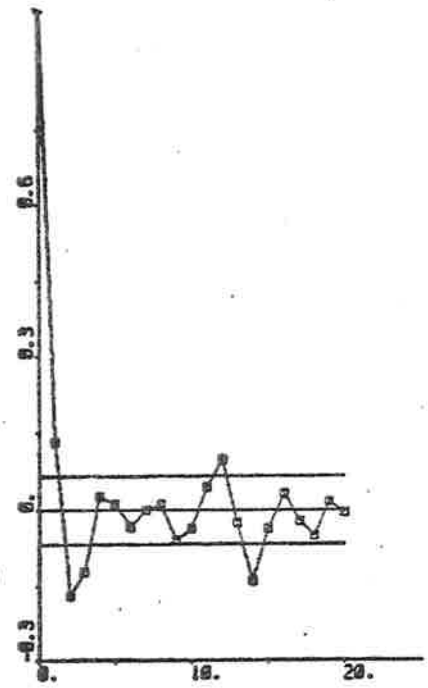

Fig. 11.5. Experiment 741126, part A. Autocovariance of the residuals of the first order model of the DO concentration V 175 with the air flow rate V 21 as input. The straight lines are the 5 % confidence limits.

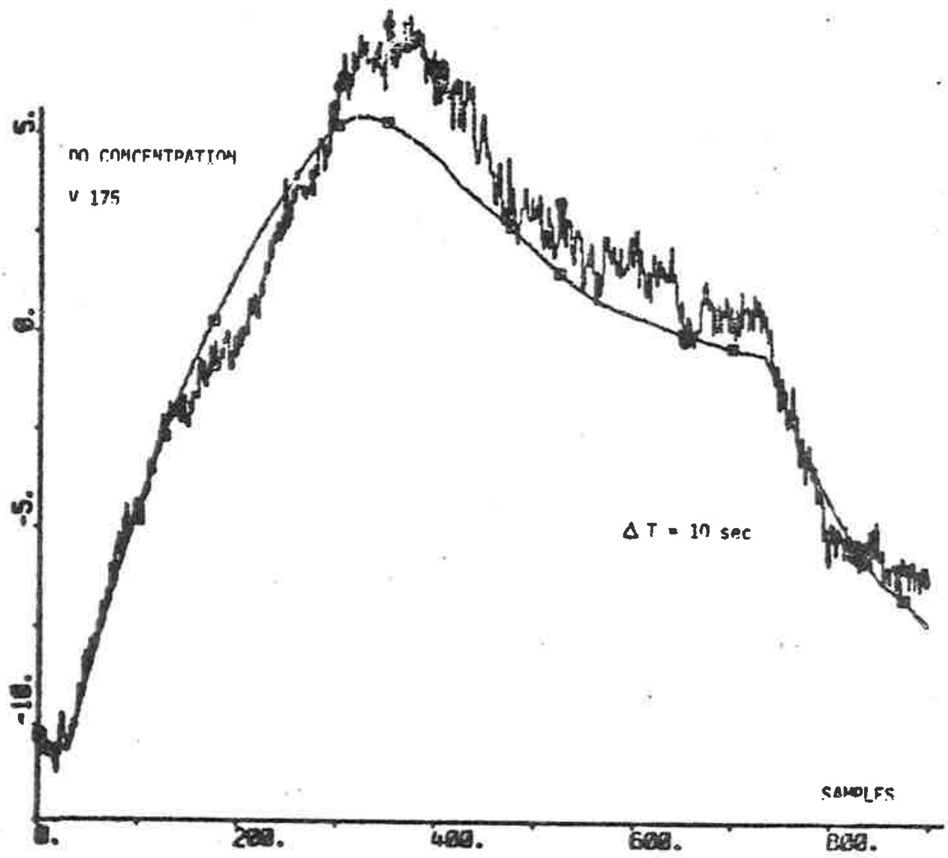

Fig. 11.6. Experiment 741126, part A. Comparison between the model output and experimental data of the DO concentration V 175. The model is of first order with one input, the air flow rate V 21.

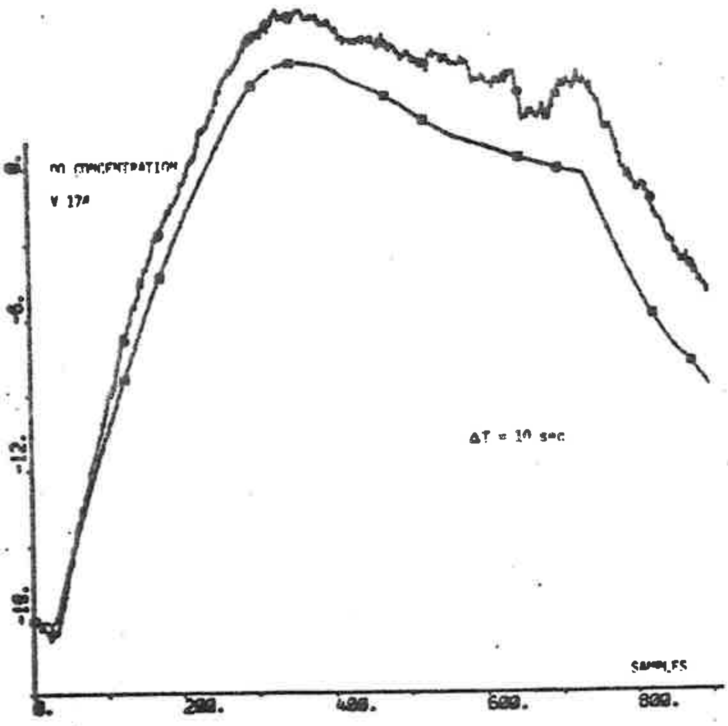

Fig. 11.7 Experiment 741126, part A. Comparison between the model output and experimental data output of the DO concentration V 174. The model is of first order with one input, the air flow rate V 21. No trend correction is made.

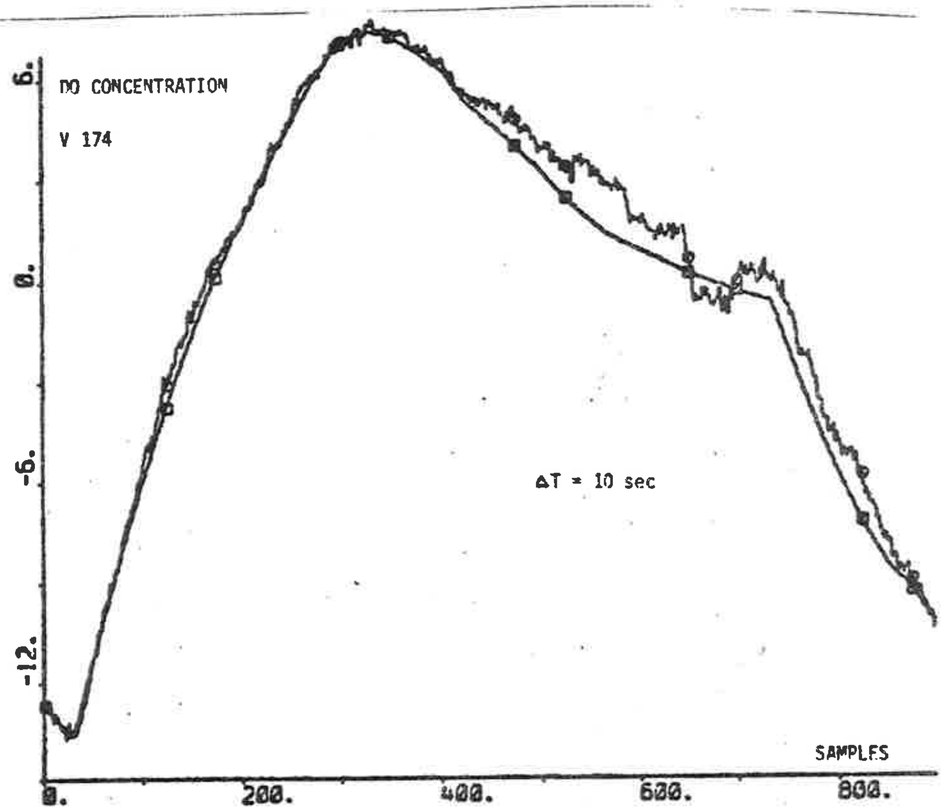

Fig. 11.8. Experiment 741126, part A. Comparison of model output and experimental data for DO concentration V 174. The model is of first order with one input, the air flow rate V 21. A linear trend in V 174 data is removed.

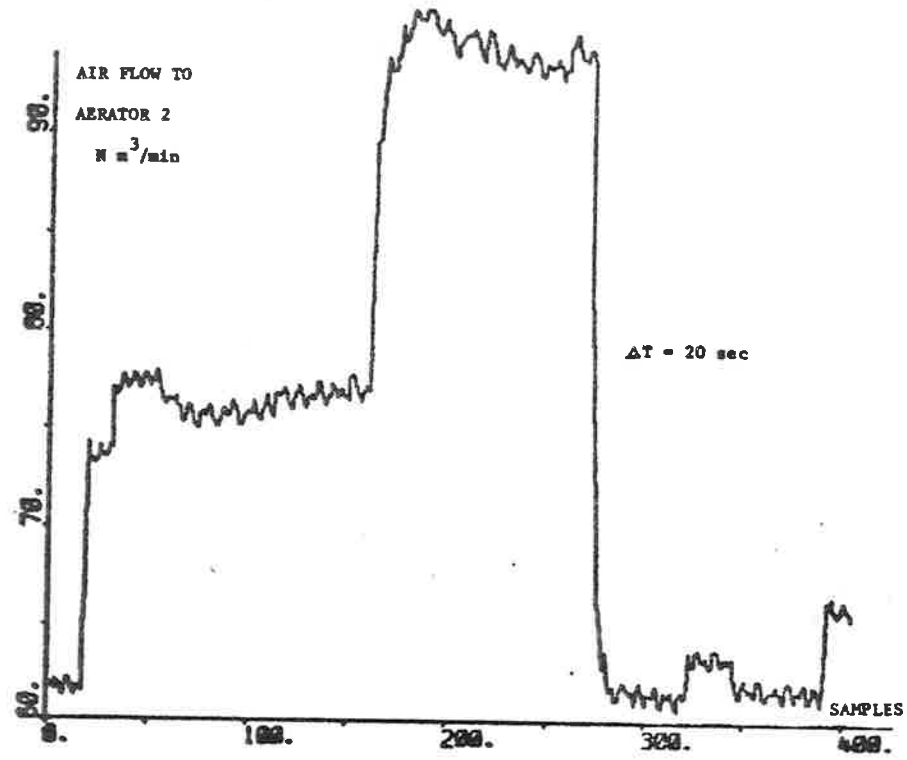

Fig. 11.9. Experiment 741126, part B. Recording of the air flow rate to aerator 2.

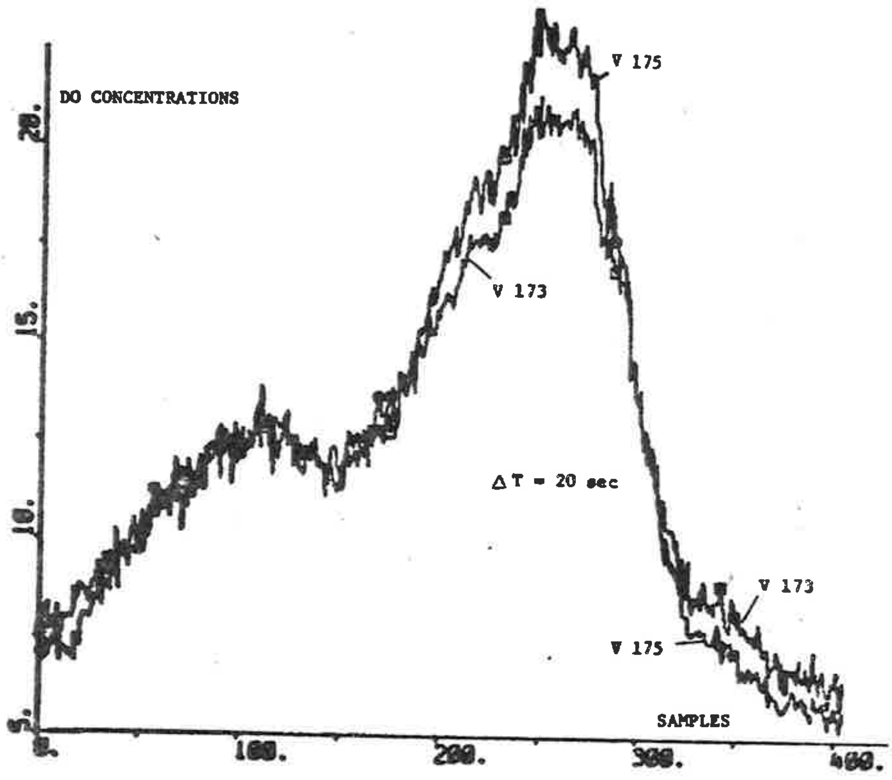

Fig. 11.10. Experiment 741126, part B. Recordings of the DO concentrations V 173 and V 175.

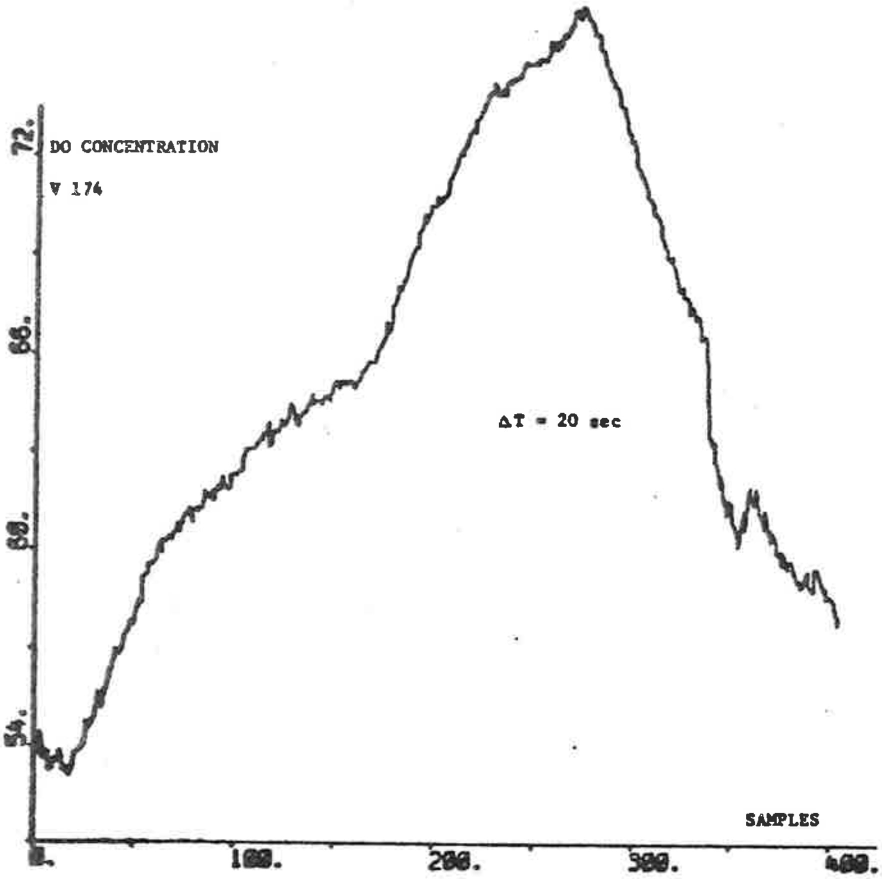

Fig. 11.11. Experiment 741126, part B. Recording of the DO concentration V 174.

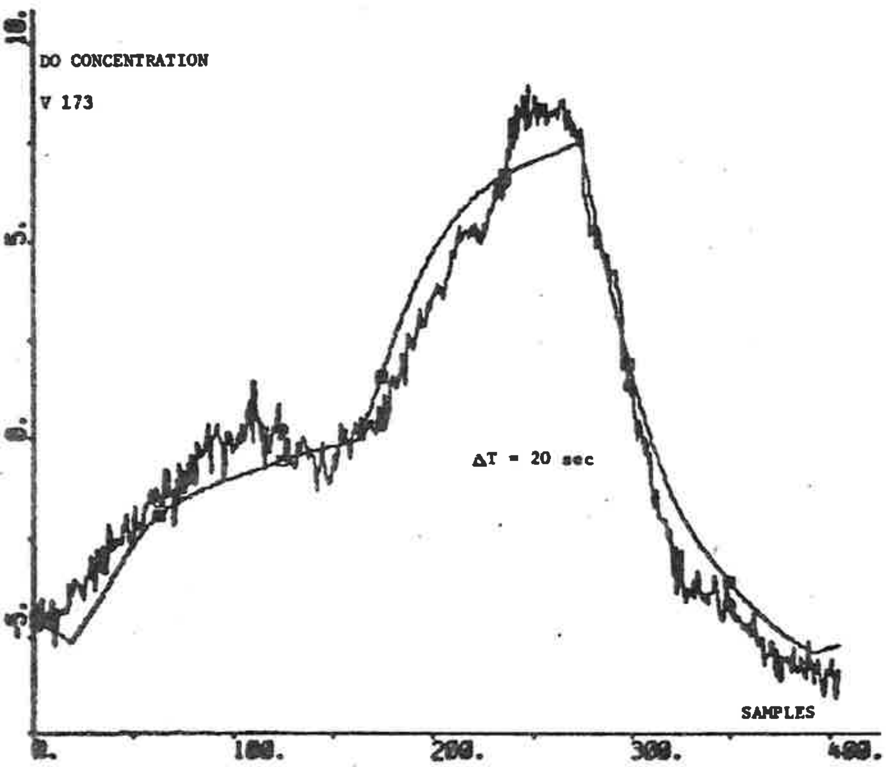

Fig. 11.12. Experiment 741126, part B. Comparison of the model output and experimental data of the DO concentration V 173. The model is of first order with the input air flow rate V 21

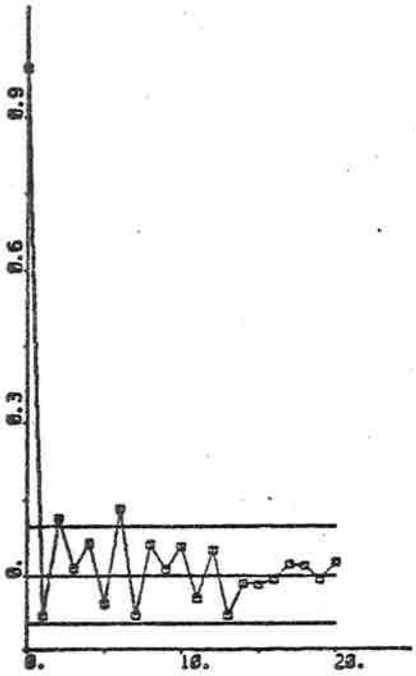

Fig. 11.13. Experiment 741126, part B. Autocovariance of the residuals of the first order model of V 173 with the air flow V 21 as input. The straight lines are the 5 % confidence limits.

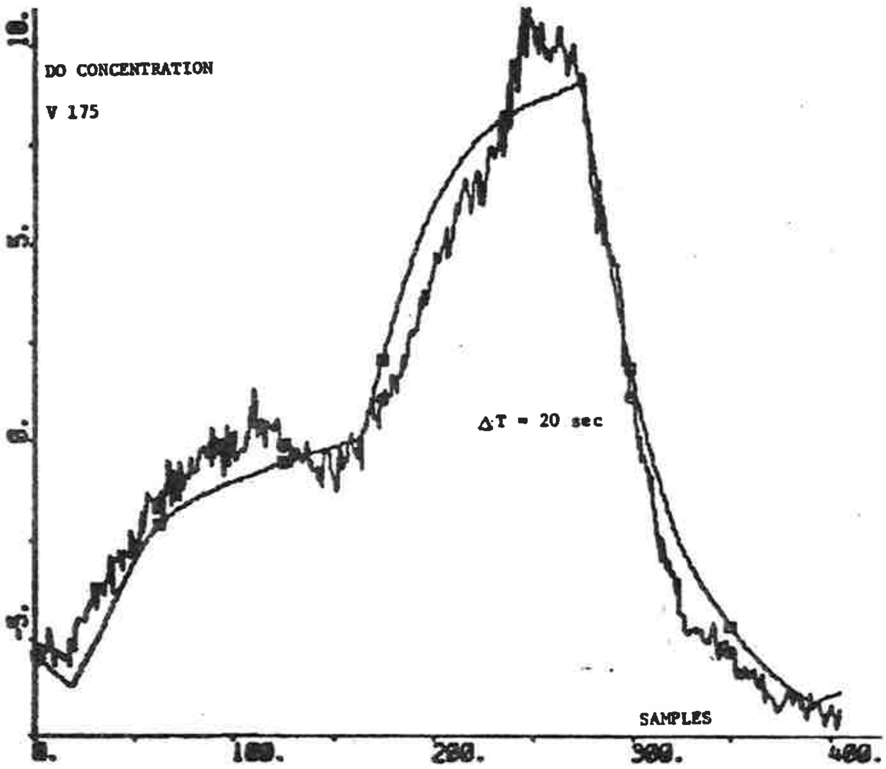

Fig. 11.14. Experiment 741126, part B. Comparison of the model output and experimental data of the DO concentration V 175. The model is of first order with the air flow rate V 21 as input.

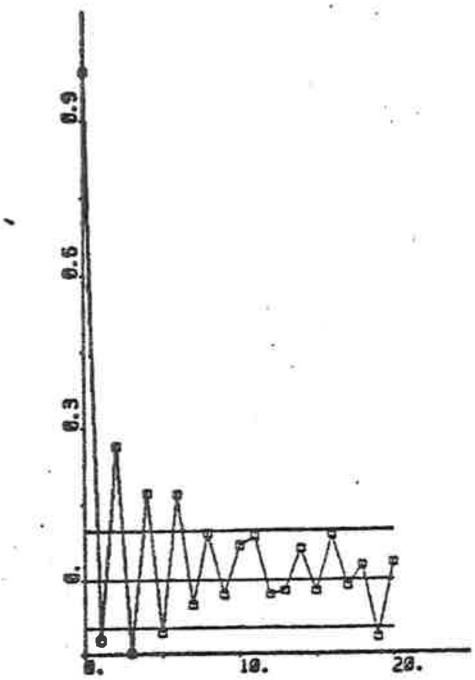

Fig. 11.15. Experiment 741126, part B. Autocovariance of the residuals of the first order model of V 175 with the air flow V 21 as input. The straight lines are the 5 % confidence limits.

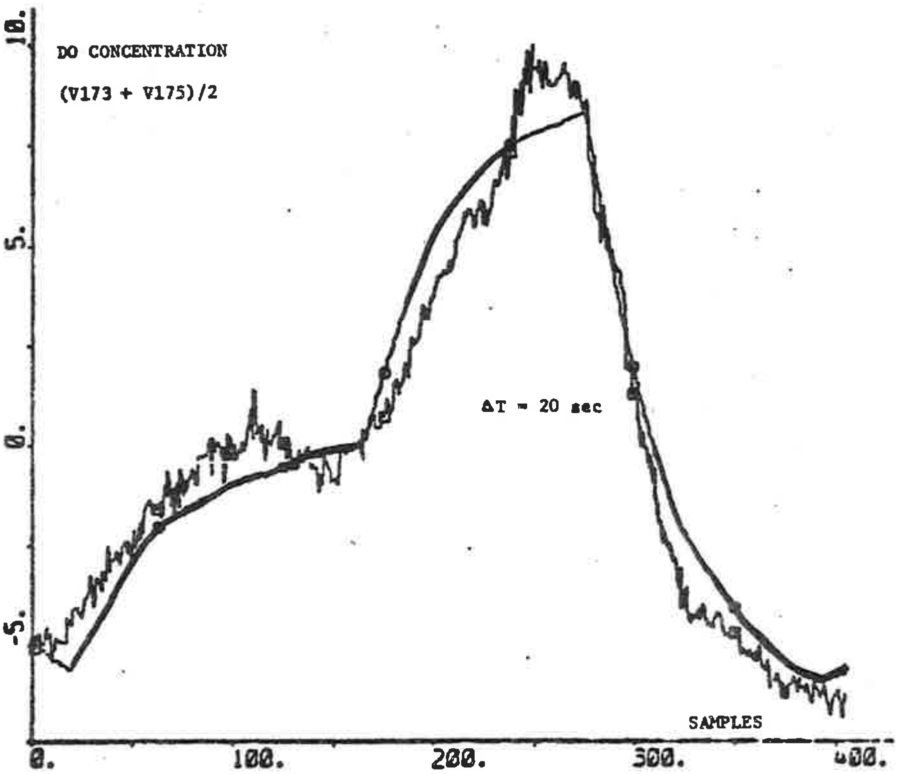

Fig. 11.16. Experiment 741126, part B. Comparison between model output and experimental data. The signal is the average value of the DO concentrations V173 and V175. The model is of first order with the air flow rate v21 as input.

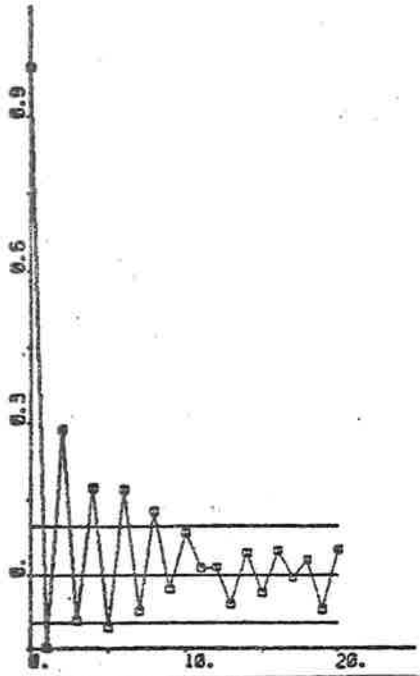

Fig. 11.17. Experiment 741126, part B. Autocovariance of the residuals of a first order model of DO concentration (V173 + V175)/2 with the air flow rate V 21 as input. The straight lines are the 5 % confidence limits.

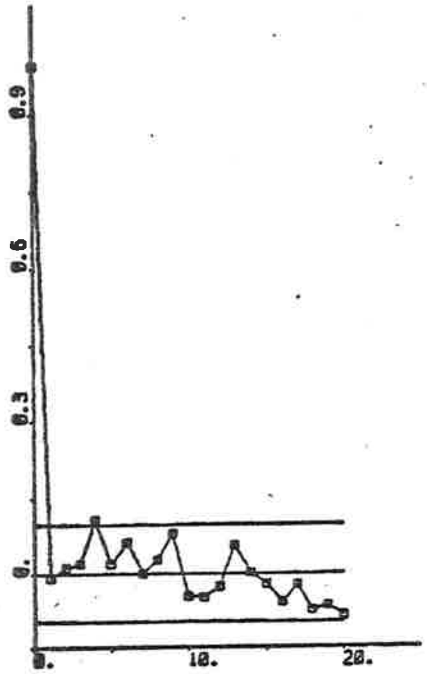

Fig. 11.19. Experiment 741126, part B. Autocovariance of the residuals of the first order model of V 174 with the air flow rate V 21 as input. The straight lines are the 5 % confidence limits.

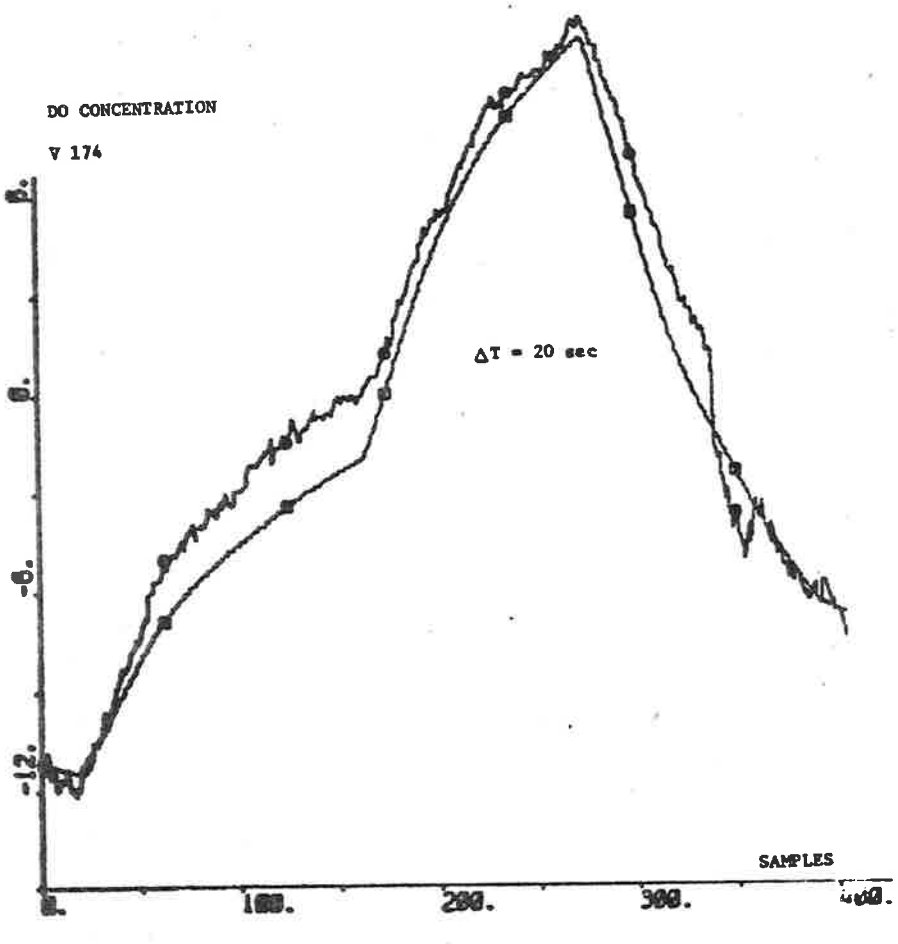

Fig. 11.18. Experiment 741126, part B. Comparison of the model output and experimental data of the DO concentration V 174. The model is of first order with the air flow rate V 21 as input.