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Water Hammer Analysis for NAJAF-KUFA Water Supply Project

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Abstract

Water hammer phenomenon in pipelines represents the complex problems that need a special treatment during network design. The required design for such systems takes into consideration the high pressures generated in pipelines and that may lead to collapse the network.

In this study, a mathematical model has been prepared for Al-Najaf-Al-Kufa united water supply project. The numerical methods such as Newton-Raphson method and Gauss elimination method have been used to solve the non-linear simultaneous equations that governed with the boundary conditions and by using the characteristics method. The partial differential equations had been transformed to ordinary differential equations, by using a computer program.

In this mathematical model, the values of the generated pressures was calculated with or with out control devices or to find the suitable number of control devices required for each pipeline to keep the pressure values within a tolerable limits.

الخلاصـــــــة

تعد ظاهرة الطرق المائي في الأنابيب من الحالات التي تحتاج الى عناية خاصة أثناء تصميم شبكة الأنابيب للموائع المختلفة . لذلك يتطلب عند تصميم تلك المشاريع الاهتمام باحتمالات تولد ضغوط كبيرة في الأنابيب الناقلة مما يؤدي إلى الاضرار بالشبكة خلال الحالة الانتقالية (Transient State) وما يترتب عليه عند تشغيل المنظومة .

في هذا البحث تم إعداد نموذج رياضي خاص لمشروع ماء النجف-الكوفة الموحد وذلك بالاستعانة ببعض الطرق العددية (طريقة نيوتن رافسون وطريقة كاوس للحذف) لحل المعادلات الأنية غير الخطية التي تتحكم بالشروط الحدودية . لقد استخدمت طريقة المعادلات المميزة لتحويل المعادلات التفاضلية الجزئية الى معادلات تفاضلية اعتيادية باعداد برنامج حاسبة لهذا الغرض.

في هذا النموذج الرياضي تم ايجاد قيم الضغوط المتولدة عند استخدام وعدم استخدام أجهزة السيطرة ودراسة تأثيرها على قيم الضغوط وباستخدام العدد المناسب من هذه الأجهزة لكي يمكن المحافظة على هذه القيم ضمن حدودها المسموحة.

1. INTRODUCTION

The intermediate-stage flow, when the flow conditions are changed from steady conditions to another steady state is called transient state flow (water hammer) [6].

Common examples of the cases of transients in engineering system are [3]:

1. Opening or closing of valves in a pipeline.
2. Starting or stopping the pumps in a pumping system.
3. Negative power failure to pumps.
4. Action of reciprocating pumps.
5. Waves on a reservoir surface.

In this study, Al-Najaf-Al-Kufa united water supply project (The Al-Zarqa) was analyzed with respect to power failure to pumps, which represents the worst case for analysis.

The problem of the transient state occurs at the Al-Zerga water supply project which represents more important problem that arises in such systems it the project working under the actual design capability.

2. METHOD OF CHARACTIRESTICS

The method of characteristics is based on the continuity and momentum equations as [3]:

$$L_1 = \frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + RQ|Q| \quad \ldots\ldots (1)$$

$$L_2 = a^2\frac{\partial Q}{\partial x} + gA\frac{\partial H}{\partial t} \quad \ldots\ldots (2)$$

in which R=f / (2DA)

where (Q, t, A, ….) are defined in the list of symbols.

By linear combination of the above equations and some arrangements leads to the following equations:

$$Q_p = C_p - C_a H_p \quad \ldots\ldots (3)$$

$$Q_p = C_n + C_a H_p \quad \ldots\ldots (4)$$

These two equations are valid along the positive (AP) and negative (BP) characteristic lines respectively as shown in Fig.(1).

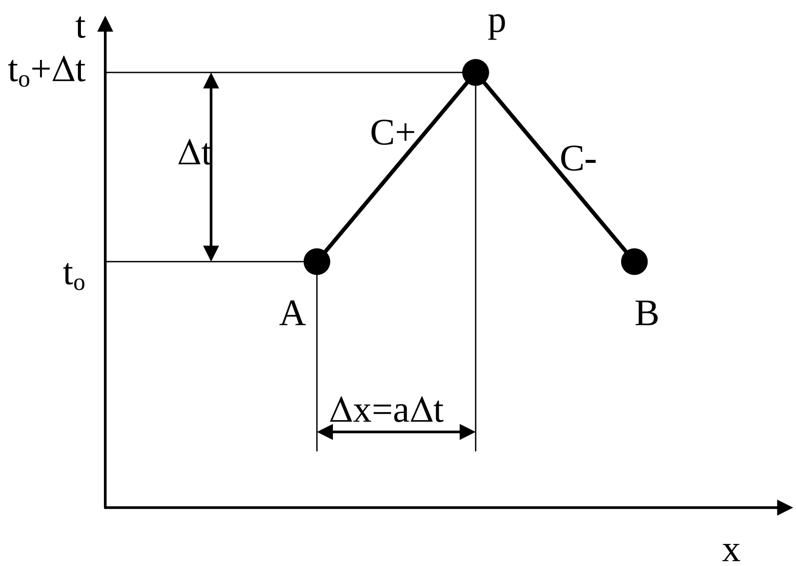

Fig.(1) Characteristic Lines in x-t plane

3. GENERAL DESCRIPTION OF AL-NAJAF-AL-KUFA UNITED WATER SUPPLY PROJECT

The purpose of Al-Zarqa project is to supply treated water to a part of Al-Najaf and Al-Kufa cities. This project was extended at the end of 1994 by constructing a new pump station in the northern part of Al-Najaf city [1] as shown in Fig.(2).

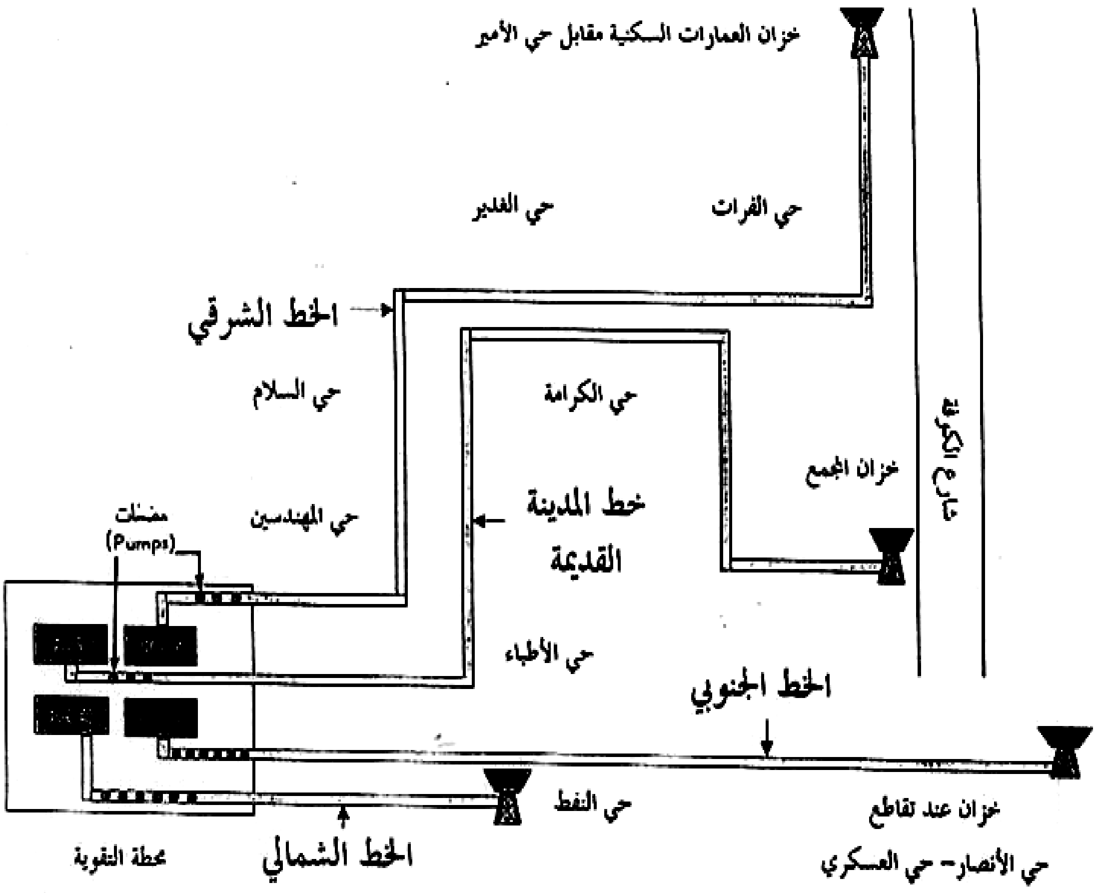

Fig.(2) Plan for the pump station and the main four pipes at Al-Najaf-Al-Kufa united water Supply project

The new project is called Al-Najaf-Al-Kufa united water supply project. This pump station is consisting of the following components:

1. Four ground level storage reservoirs of 9000m^3 capacity each made of reinforced concrete. Each of reservoirs at the station has an inlet controlled by a float valve located above the maximum reservoir water level.
2. Four main groups of pumps delivering the treated water from the above reservoirs to four elevated reservoirs located over the area of Al-Najaf city.
   a) First group consists of (3) pumps and (1) stand by of 1320 m^3/hr. discharge capacity. The treated water is stored in a high reservoir of capacity about $3.41 * 10^6$ liter in the old city.

b) Second group consists of (3) pumps and (1) stand by 1340 m^3/hr. discharge capacity. The treated water is stored in a high reservoir of storage capacity about $2.273*10^6$ liter in the eastern side of Al-Najaf city.

c) Third group consists of (6) pumps and (2) stand by of 134 m^3/hr. discharge capacity. The treated water is stored in a high reservoir of storage capacity about $4.46*10^6$ liter in the southern side of Al-Najaf city.

d) Fourth group consists of (6) pumps and (2) stand by of 990 m^3/hr. discharge capacity. The treated water is stored in a high reservoir of storage capacity about $2.273*10^6$ liter in the northern side of Al-Najaf city.

4. BOUNDARY CONDITIONS FOR POWER FAILURE TO PUMPS

The boundary condition at the new Al-Zarqa water supply project to pumps is a function of speed and discharge of one type of pumps and discharge of air vessel (Q_{av}).

The resulting three non-linear equations relating these variables can be written as [3]:

$$F_1 = Ca(H_{res} - HLv_p^2 + Hr(\alpha_p^2 + v_p^2))(a_1 + a_2 \tan^{-1}(\frac{\alpha_p}{v_p})) + Cn - NppQrv + Qr_p v + NavQ_{pav} \quad \text{............ (5)}$$

$$F_2 = \alpha_p - C_6(\alpha_p^2 + v_p^2)(a_1 + a_2 \tan^{-1}(\frac{\alpha_p}{v_p})) - \alpha - C_6\beta \quad \text{..................... (6)}$$

$$F_3 = ((NppQr_p v - NavQ_{pav} - Cn)/Ca + Hb - Z - 0.5\Delta t(Q_{av} + Qpav)/Ac - HlavQ_{pav}|Q_{pav}|/Q_{sav}^2)(V_{av} - 0.5\Delta t(Q_{av} + Qpav))^{1.2} - C \quad \text{.............. (7)}$$

where the variables are defined in the list of symbols.

These equations are termed the head balance, pump speed change, air vessel operation equations respectively. Since each pump is provided by a non-return valve at its discharge pipe, set v_p=0 in equation F1, the term (α_p / v_p) will be infinity, and that is when $\theta=\tan^{-1}(\alpha_p / v_p)$ equal to 90^o or 270^o depending on the direction of the pump rotation, when the pump rotation is the positive direction $\theta=90^o$ and when in negative direction $\theta=270^o$. Since there is no reverse flow through the pumps due to action of the non-return valve, the pump rotation is always positive and $\theta=90^o$. Therefore, the criteria for positive flow through the pumps may be written as:

$$FLC = Ca(H_{res} + H_r \alpha_p^2 (a_1 + a_2\theta)) + C_n + N_{av} Q_{av} \quad \text{.....................} \quad (8)$$

were the variables are defined in the list of symbols

If FLC greater than zero, positive flow occurs, otherwise the non-return valve is closed and $v_p=0$.

Now, these non-linear equations F1, F2 and F3 are solved by the Newton-Raphson method and Gaussian elimination method [4,8].

A computer program based on quick basic language was developed to solve the transient state by the method of characteristics. See the flow chart for boundary conditions at the new Al-Zarqa water supply project.

5. SCOPE OF THE ANALYSIS

The analysis has the following purposes:

1. To determine the magnitude of maximum and minimum pressure developed during the transient state caused by power failure to pumps without using pressure control devices.
2. To determine the number of pressure control devices needed to keep the transient pressure without specified limits.

The limiting pressure is generally taken as 100 m the result of the transient state analysis will therefore be evaluated in view of the following:

a) Preventing negative transient pressure.
b) Preventing high transient pressure from exceeding a maximum pressure of 100 m that the pipe can withstand.

6. THE RESULTS

Results were obtained using the system data, steady state, discharge, head, friction factors, pumps and air vessel characteristics, a time increment of 0.25 second is chosen, for all cases, it is assumed first that no pressure controls are installed and that water level in the main reservoir at the minimum operation level. The following Tables and Figures from Fig.(3) to (14) show the transient analysis for the pipeline with and without air vessels. The analysis with two air vessels for old city, Eastern and southern pipelines and one air vessel for northern pipeline is very suitable to keep the transient pressure within tolerable limits.

7. CONCLUSIONS

Under the limitations imposed on this investigation the following conclusions can be drawn:

1. The values of maximum and minimum pressure head for the case transient analysis for the old city pipeline with out air vessels are exceed the tolerable limits.
2. when the discharge varied between negative and positive is harmonize with negative and negative pressure which is lead to decrease the maximum pressure and increase the minimum pressure in case with air vessels for old city pipe line.
3. For the eastern pipe line in case without air vessels the both values of minimum and maximum pressure head are exceeding the limits while with air vessels the values are accepted because they are not exceeding the tolerance limits.
4. In case of without air vessels for southern pipe line, the values of maximum and minimum pressure head exceed the tolerable limits, while in case with air vessels accepted results comparing with the tolerable results.
5. The variation of pressure head of the northern pipe line is very rapid in case of without air vessel, while by using one air vessel the results are considered very prefect because they are far-of from the tolerance limits.
6. The size of the common time increment is indicated by the stability condition requirements and wave speed of each pipe. The suitable time increment computer for each pipe was 0.25 second.
7. Many values of head loss through the vessel out let were assumed to give the desirable limits for pressure head and minimum number used of control devices at the same time.

8. REFERENCES

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NOTATIONS

The Following symbols are used in this paper:

A	Cross-section area of pipe.
Ac	Cross-section area of air vessel.
Av	Area of valve opening.
A	Speed of pressure wave.
Ca	Pipe line constant in characteristic equation.
Cd	Discharge coefficient of a valve.
Cn, Cp	Constant in characteristic equation.
C+, C-	Designations of the positive and negative characteristic lines.
D	Pipe diameter.
E	Young's modulus of elasticity.
e	Pipe wall thickness.
ē	Pipe roughness.
f	Darcy-Weisbach friction factor.
g	Gravitational acceleration.
H	Steady state head; Dimensionless pump head.
HL	Head loss through suction and discharge pipes of a pump.
Hl_{av}	Head loss through air vessel outlet.
Hp	Head loss at unknown computational point at x-t plane.
Hr	Rated heads at a pump.
I	Polar moment of inertia of rotating elements.
i	Index denoting section numbering along a pipe.
K	Bulk modulus of elasticity.
k	Minor losses coefficient.
L	Pipe length.
mld	Million liter per day.
N	Number of pipe reaches.
N_{av}	Number of air vessels.
Npp	Number of parallel pumps.
Nr	Rated pumps speed.
P	Solution point in x-t plane; pressure.
Q_{av}	Air vessel discharge.
Q_o	Steady state discharge.

Qr	Rated pump discharge.
R	Reynolds number.
r	Pipe radius.
T	Steady state pump torque.
Tr	Rated pump torque.
TDH	Total dynamic head.
T_{th}	Theoretical period of vibration of a system.
t	time.
v	Mean velocity; dimensionless pump discharge.
V	Volume of air at top of air vessel.
X	Distance along pipeline.
Z	Elevation above the datum.
α	Dimensionless pump speed.
γ	Specific weight of fluid.
β	Dimensionless pump torque.
λ	Multiplier in characteristic method.
ρ	Mass density.
σ	Shear stress.
ϕ	Non-dimensional parameter depending upon the elastic properties of pipe.
ψ	Permissible variation in the pressure wave speed.

Table (1) Results of Analysis without using Air Vessels

Pipe Name	Maximum Pressure (m)	Section No.	Time (s)	Minimum Pressure (m)	Section No.	Time (s)
Old City	118	1	23	-27	1	15
Eastern	114	1	25	-20	1	17
Southern	121	1	32	-26	1	21
Northern	105	1	220	-11.2	1	222

Table (2) Results of Analysis by using Air Vessels

Pipe Name	Maximum Pressure (m)	Section No.	Time (s)	Minimum Pressure (m)	Section No.	Time (s)
Old City	57.6	3	21	24.65	2	13
Eastern	85.5	9	14	25.22	2	25
Southern	63.25	1	18	24.6	2	10
Northern	52.62	2	32	37.72	1	3

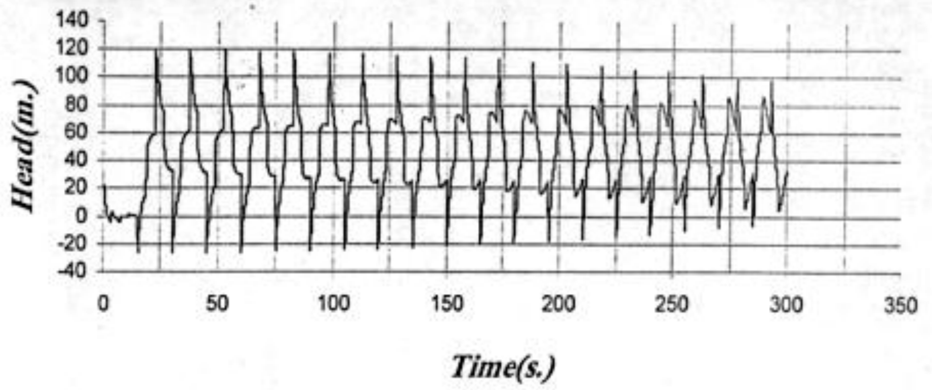


Figure (3): Transient State Analysis for Old City Pipeline Without Using Air Vessels

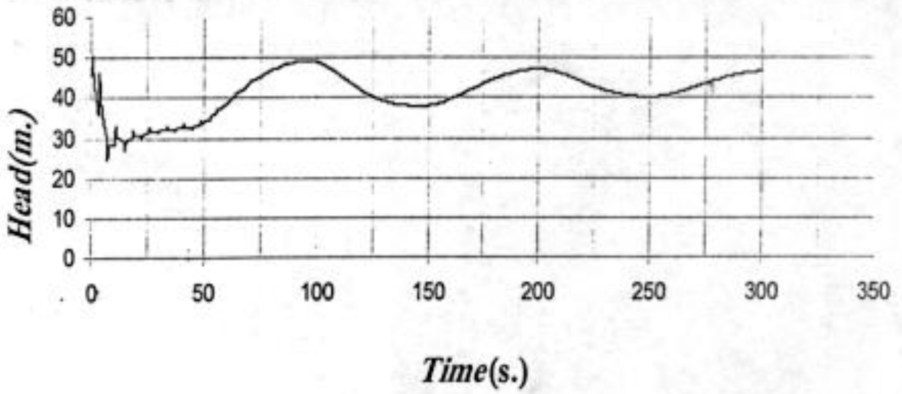


Figure (4): Transient State Analysis for Old City Pipeline Using (2) Air Vessels

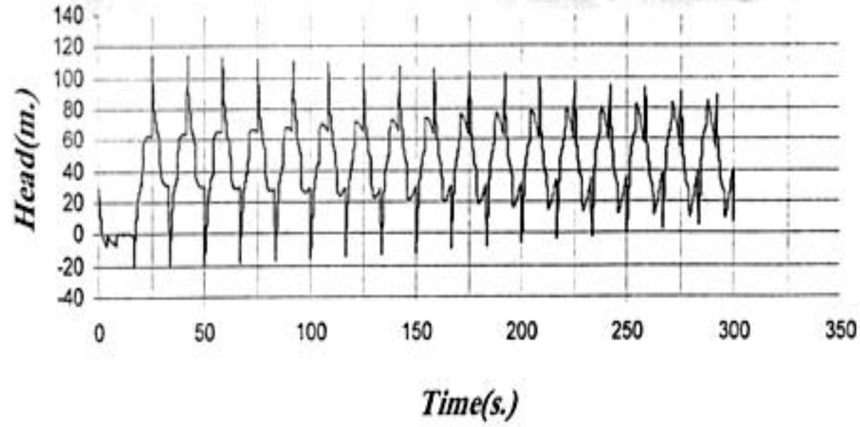


Figure (5): Transient State Analysis for Eastern Pipeline without Using Air Vessels

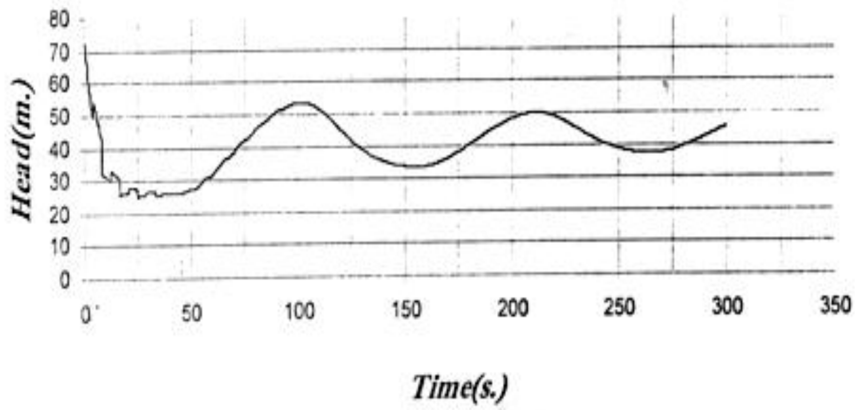


Figure (6): Transient State Analysis for Eastern Pipeline Using (2) Air Vessels

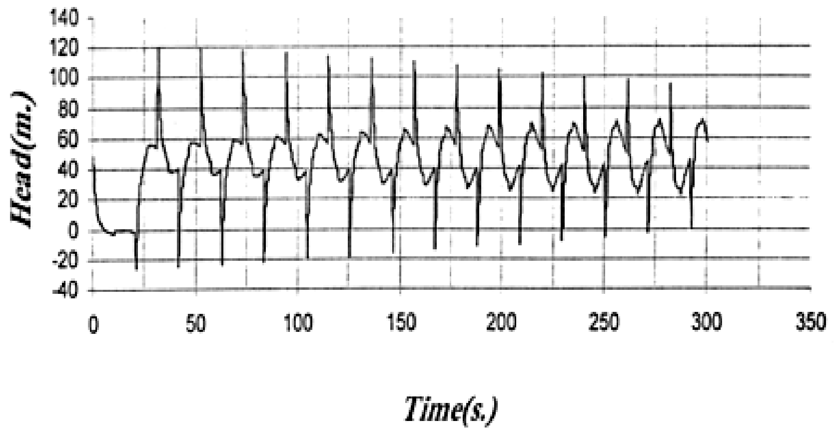


Figure (7): Transient State Analysis for Southern Pipeline without Using Air Vessels

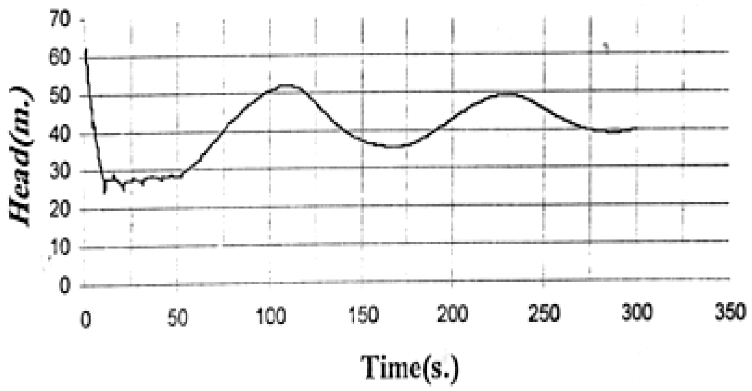


Figure (8): Transient State Analysis for Southern Pipeline Using (2) Air Vessels

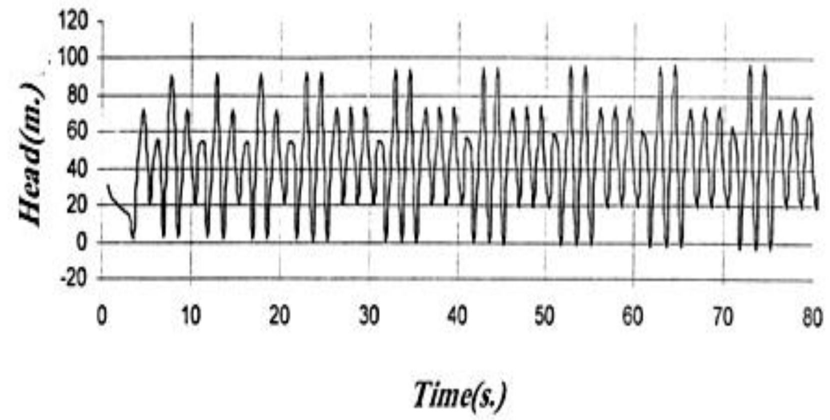


Figure (9): Transient State Analysis for Northern Pipeline without Using Air Vessels

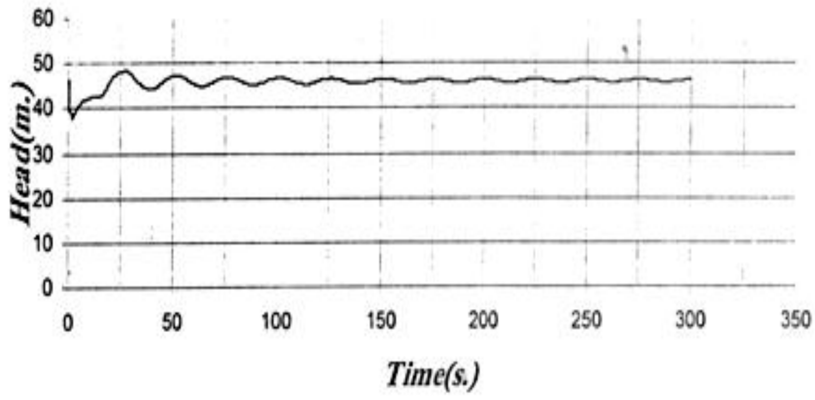


Figure (10): Transient State Analysis for Northern Pipeline Using (1) Air Vessel

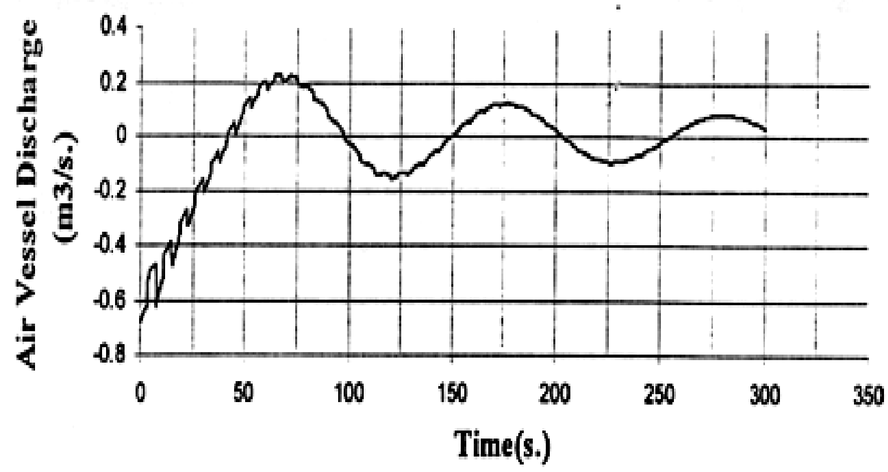


Figure (11): Variation of Air Vessel Discharge with Time for Old City Pipeline

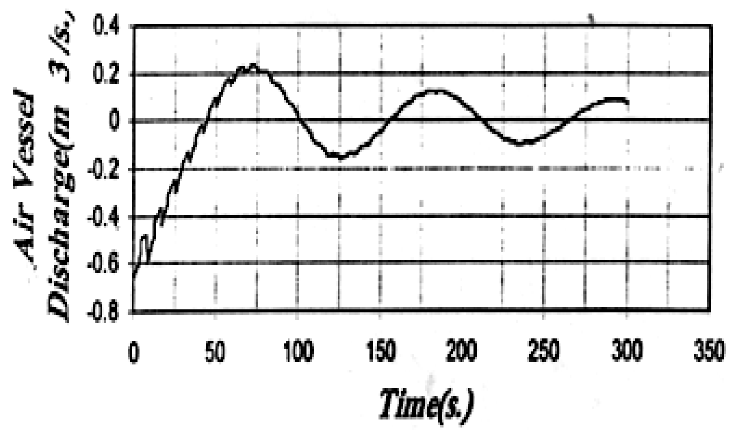


Figure (12): Variation of Air Vessel Discharge with Time for Eastern Pipeline

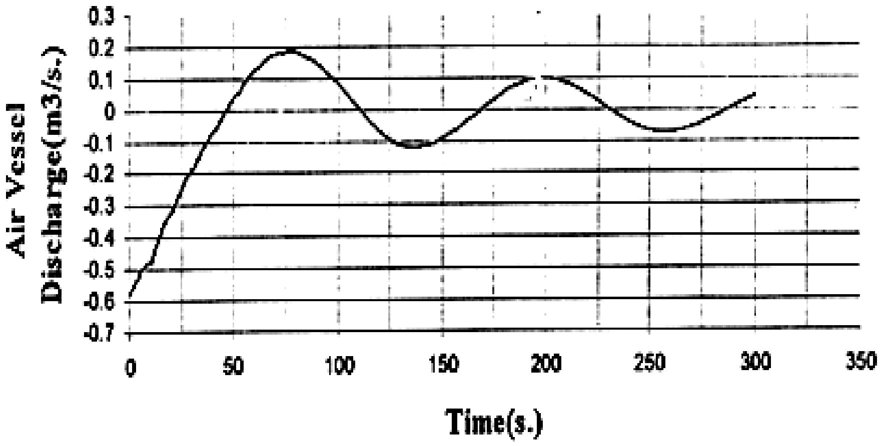


Figure (13): Variation of Air Vessel Discharge with Time for Southern Pipeline

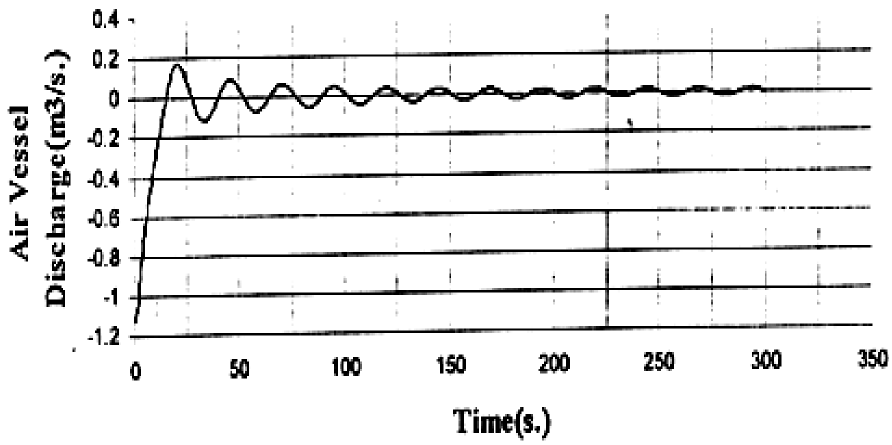
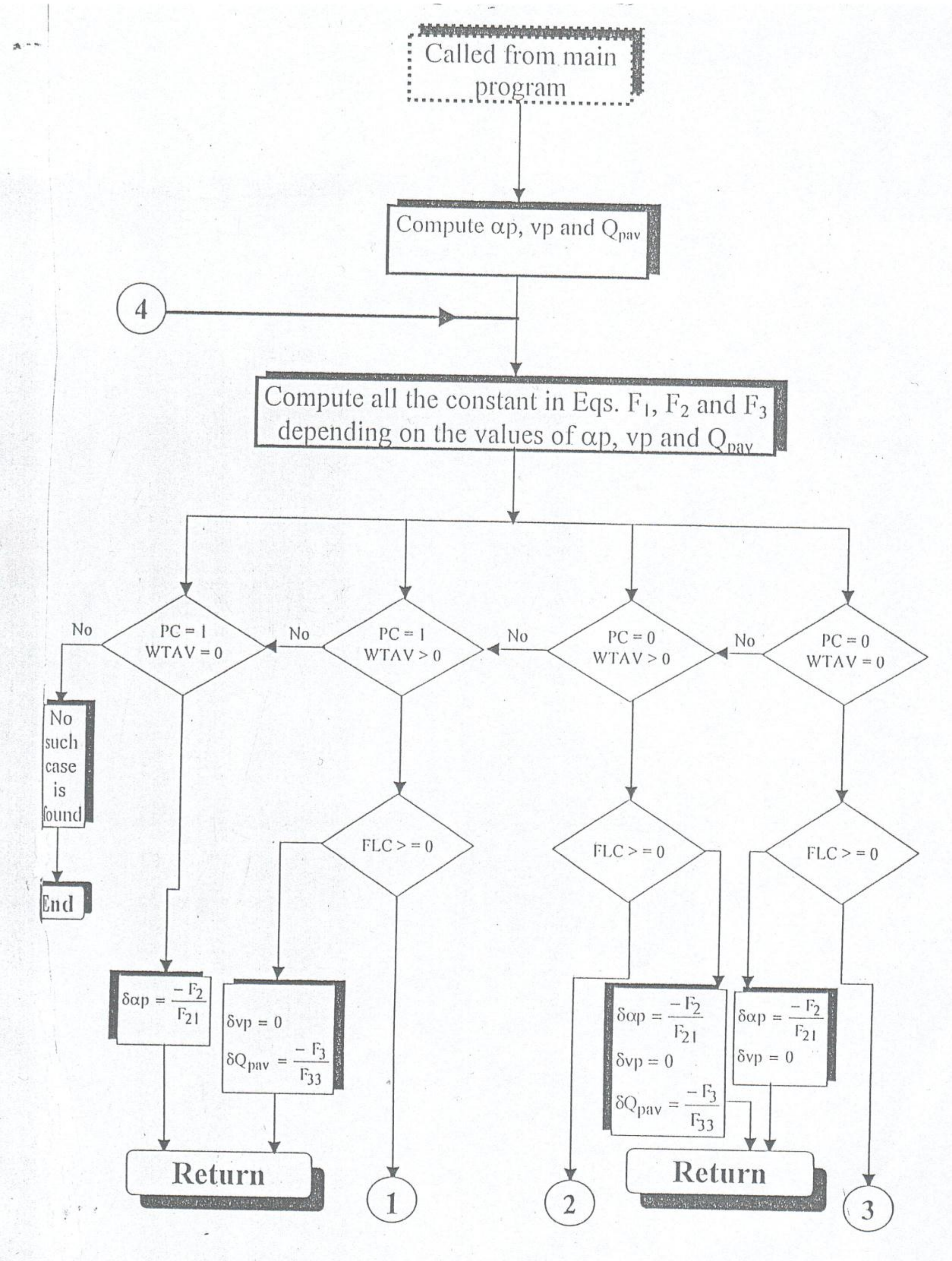
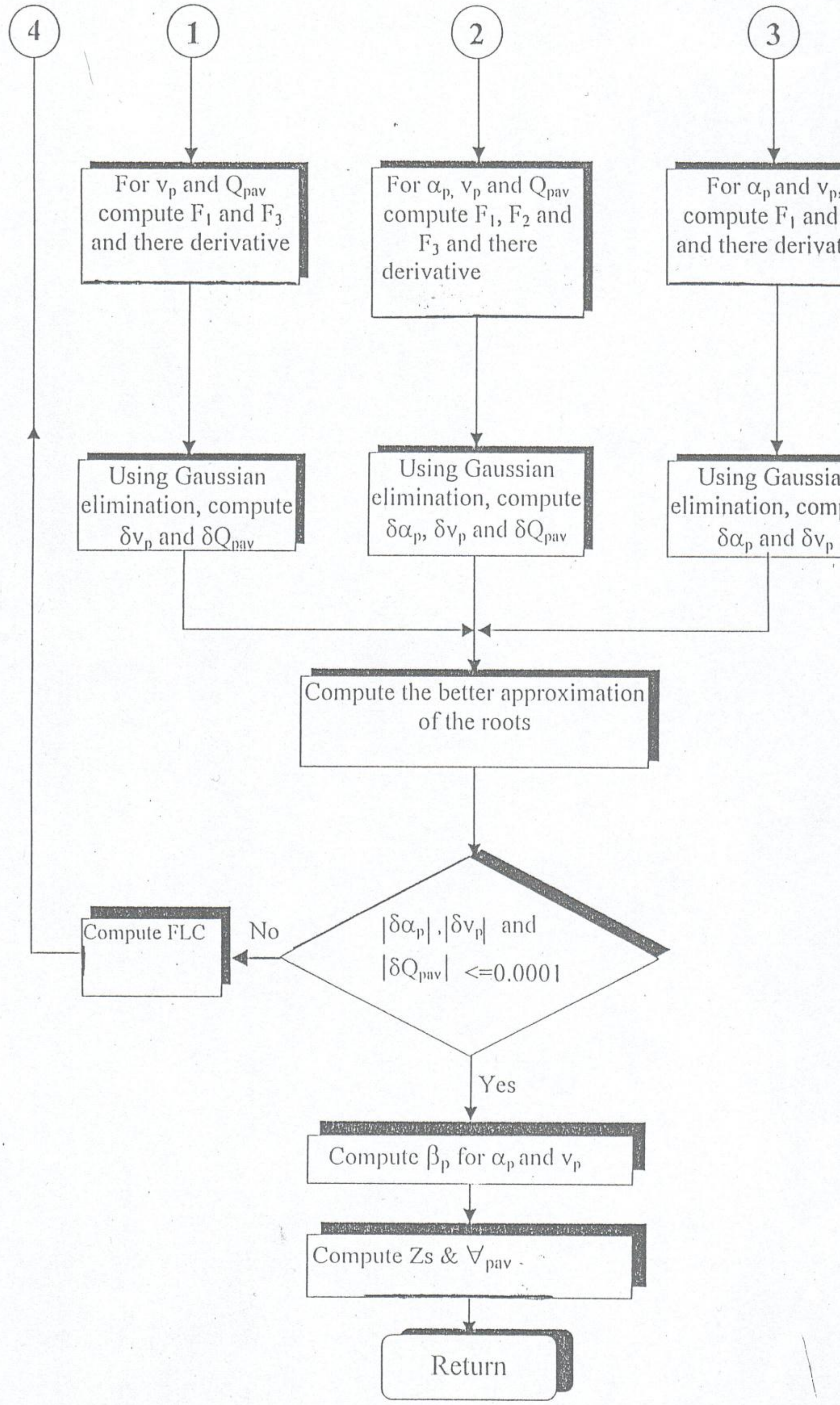


Figure (14): Variation of Air Vessel Discharge with Time for Northern Pipeline

APPENDIX A


Called from main program
Compute αp, vp and Qpav
4
Compute all the constant in Eqs. F1, F2 and F3 depending on the values of αp, vp and Qpav
PC = 1 WTAV = 0
PC = 1 WTAV > 0
PC = 0 WTAV > 0
PC = 0 WTAV = 0
No
No
No
No
No such case is found
End
FLC > = 0
FLC > = 0
FLC > = 0
δαp = −F2/F21
δvp = 0
δQpav = −F3/F33
δαp = −F2/F21
δvp = 0
δQpav = −F3/F33
δαp = −F2/F21
δvp = 0
Return
1
2
Return
3


4
1
2
3
For v_p and Q_{pav} compute F_1 and F_3 and there derivative
For α_p, v_p and Q_{pav} compute F_1, F_2 and F_3 and there derivative
For α_p and v_p, compute F_1 and F_2 and there derivative
Using Gaussian elimination, compute δv_p and δQ_{pav}
Using Gaussian elimination, compute $\delta\alpha_p$, δv_p and δQ_{pav}
Using Gaussian elimination, compute $\delta\alpha_p$ and δv_p
Compute the better approximation of the roots
$|\delta\alpha_p|$, $|\delta v_p|$ and $|\delta Q_{pav}|$ <=0.0001
No
Compute FLC
Yes
Compute β_p for α_p and v_p
Compute Zs & $\forall_{pav}$
Return