Republic of Iraq,

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& Scientific Research ,

University of Babylon.

A Modeling Study of Oscillating Flow in Pressurized Piping System

A Thesis

Submitted to the College of Engineering of the University of Babylon in Partial Fulfillment of the Requirements for the Degree of Master Science

in

Mechanical Engineering

By

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(B.Sc. Mech. Eng.)

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بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

((وَقلْ رَّبِ زِدْنِي عِلْمَا))

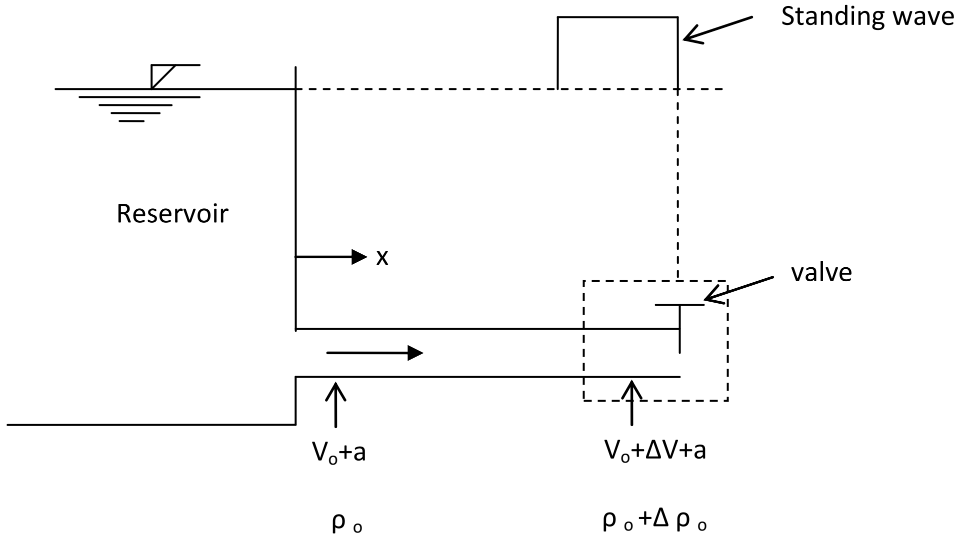
صدق الله العظيم

سورة طه – الآية ١١٤

APPENDIX II

DERIVATION OF EQ. (٣.٧)

Let's consider the piping system shown in Figure below and assume that the distance (x) and velocity (v) as positive in the downstream direction, [Ref.١]



Piping system

In which:

a = wave speed (m/s)

V_o = steady-state velocity (m/s)

ρ_o = fluid density steady-state (kg/$m^{٣}$)

P_o = steady –state pressure

ΔV =change in velocity during the time

$\Delta \rho$ =change in fluid density during the time

ΔP =change in pressure during the time

Then the rate of change of momentum in the positive x-direction is:

$= \rho_o(V_o+a)A[(V_o+ \Delta V+a)-(V_o+a)]$ ....(II.١)

$= \rho_o(V_o+a)A \, \Delta V$ ....(II.٢)

Neglecting friction, the resultant force, F, acting on the fluid segment in the positive x- direction is:

$P_oA-(P_o+ \Delta P)A$,i.e,

$F=- \Delta PA$ .... (II.٣)

According to Newton's law of motion, the time rate of change of momentum is equal to the resultant force. Hence, it follows from Eq. (II.٢) and Eq. (II.٣) that

$$\Delta P = -\rho_o(V_o+a)\,\Delta V \quad \text{...} (II.٤)$$

The value of (V_o) is very small as compared to (a) and may be neglected. Also since

$$\Delta P = \rho g\,\Delta H \quad \text{...} (II.٥)$$

in which (H) is the piezometric head, (g) is gravity acceleration.

Eq. (II.٤) may be written as :

$$\Delta P = -\rho_o\, a\,\Delta V \quad \text{...} (II.٦)$$

Or

$$\Delta H = -\frac{a}{g}\Delta V \quad \text{...} (II.٧)$$

The negative sign on the right-hand side of Eq. (II.٧) indicates that the pressure increases (i.e., ΔH is positive) for a reduction in velocity (i.e., for negative ΔV).

Proceeding similarity, it can be proved that, if the velocity was changed at the upstream end and the wave was moving in the downstream direction.

$$\Delta H = \frac{a}{g}\Delta V \quad \text{...} (II.۸)$$

APPENDIX III

''PROGRAM FOR ANALYSIS OF RESONACE IN PRESSURIZED PIPING SYSTEM, DONE By ABDUL-KAREEM M. JASSIM

```
Option Explicit

Dim L١, L٢, L٣, D١, D٢, D٣, A١, A٢, A٣ As Single

Dim Qo, Ho, wth, Tth, k, Tau, wr, w, b١, b٢, b٣ As Single

Dim ar١, ar٢, ar٣, c١, c٢, c٣ As Single

Dim f١r(١٠, ١٠), f٢r(١٠, ١٠), f٣r(١٠, ١٠) As Single

Dim f١i(١٠, ١٠), f٢i(١٠, ١٠), f٣i(١٠, ١٠) As Single

Dim pr(١٠, ١٠), pi(١٠, ١٠) As Single

Dim f٢pr(١٠, ١٠), f٢pi(١٠, ١٠), fur(١٠, ١٠), fui(١٠, ١٠) As Single

Dim q١rr, q١ri, q٣lr, q٣li, h٣lr, h٣li, hr, qr As Single

Dim qar, qai, qbr, qbi As Single

Dim w١, wn, dw As Single

Dim alpha, beta, cas As Single



Private Sub Command١_Click()

Dim i As Integer, j As Integer, m As Integer, y As Integer

Dim z١, z٢, hp, qp, hrp, expand As Single

Dim hr١, hi١, hr٢, hi٢, hr٣, hi٣, hrr As Single


w١ = Val(Text١٤): wn = Val(Text١٥)

'ReDim res((wn - w١) / Val(Text١٦) + ١, ٣) As Single
```

```
L١ = Val(Text١): D١ = Val(Text٢): A١ = Val(Text٣)

L٢ = Val(Text٤): D٢ = Val(Text٥): A٢ = Val(Text٦)

L٣ = Val(Text٧): D٣ = Val(Text٨): A٣ = Val(Text٩)


Qo = Val(Text١٠): Ho = Val(Text١١): k = Val(Text١٢): Tau = Val(Text١٣)

dw = Val(Text١٦): expand = Val(Text١٧)

Tth = (L١ / A١ + L٢ / A٢) * ٤

wth = (٤٤ / ٧) / Tth


alpha = Val(Text١٨): beta = Val(Text١٩)


If Check٢.Value = ١ Then

Open "C:\data\wr.txt" For Output As #١

Open "C:\data\h١.txt" For Output As #٢

Open "C:\data\q١.txt" For Output As #٣

Open "C:\data\h٢.txt" For Output As #٤

Open "C:\data\q٢.txt" For Output As #٥

Open "C:\data\hrr١.txt" For Output As #٦

Open "C:\data\hrr٢.txt" For Output As #٧

End If


ar١ = ٠.٧٨٥٤ * D١ ^ ٢: ar٢ = ٠.٧٨٥٤ * D٢ ^ ٢: ar٣ = ٠.٧٨٥٤ * D٣ ^ ٢

For cas = ١ To ٢

If cas = ١ Then

  ' case ١: time is aproched to zero

b١ = (L١ * (alpha ^ ٢ + beta ^ ٢) ^ ٠.٥) / (A١ * ٢ ^ ٠.٥)

b٢ = (L٢ * (alpha ^ ٢ + beta ^ ٢) ^ ٠.٥) / (A٢ * ٢ ^ ٠.٥)
```

```
b٣ = (L٣ * (alpha ^ ٢ + beta ^ ٢) ^ ٠.٥) / (A٣ * ٢ ^ ٠.٥)

Else

  ' case ٢: time is aproched to infinity

b١ = (L١ * beta) / A١

b٢ = (L٢ * beta) / A٢

b٣ = (L٣ * beta) / A٣

c١ = A١ / (٩.٨١ * ar١): c٢ = A٢ / (٩.٨١ * ar٢): c٣ = A٣ / (٩.٨١ * ar٣)

End If



For wr = w١ To wn Step dw

w = (wr * wth) * expand



For i = ١ To ١٠

For j = ١ To ١٠

f١r(i, j) = ٠: f١i(i, j) = ٠

f٢r(i, j) = ٠: f٢i(i, j) = ٠

f٣r(i, j) = ٠: f٣i(i, j) = ٠

pr(i, j) = ٠: pi(i, j) = ٠

f٢pr(i, j) = ٠: f٢pi(i, j) = ٠

fur(i, j) = ٠: fui(i, j) = ٠

Next j

Next i


' -----------F١ calculations-----------

f١r(١, ١) = Cos(b١ * w)

f١r(٢, ٢) = f١r(١, ١)
```

```
f١i(١, ٢) = -Sin(b١ * w) / c١

f١i(٢, ١) = -Sin(b١ * w) * c١


List١.AddItem f١r(١, ١) & " +j" & f١i(١, ١) & "    " & f١r(١, ٢) & " +j" & f١i(١, ٢)

List١.AddItem f١r(٢, ١) & " +j" & f١i(٢, ١) & "    " & f١r(٢, ٢) & " +j" & f١i(٢, ٢)


' -----------F٢ calculations-----------

f٢r(١, ١) = Cos(b٢ * w)

f٢r(٢, ٢) = f٢r(١, ١)

f٢i(١, ٢) = -Sin(b٢ * w) / c٢

f٢i(٢, ١) = -Sin(b٢ * w) * c٢


List١.AddItem "  "

List١.AddItem f٢r(١, ١) & " +j" & f٢i(١, ١) & "    " & f٢r(١, ٢) & " +j" & f٢i(١, ٢)

List١.AddItem f٢r(٢, ١) & " +j" & f٢i(٢, ١) & "    " & f٢r(٢, ٢) & " +j" & f٢i(٢, ٢)


' -----------F٣ calculations-----------

f٣r(١, ١) = Cos(b٣ * w)

f٣r(٢, ٢) = f٣r(١, ١)

f٣i(١, ٢) = -Sin(b٣ * w) / c٣

f٣i(٢, ١) = -Sin(b٣ * w) * c٣


List١.AddItem "  "

List١.AddItem f٣r(١, ١) & & "    " & f٣r(١, ٢) & " +j" & f٣i(١, ٢)

List١.AddItem f٣r(٢, ١) & " +j" & f٣i(٢, ١) & "    " & f٣r(٢, ٢) & " +j" & f٣i(٢, ٢)


pr(١, ١) = ١: pi(١, ٢) = f٣i(١, ٢) / f٣r(١, ١): pr(٢, ٢) = ١

'pi(١, ٢) = ٠ ' ************** MEANS THE BRANCH IS EXIST  *********************
```

```
List١.AddItem "  "

List١.AddItem pr(١, ١) & " +j" & pi(١, ١) & "    " & pr(١, ٢) & " +j" & pi(١, ٢)

List١.AddItem pr(٢, ١) & " +j" & pi(٢, ١) & "    " & pr(٢, ٢) & " +j" & pi(٢, ٢)


'*********************** CALCULATION OF F٢ MATRIX  *  P  MATRIX ******************************

For i = ١ To ١٠

For j = ١ To ١٠


For m = ١ To ١٠

f٢pr(i, j) = f٢pr(i, j) + f٢r(i, m) * pr(m, j) - f٢i(i, m) * pi(m, j)

f٢pi(i, j) = f٢pi(i, j) + pi(m, j) + f٢i(i, m) * pr(m, j)

Next m


Next j

Next i


List١.AddItem "  "

List١.AddItem f٢pr(١, ١) & " +j" & f٢pi(١, ١) & "    " & f٢pr(١, ٢) & " +j" & f٢pi(١, ٢)

List١.AddItem f٢pr(٢, ١) & " +j" & f٢pi(٢, ١) & "    " & f٢pr(٢, ٢) & " +j" & f٢pi(٢, ٢)


'*********************** CALCULATION OF TRNSFER  MATRIX  **************************


For i = ١ To ١٠

For j = ١ To ١٠


For m = ١ To ١٠
```

```
fur(i, j) = fur(i, j) + f٢pr(i, m) * f١r(m, j) - f٢pi(i, m) * f١i(m, j)

fui(i, j) = fui(i, j) + f٢pr(i, m) * f١i(m, j) + f٢pi(i, m) * f١r(m, j)

Next m


Next j

Next i

fur(٣, ٣) = ١


List١.AddItem "  "

List١.AddItem fur(١, ١) & " +j" & fui(١, ١) & "    " & fur(١, ٢) & " +j" & fui(١, ٢)

List١.AddItem fur(٢, ١) & " +j" & fui(٢, ١) & "    " & fur(٢, ٢) & " +j" & fui(٢, ٢)


'list١.AddItem "  "

'list١.AddItem " Ho= " & Ho & " Qo= " & Qo & " k= " & k & " Tau= " & Tau


qar = fur(٢, ٣) - ٢ * (Ho / Qo) * fur(١, ٣) + (٢ * Ho * k / Tau) * fur(٣, ٣)

qai = fui(٢, ٣) - ٢ * (Ho / Qo) * fui(١, ٣) + (٢ * Ho * k / Tau) * fui(٣, ٣)

qbr = fur(٢, ١) - (٢ * Ho / Qo) * fur(١, ١) + (٢ * Ho * k / Tau) * fur(١, ٣)

qbi = fui(٢, ١) - (٢ * Ho / Qo) * fui(١, ١) + (٢ * Ho * k / Tau) * fui(١, ٣)

q١rr = -(qar * qbr + qai * qbi) / (qbr ^ ٢ + qbi ^ ٢)

q١ri = -(qai * qbr - qar * qbi) / (qbr ^ ٢ + qbi ^ ٢)


  List١.AddItem "  "

  List١.AddItem q١rr & " +j" & q١ri


q٣lr = fur(١, ١) * q١rr - fui(١, ١) * q١ri + fur(١, ٣)

q٣li = fur(١, ١) * q١ri + fui(١, ١) * q١rr + fui(١, ٣)

  List١.AddItem "  "
```

```
  List١.AddItem "q٣l=  " & q٣lr & " +j" & q٣li



h٣lr = fur(٢, ١) * q١rr - fui(٢, ١) * q١ri + fur(٢, ٣)
h٣li = fur(٢, ١) * q١ri + fui(٢, ١) * q١rr + fui(٢, ٣)
  List١.AddItem "  "
  List١.AddItem "h٣l=  " & h٣lr & " +j" & h٣li

'**********THE END RESULTS *********************


hr = ٢ * ((h٣lr ^ ٢ + h٣li ^ ٢) ^ ٠.٥) / Ho
qr = ٢ * ((q٣lr ^ ٢ + q٣li ^ ٢) ^ ٠.٥) / Qo
hr = Round(hr, ٤)
qr = Round(qr, ٤)
wr = Round(wr, ٥)
  List١.AddItem "  "
  List١.AddItem "hr=  " & hr & "qr = " & qr


If cas = ١ Then
List٢.AddItem wr & "        " & hr & "       " & qr
If Check٢.Value = ١ Then Write #١, wr: Write #٢, hr: Write #٣, qr

Else
List٤.AddItem wr & "        " & hr & "       " & qr
If Check٢.Value = ١ Then Write #٤, hr: Write #٥, qr
```

```
End If

hr١ = fur(١, ٢) * fur(٢, ١) - fui(١, ٢) * fui(٢, ١)

hi١ = fur(١, ٢) * fui(٢, ١) + fui(١, ٢) * fur(٢, ١)

hr٢ = (hr١ * fur(١, ١) + hi١ * fui(١, ١)) / (fur(١, ١) ^ ٢ + fui(١, ١) ^ ٢)

hi٢ = (hi١ * fur(١, ١) - hr١ * fui(١, ١)) / (fur(١, ١) ^ ٢ + fui(١, ١) ^ ٢)

hr٣ = fur(٢, ٢) - hr٢

hi٣ = fui(٢, ٢) - hi٢

hrr = (hr٣ ^ ٢ + hi٣ ^ ٢) ^ ٠.٥

If cas = ١ Then

List٣.AddItem wr & "        " & hrr

If Check٢.Value = ١ Then Write #٦, hrr

Else

List٥.AddItem wr & "        " & hrr

If Check٢.Value = ١ Then Write #٧, hrr

End If

'*****************  DRAWING  GRAPHS  BETWEEN  (W) AND THE hrr
*******************************

If wr = w١ Then hp = hr: hrp = hrr: qp = qr: z١ = wr: GoTo ١٠

If cas = ١ Then
```

```
Form٥.P١.Line ((wr - z١) * ١٠ + ١٠, ١٠٠ - ٥ * hrr)-((wr - dw - z١) * ١٠ + ١٠, ١٠٠ - ٥ * hrp), vbRed

Else

Form٥.P١.Line ((wr - z١) * ١٠ + ١٢٠, ١٠٠ - ٥ * hrr)-((wr - dw - z١) * ١٠ + ١٢٠, ١٠٠ - ٥ * hrp), vbRed

End If


'*****************  DRAWING  GRAPHS  BETWEEN  (Wr) AND THE (qr)  ,  (hr )
********************************


If cas = ١ Then

Form٣.P١.Line ((wr - z١) * ١٠ + ١٠, ١٠٠ - ١٠٠ * hr)-((wr - dw - z١) * ١٠ + ١٠, ١٠٠ - ١٠٠ * hp), vbRed

'Form٣.P١.Line.DrawStyle = ٣'

Form٣.P١.Line ((wr - z١) * ١٠ + ١٠, ١٠٠ - ١٠٠ * qr)-((wr - dw - z١) * ١٠ + ١٠, ١٠٠ - ١٠٠ * qp), vbBlue

Else

Form٣.P١.Line ((wr - z١) * ١٠ + ١٢٠, ١٠٠ - ١٠٠ * hr)-((wr - dw - z١) * ١٠ + ١٢٠, ١٠٠ - ١٠٠ * hp), vbRed

Form٣.P١.Line ((wr - z١) * ١٠ + ١٢٠, ١٠٠ - ١٠٠ * qr)-((wr - dw - z١) * ١٠ + ١٢٠, ١٠٠ - ١٠٠ * qp),
vbBlue

End If


'*****************  DRAWING  GRAPHS  BETWEEN   (qr)  &  (hr ) ******************

١٠

Form٤.P١.Line (٢٠٠ * qr + ١٠, ١٠٠ - ١٠٠ * hr)-(٢٠٠ * qp + ١٠, ١٠٠ - ١٠٠ * hp), vbRed


hp = hr: qp = qr: hrp = hrr


DoEvents

Next wr

Next cas
```

```
If Check٢.Value = ١ Then
Close #١
Close #٢
Close #٣
Close #٤
Close #٥
Close #٦
Close #٧
End If
End Sub

Private Sub Command٢_Click()
Form٢.Visible = True
End Sub

Private Sub Command٣_Click()
Form٢.Visible = False
End Sub

Private Sub Command٤_Click()
Dim i As Integer

Form٣.P١.Line (١٠, ١٠٠)-(١١٠, ١٠٠): Form٣.P١.Line (١٢٠, ١٠٠)-(٢٢٠, ١٠٠)
Form٣.P١.Line (١٠, ١٠)-(١٠, ١٠٠)

Form٣.P١.Line (١٢٠, ١٠)-(١٢٠, ١٠٠)
```

```
For i = ١ To ٢١
If i <> ١١ Then
Form٣.P١.Line (i * ١٠ + ٥, ١٠٠)-(i * ١٠ + ٥, ١٠٣)
End If
Next i

Form٣.Visible = True
Form٤.Visible = False
Form٥.Visible = False

End Sub

Private Sub Command٥_Click()
List١.Clear
List٢.Clear
List٣.Clear
List٤.Clear
List٥.Clear
Form٣.P١.Cls
Form٤.P١.Cls
Form٥.P١.Cls
End Sub

Private Sub Command٦_Click()
Dim i As Integer

Form٤.P١.Line (١٠, ١٠٠)-(١٤٥, ١٠٠)
Form٤.P١.Line (١٠, ١٠)-(١٠, ١٠٠)
```

```
For i = ١ To ١٠
If i < ٨ Then
Form٤.P١.Line (i * ٢٠ - ١٠, ١٠٠)-(i * ٢٠ - ١٠, ١٠٣)
Form٤.P١.Line (i * ٢٠, ١٠٠)-(i * ٢٠, ١٠١.٥)
End If
Form٤.P١.Line (٨, ١١٠ - i * ١٠)-(١٠, ١١٠ - i * ١٠)
Next i

Form٣.Visible = False
Form٤.Visible = True
Form٥.Visible = False


End Sub

Private Sub Command٧_Click()
Dim i As Integer

Form٥.P١.Line (١٠, ١٠٠)-(١١٠, ١٠٠): Form٥.P١.Line (١٢٠, ١٠٠)-(٢٢٠, ١٠٠)
Form٥.P١.Line (١٠, ١٠)-(١٠, ١٠٠)
Form٥.P١.Line (١٢٠, ١٠)-(١٢٠, ١٠٠)

For i = ١ To ١٠
Form٥.P١.Line (i * ٩.٨ + ٥, ١٠٠)-(i * ٩.٨ + ٥, ١٠٣)
Next i
```

```
For i = ١٢ To ٢١
Form٥.P١.Line (i * ٩.٨ + ٨, ١٠٠)-(i * ٩.٨ + ٨, ١٠٣)
Next i

Form٣.Visible = False
Form٤.Visible = False
Form٥.Visible = True



'Form٣.P١.Line (١٠, ١٠٠)-(١١٠, ١٠٠): Form٣.P١.Line (١٢٠, ١٠٠)-(٢٢٠, ١٠٠)
'Form٣.P١.Line (١٠, ١٠)-(١٠, ١٠٠)

'Form٣.P١.Line (١٢٠, ١٠)-(١٢٠, ١٠٠)


'For i = ١ To ٢١
'If i <> ١١ Then
'Form٣.P١.Line (i * ١٠ + ٥, ١٠٠)-(i * ١٠ + ٥, ١٠٣)
'End If
'Next i

'Form٣.Visible = True
'Form٤.Visible = False
'Form٥.Visible = False

End Sub
```

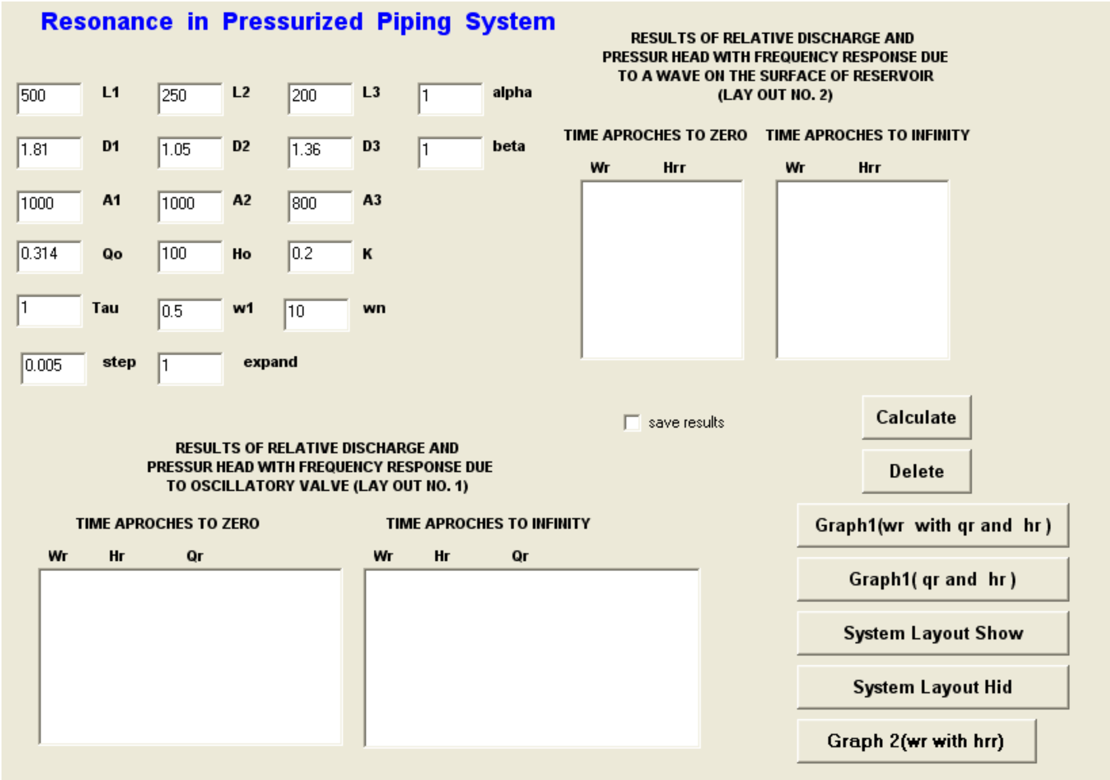
APPENDIX IV

THE PROCEDURE OF

USING SOFTWARE PROGRAM

After running the software program, the user can use the following steps:

- Click on button "System Layout Show" to see the piping system.
- Click on button "System Layout Show" to hide the piping system.
- Enter the required data into text boxes as indicated in front of each of them, (i.e., L١, L٢, L٣, D١, D٢, D٣, …, etc.)
- Click on button "Calculate" which presents the results on list boxes.
- If the user wants to change the data after running, he can click on button "Delete".
- Click on button "Graph١ (w_r with q_r and h_r)" to see the graph of the relationship between w_r with q_r and h_r.
- Click on button "Graph١ (q_r and h_r)" to obtain graph concerning the relationship between q_r and h_r.



Window for Using Program

APPENDIX I

CALCULATION OF WAVE VELOCITY (a)

Halliwell presented the following expression for calculation the wave velocity (a): [Ref. ٢٩] page ٤١

$$a = \sqrt{\frac{k}{\rho[1+(k/E)\psi]}}$$

In which:

ψ = non dimensional parameter depends on the elastic properties of the conduit.

E = Young’s modulus of elasticity of the conduit (Table ١).

K & ρ = The bulk modulus of elasticity and density of the fluid respectively. (Table ٢)

In practice, it was found that the value of wave velocity for steel pipe discharging water is between ٨٠٠ m/s to ١٤٠٠ m/s.

Table ١ : Modulus of elasticity for some materials.

Material	Modulus of elasticity (E)
Alluminum alloys	٦٨-٧٣
Asbestose	٢٤
Brass	٧٨-١١٠
Cast iron	٨٠-١٧٠
Concrete	١٤-٣٠
Copper	١٠٧-١٣١
Glass	٤٦-٧٣
Lead	٤.٨-١٧
Mild steel	٢٠٠-٢١٢
Plastic (PVC)	٢.٤-٢.٧٥

Table ٢ : Bulk Modulus of Elasticity & Density of some liquids.

Liquids	Temperature (^oc)	Density ρ (Kg / m٣)	Bulk Modulus of Elasticity k (Gpa)
Benzene	١٥	٩٩٠	١.٠٥
Ethyl alcohol	٠	٧٩٠	١.٣٢
Glycerin	١٥	١٢٦٠	٤.٤٣
Kerosene	٢٠	٨٠٤	١.٣٢
Oil	١٥	٩٠٠	١.٥
Fresh Water	٢٠	٩٩٩	٢.١٩
Sea Water	١٥	١٠٢٥	٢.٢٧

Abstract

The purpose of this study is to analyze the fluctuations in pressure head and discharge flow resulting from oscillating flow in pressurized piping system.

An oscillating flow in that system depends upon the type of forcing function such as, a periodic motion of closing and opening an oscillating valve, a reciprocating pump, and a pressure head oscillation in the reservoir.

This study will take the first type since it creates a fluctuation in both the pressure head and the discharge flow, while the others create one of them only.

The method used for the analysis here is Transfer Matrix Method (TMM). The studying of oscillating flow in pressurized piping system is of more importance to detect the locations of some problems which may occur in hydraulic pipelines, for example, leaks and blockage.

The analysis will be done by a program using Visual Basic language which introduces a window for entering necessary data to obtain the results of the analysis.

The results obtained from the study indicate that the pipe parameters (length, wave velocity, and the power of the exponent in equation of variation of discharge, pressure, and valve motion) have effectiveness on the shape of the frequency response. On the other hand the other pipe parameters (diameter, reservoir head, and the mean discharge) do not effect on the shape of the oscillating flow. Those results are verified with a pioneer work of Chaudhry [Ref.١].

Finally the program will present graphs to show the shape of the wave of the oscillating flow for some data. In addition, the effects of the system parameters on the frequencies of the oscillating flow will be discussed.

Contents

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List of Symbols

Symbol	Description	Unit
A	Cross-sectional area of pipe	$m^{٢}$
a	Pressure Wave Velocity	m/s
$C_{١}$, $C_{٢}$	Arbitrary constants	-
D	Diameter of pipe	m
f	Coefficient of friction	-
F_i	Field Matrix for i^{th} pipe	-
g	Gravitational acceleration	$m/s^{٢}$
H	Instantaneous Pressure Head	m
h*	Pressure Head Variation from the mean	m
H_o	Mean Pressure Head	m
h_r	Pressure Response	-
j	Imaginary part of complex number $\sqrt{-1}$	-
K	Amplitude of valve motion	-
L	Pipe length	m
P_i	Point matrix	-
Q	Instantaneous Discharge	$m^{٣}/s$
q*	Discharge Deviation from the mean	$m^{٣}/s$
Q_o	Mean Discharge	$m^{٣}/s$
q_r	Discharge Response	-

Symbol	Description	Unit
t	**Time**	**s**
T_{th}	**Theoretical Period**	**s**
U	**Over all transfer matrix**	**-**
V	**Velocity of Flow**	**m/s**
w	**Frequency**	**rad/s**
w_r	**Frequency ratio**	**-**
w_{th}	**Theoretical frequency**	**rad/s**
Z	**State Vector**	**-**
Z_o , Z_∞	**Characteristic impedance for the pipe (t → ٠) , (t →∞) respectively**	$s/m^{٢}$
h_i^R	**Pressure head variation at right side of the grid**	**m**
h_i^L	**Pressure head variation at left side of the grid**	**m**
q_i^R	**Discharge variation at right side of the grid**	**m**
q_i^L	**Discharge variation at left side of the grid**	**m**
$\tilde{U}$	**Over all transfer matrix for branched pipe**	**-**
α	**Power Factor In sinusoidal equations**	**-**
β	**Power Factor In sinusoidal equations**	**-**
τ	**Instantaneous of relative gate valve opening**	**-**
τ^*	**Deviation of the relative gate opening from the mean**	**-**
τ_o	**Mean relative gate opening**	**-**

List of Figures

INTRODUCTION

١-١ Description of Oscillating Flow in Pressurized Piping System

Sometimes when disturbance is introduced into piping system, it is amplified with time instead of decaying and results in severe pressure and flow oscillations. This condition which depends upon the characteristic of the piping system and the excitation is termed *Oscillating Flow*. The oscillating flow phenomenon is caused by forcing function such as the action of an oscillating valve, the reciprocating pump, and the pressure head oscillation in the reservoir. An oscillating valve causes fluctuation in the pressure head and flow, while the reciprocating pump results in fluctuation in flow only but when there is oscillation in reservoir head, the fluctuation will occur in the pressure head in the piping system. The system which has an oscillation valve and constant reservoir level will be discussed in this study.

For more explanation, assuming that there is a piping system having a reservoir at the upstream end and a valve at the downstream end. When the valve is initially in closed position but it will be opened and closed sinusoidally at a specified frequencies starting at a time equal to zero, a beat develops first (transient state) and then the flow and the pressure oscillate at an amplitude with the same frequency. Such a periodic flow is termed steady- oscillatory flow. The characteristics of the steady- oscillatory flow in a hydraulic system may be considered the same as the steady vibrations of the spring-mass system. The displacement of the spring at the fixed end in a spring-mass system is zero. The water level in the upstream reservoir of the hydraulic system is constant. Therefore, the amplitude of the pressure oscillations at the reservoir is zero or in the other words, there is a pressure node at the reservoir. In spring-mass system there is only one mass and one spring; therefore, there is only one mode of vibrations or one degree of freedom and the system has only one natural frequency (or natural period). If the compressibility of the fluid is taken into consideration, the fluid in pipeline of a hydraulic system is comprised of an infinite number of masses and springs; therefore, the hydraulic system which has infinite modes of oscillations or degree of freedom.

Many problems may be occurred in a hydraulic piping system such as leaks, and blockage. In recent researches concerning the subject of the oscillating flow in hydraulics, the researchers were very interested in studying those problems by making use of the analysis of the oscillating flow in pressurized piping system for an accurate estimation of leak and blockage locations in the hydraulic pipelines.

١-٢ Objective of the Study

١. To develop a numerical model for analysis the oscillating flow in pressurized piping system by using a Transfer Matrix Method technique.

٢. To develop friendly user software in Visual Basic language using the numerical model developed above for analysis.

١-٣ Layout of the work

In the present study, chapter one describes the oscillating flow phenomenon in pressurized piping system and the objective of the study. Chapter two presents a review of the literature related to the present work. The mathematical model developed in the present study will be presented in chapter three. In chapter four, the application, results and discussion for a hypothetical case steady will be reported including graphs to show the effects of the parameters on the behavior of the fluid in piping system during resonance occurred. Chapter four also shows the verification of the mathematical model results with a pioneer work of Chaudhry [Ref. ١]. Conclusion and Recommendation are listed in chapter five.

In addition, the study is supported by appendixes include a computer program, useful tables, and some derivations of equations related to the subject of the study.

١-٤ Analysis of Steady-Oscillatory Flow in Pipes

Whenever the steady-state conditions in a pipe are distributed, transient conditions are initiated. Such disturbances may be amplified with time, causing severe pressure and flow oscillations. When these oscillations occur at constant amplitude with a certain frequency, a periodic flow called steady-oscillatory flow is developed.

Steady-oscillatory flow may be analyzed in the time domain or in the frequency domain. Chaudhry[١] stated that when analyzing a system in the time domain, the process of convergence from the transient to the steady-oscillatory conditions is slow. The analysis in the frequency domain, however, uses a small amount of computer time, since the frequency response is determined directly. Thus this work will focus on the use of the frequency domain analysis.

In the frequency domain analysis, both momentum and continuity equations describing unsteady flow in pipes in the time domain are converted into the frequency domain by assuming a sinusoidal variation of pressure and flow, and nonlinear functions, such as friction term and nonlinear boundary condition are linearized. A hydraulic system is usually made up of several components.

Transfer matrices are classified into three types, the field matrix (F) relating state vectors at two adjacent sections of a pipe, the point matrix (P) relating state vectors just to the left and to the right of a discontinuity, and the overall transfer matrix (U) relating state vectors at one end of the system to those at the other end. The details of these matrices will be discussed in chapter three.

١-٥ System Parameters and assumption in Oscillating flow Analysis

To study the oscillating flow in pressurized piping system and to prepare the elements required for construction the transfer matrices, the following parameters are required:

١. Length of pipes
٢. Pressure wave velocity

٣. Diameter of pipes

٤. Mean flow discharge

٥. Mean pressure head

٦. Type of forcing function which causes resonance

٧. Shape of sinusoidal behavior of the forcing function depending on the magnitude of (α) and (β) in the following formulas:

$$q^* = \mathrm{Re}\left[q(x)\left\{ e^{\alpha jwt} + e^{\beta jwt} \right\} \right] \text{..............................(١.١)}$$

$$h^* = \mathrm{Re}\left[h(x)\left\{ e^{\alpha jwt} + e^{\beta jwt} \right\} \right] \text{..............................(١.٢}$$

$$\tau^* = \mathrm{Re}\left[k\left\{ e^{\alpha jwt} + e^{\beta jwt} \right\} \right] \quad \text{..............................(١.٣)}$$

In chapter four, the effects of the parameters mentioned above on the flow conditions when the oscillating flow in pressurized piping system occurs will be discussed.

The assumptions are that the fluid inside the piping system is incompressible and the system contains a reservoir connected with a two main pipes and branched pipe as shown in the layout system .

LITERATURE REVIEW

Several methods had been used for analyzing the oscillating flow in pressurized piping system. Because of the importance of this subject, the researchers and the authors presented many papers and chapters to study some problems related to this field by using these methods, such as leaks, blockages…etc which may occur in pipelines and network.

The concept of steady-oscillatory flow and pipeline resonance were well established and details can be found in ,Chaudhry[١], Zielke *et al*.[٢] Chaudhry[٣], and Wylie *et al*.[٤] .

Liou[٥] developed a model for a single pipeline by using transient flow simulation for measurements of resonance in the pipeline. In this analysis, he made a comparison between the computed values from the model and the measured real-time values of pressure and the flow at pipe ends. His research helped him to identify and locate leaks in pipeline by using the frequency response method.

Nicholas[٦] also used a real-time transient analysis. He formulated a leak detection method by using a mass balance approach to compensate for the rate of change of inventory in the pipeline and made a comparison of his method with the frequency response method.

Pudar and Liggett[٧] proposed a method for water distribution system in which an inverse problem is solving by using measurements of pressure, flow for steady-state flow, and steady-oscillatory state. They used a frequency domain method for their study.

Johnson and Larson[٨] used the time domain reflection method for measurements of the fluctuation in flow and pressure during the steady-oscillatory state. Their method is considered as one of the types of the frequency domain method.

Wylie *et al.*[٤] used the impedance equation to generate the transfer function for a single pipeline system. The input and the output were defined as the complex discharge and complex head at a point in the pipeline, respectively. He used the transfer function to describe the relationship between the frequency spectra of the input and the output by using linear system theory.

Liggett and Li-Chung[٩] used a transient analysis with large amounts of data to obtain a more precise calculation of resonance in network. Their calculation was considered as a better prediction of leak detection in pipeline.

Also Qunli[١٠] studied the eigen frequency shift pattern to detect the the blockage size in duct.

Again Johnson[١١] showed the effect of a small leak on pressure transients by using a computer simulations and laboratory measurements. He depended in his study on analyzing the steady-oscillatory flow and the resonance in pressurized piping system. The results obtained by his method were plotted and showed the agreement between the computed results and the experimental results.

Silva *et al.*[١٢] presented an on-line computational required to analyze hydraulic resonance in a single pipeline. An on-line computer program reads the transducer data and displays transient plots that give information on leak location in the pipeline.

Jiang *et al.*[١٣] developed a procedure to detect leakage or blockage in a water network utilizing the distribution of pressure fluctuation during oscillatory-state flow which is measured at several points along the network.

Sharp and Campbell[١٤] studied the resonance in pressurized piping system by using the acoustic pulse reflection method. They made use of this method and made a comparison between it and the frequency response method. Their conclusion leads to find the location of the blockage in a single pipeline.

Curto and Napoli[١٥] used a sensitivity analysis method. Their methods had been developed to assist the identification with the leak location.

Again Loui[١٦] found that a transfer function describing the relationship between the frequency spectra of the input and the output data can be obtained by using a linear systems theory. This method led to find the location of leak or blockage in a pressurized piping system depending on the maximum relative pressure head and discharge.

De Salis and Oldham[١٧] presented a method to determine the blockage area function in a duct as a function of the resonance and anti-resonance frequencies of the unblocked and partially blocked duct. They extended this method for determination of the blockage area function of a duct from a single measurement of its transfer function.

Liu and Scott[١٨] developed a method for detecting partial blockage in gas pipelines. Their method was based on the pressure transient analysis of shut-in test. It could locate the blockage when blockage size had been determined by the back pressure teqnique. They compared the results obtained with the frequency response method and showed that there was a great convergence between them.

Ferrante *et al*.[١٩] indicated that the location of leaks affects the relative magnitude of one oscillating flow peak in the transfer function, but the impact of a leak on the location resonance frequencies is minimal, except in the case of large leaks.

Witness *et al*.[٢٠] used a frequency response to determine the location and the rate of the leakage in the open loop piping system. A steady-oscillatory flow produced by the periodic opening and closing of valve was analyzed in the frequency domain by using the transfer matrix method and a frequency response diagram at the valve was developed.

Mpesha *et al*.[٢١] reported that measurements of flow and pressure variations at a single point in a pipeline could be used to generate frequency response function that helped to detect the position of a leak in branched system.

Wang *et al*.[٢٢] analyzed the resonance in pressurized piping system by using the damping fluid transient method. Then that analysis helped to discuss the leak detection in pipeline, however, it did not require extensive measurements all over the system.

Lee *et al*.[٢٣] studied the impact of leak on the frequency response diagram measured at the end of the pipe. The results he found indicate that a leak causes a non-uniform pattern in the resonance peaks.

Vitkovsky *et al*.[٢٤] derived the unsteady friction model which follows the frequency-domain representation of Zielke [٣٣]. In the peak-sequencing teqnique, the removal of the unsteady frictional distortion of the peaks can be achieved by an array of scaling factors derived numerically for a leak-free case between steady friction and unsteady friction results.

Covas and Ramos[٢٥] investigated the effect of frequency-dependent phenomenon in the application of the teqnique such as unsteady friction, pipe-wall visco elasticity and dissolved gas in fluid. These phenomena affected the pressure response diagram by damping maximum pressure peaks.

Pedro J. Lee *et al*.[٢٦] introduced leaks detection method that involve the injection of a fluid transient into the pipeline, with the resultant transient trace analyzed in the frequency domain. In that paper two methods of leak detection using the frequency response of the pipeline are proposed. The inverse resonance method involved matching the modeled frequency response to those observed to determine the leak parameters. The peak-sequencing method determined the region in which the leak is located by comparing the relative sizes between peaks in the frequency response diagram.

Covas and Ramos[٢٧] again used a Standing wave difference method (SWDM) to analyze the generation of a steady-oscillatory flow in a pipe system. They made use of their method to find the location of the leak in pipeline. Their method was based on the sinusoidal motion of a valve. They found that the pressure measurement and the spectral analysis of the maximum pressure amplitude at the excitation site enable the identification of the leak frequencies and, consequently, the estimation of the leak approximate location.

Mohaptra and Chaudhry[٢٨] presented a methodology for detection of partial blockage in single pipelines by the frequency response method. They analyze the steady-oscillatory flow produced by the period opening and closing of a valve located at the downstream end in the frequency domain method.

Their analysis was based on the comparison between the peak pressure frequency obtained by using the frequency response method and the method of characteristic and they found that the two methods were compatible.

In this study the Transfer Matrix Method (TMM) will be used to analyze the oscillating flow in pressurized piping system. This analysis is supported by a software program using visual basic language which can be of assistance to hydraulic engineers interested in studying fluctuation in pressure head and flow.