Study of the charismatic forces upon the ships inside the navigation locks

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In the present research paper, it is intended to investigate the forces affecting upon the ships inside the navigation locks under the effect of the different parameters, which could be helpful in the designing of both the navigation locks and the barges. The experiments were carried out on the ship at both the critical position and the critical orientation inside the lock chamber. The filling/emptying processes of the lock chamber was carried out through a duct and ports of an end-filling system, which was taken place in the lock floor. The experiments were carried out on a single ship representative to the standard ship used in the Nile River. In this research paper, the effects of the head difference (ΔH), the valve opening time (t), the weight of the ship (W), the water depth inside the lock chamber (h), the lock chamber dimensions (LxB), the area of the ports (A_{op}), and the area of the filling/emptying duct (A_d), on the resulted forces affecting the ship inside the lock chamber were considered. It was found that the maximum value of the relative force (F/W) was directly proportional to both the relative head difference ($\Delta H/h$) and the relative area of the duct (A_d/A_{op}), while it was inversely proportional to both the velocity ratio (V/c) and the ratio of the lock chamber dimensions (L/B). The relationships between both the minimum and maximum longitudinal force versus the different parameters were also obtained. A general dimensionless equation, which describes the relationship between the dimensionless maximum force on the ship inside the lock chamber and the aforementioned parameters was also developed.

الهدف من هذا البحث هو التحقق من القوى المؤثرة على البواخر داخل غرفة الأهوسة الملاحيةِ تحت تأثير المتغيرات المختلفة، و التـــي يمكن أن تكون مفيدة خلال تصميم كل من الأهوسة الملاحية و المراكبَ المارة خلالها. و لقد أجريت التجارب عند كل من الوضــع الحرج و التوجيه الحرج للمركب داخل الهويس. و تتم عمليتى الملئ و التفريغ لحوض الهويس من خلال نظام للملئ و الـــتفريغ مدفون فى داخل فرش أرضية حوض الهويس. و قد أجريت التجارب على مركب ممثلة للمركب القياسي المستخدمة في نهـــر النـــيل. و فـــى هـــذا البحثِ ، أخذ فى الاعتبار كل من تأثير فرق الضاغط على الهويس ، زمن فتح صمام الملئ ، وزن المركـــب ، عمـــق الماء داخل غرفة الهويس ، أبعاد غرفةِ الهويس، مساحة فتحات الملئ و التفريغ، ومساحة مقطع قناةِ الملئ و التفريغ على القوى الناتجة على الباخرةِ داخل غرفة الهويس. و قد وَجدَ أن القيمة القصوىَ للقوةِ المؤثرة على المركب (F/W) تتناســـب طـــرديا مع كل من فرق الضاغط النسبى (ΔH/h) والمساحة النّسبية لقناة الملئ و التفريغ (Ad/Aop) بينما تتناسب عكســيا مـــع الســـرعة النسبية (V/c) ونسبة أبعادِ غرفةِ الهويس (L/B). كما تم الحصول على العلاقات بين القوى الطولية الحـــرجة المؤثـــرة علـــى المركب و المتغيرات المختلفة فى كل من حالتي الملئ و التفريغ. أيضا تم استنباط معادلة عامة تحكم العلاقة بين القوة المؤثرة على المركب و المتغيرات السالفة الذكر.

Keywords: Navigation locks, Nile cruise, Lock chamber, Filling system, Force upon ship

1. Literature review

In many countries, the transportation by ships through the inland navigation is an economic way in comparison to the other types of transportation, Kooman et al. [1]. The inland navigation consists of navigable rivers, canals or lakes and the corresponding navigation locks, and the self-propelled ships or barges (towed or pushed), Boogaard [2]. As stated by De Heer et al. [3], the inland waterways may be classified according to the dimensions and the tonnage of the traditional standard vessels. As stated by Albes [4] and Partcrscky [5], the American barges and lakes ships were considerably larger than those

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used in other countries, where the locks dimensions used for those barges ranged from 17 m width and 122 m length for small barges to 33.5 m width and 366 m length for multiple barges and oceans-going vessels. The end-filling/emptying system graven in the floor is one of the most common system in filling and emptying the modern lock chamber. As stated by Murphy [6] and Rescher [7], the graven end-filling system in the floor was used in all modern locks, which were built on the Danube River in Austria. Kalkwijk [8] studied the computation of the longitudinal forces resulted from the translatory waves during the filling and the emptying of the lock chamber for the account of the Ministry of Transport and Public Works in Netherlands. Kalkwijk [8] concluded that the alternative procedure was reliable for giving advice about filling and emptying systems in the locks. Also, his recommendation for the future investigation is concerned with the bottom and the wall filling systems.

2. Theoretical approach

The hydraulic forces affecting upon the mooring ship inside the lock chamber are the longitudinal force and the transverse force. The study carried out by the authors illustrated that the longitudinal forces on the ship inside the lock chamber was much more than the lateral ones, so the study here was focused only on the longitudinal forces. As mentioned by Vrijer [9], the longitudinal force could be resulted from the one-dimensional external translatory waves and also the three-dimensional force on the ship inside the lock chamber at the door-filling system.

2.1. Components of the longitudinal force

As stated by De Jong et al. [10], the longitudinal force affecting the ship inside the lock chamber could be resulted from the translatory waves, the decreasing of the velocity in direction of the downstream gates, the skin friction of the ship, the resistance of the ship to the flowing water; and the action of the filling jet against the bow of the ship Considering of the aforementioned aspects, the water and ship movements could be described by means of the following equations:

Continuity equation:

$$\frac{\partial Q}{\partial X} + \frac{\partial}{\partial t}(A_k - A_s) = 0 . \tag{1}$$

Equation of motion:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial X}\left(\frac{Q^2}{A_k - A_s}\right) + g(A_k - A_s)\frac{\partial h}{\partial x} + g\frac{Q|Q|}{C^2(A_k - A_s)R} = 0 . \tag{2}$$

Rearrangement of eqs. (1) and (2) yields to:

$$F_s^- \cong -\frac{\partial h}{\partial x} = \frac{1}{g(A_k - A_s)}\left[\frac{\partial Q}{\partial t} + \frac{\partial}{\partial X}\left(\frac{Q^2}{A_k - A_s}\right) + g\frac{Q|Q|}{C^2(A_k - A_s)R}\right] = 0 , \tag{3}$$

in which :

F_s^- is the dimensionless longitudinal force = F_s/W,
A_k is the b_k. h the transverse section of the lock chamber,
b_k is the width of the lock chamber,
h is the water depth in the lock chamber at distance x and time t,
Q is the discharge,
C is the Chezy coefficient,
R is the hydraulic radius,
W is the weight of the ship = m.g,
G is the gravitational acceleration,
M is the mass of the ship = v.ρ,
ρ is the water density ,
v is the submerged volume of the ship ,
A_s is the b_s .e transverse section of the ship,
E is the draft of the ship at distance x and time t, and
b_s is the width of the ship.

De Jong et al. [10] stated that at the high values of the discharge, the average value of the longitudinal force depends mainly on the values of both the first and the second. The third term, which represented the friction, was less importance compared with to the other two terms. De Jong et al. [10] presented the following restrictions for the solution of the above one-dimensional equation:

- Only the phenomenon in the longitudinal direction was described,
- Acceleration in the longitudinal direction was much greater than that in the vertical or the transverse direction,
- Homogeneous velocity distribution over the transverse section of the lock chamber,
- Hydrostatic distribution of water pressure,
- The ratio between water depth and wave length $(d/L) < 0.04$, and
- The waves were totally reflected against the gates.

2.2. Criteria of the longitudinal forces

Lahmeyer et al. [11] stated that the criteria for the mooring forces could be defined as the ratio of the maximum force to be absorbed to the ship's displacement. As stated by Lahmeyer et al. [11] this fraction equals 1/600 in France and Germany, while in Netherlands and Belgium it equals 1/1000. Vrijer [9] stated that in Netherlands, the permitted stress of the hawser of the barges during lockage was limited to 1/1000 of the displacement. Also, In case of locks, which were recently built in Belgium, hawser stresses were well within this limit (1/1000), De Heer [3]. In U.S.A. and Austria the permitted hawser force for the shallow draft vessels during lockage was 50 KN. This limit was considered in U.S.A. by considering the safe strength of the old manila hawsers of diameter 2.5 inches, Dumas [12].

3. Experimental model

The experiments were carried out on the ship at both the critical position and the critical orientation inside the lock chamber, which were defined by the authors. The experimental navigation lock model was built in the Hydraulic Research Institute (HRI) [13] with a scale 1:20 to represent a lock of dimensions 180 m x 17 m as illustrated in fig.1. and Photo 1. Both the upstream and the downstream basins were provided with tail gates for obtaining a constant head in both basins. High accuracy electronic point gauges were used to record continuously both the increase and the decrease in water level in the lock chamber. The dissipation and distribution ports consisted of a chamber arranged below the floor of the lock chamber near to the downstream gate as illustrated in fig. 2. The dissipation and distribution ports were connected to the upstream basin by an inflow duct and to the downstream basin by an outflow duct of cross-sectional area 20.0 cm x 20.0 cm. Each duct was provided with a valve connected to a variable speed motor enable to open or to close the valve, within a range of 27 to 80 seconds. The model was fed with water by a pump of a discharge 200 L/s. The dimensions of the model ship was representative to the Nile cruise, which were selected with the co-ordination with the General Egyptian Authority of Navigation and Transportation (GEANT). Using a scale 1:20, the dimensions of the used model ship were 3.6 m length, 0.675 m width, 0.180 m height, and 0.09 m draft. Photo 2 shows a general view of the ship inside the lock chamber. Electromagnetic force transducers of a capacity ranged from 0 to 60 Newton were fitted on both the upstream and downstream of the ship to measure the forces affecting upon the ship inside the lock chamber. An electromagnetic current meter was used in measuring the velocity near the ship. A data logger and data processing units were used to record and process the signals resulted from the force transducers, the water level gauges, and the current meter with time interval equal to 1.0 sec. The data logger was connected to a personal computer and the signals from the data logger were scanned and stored separately for each run on the hard disk.

4. Analysis and discussion of the results

The different parameters, which may affect the resulting forces affecting upon the ship inside the lock chamber, were studied. These parameters are; the head difference (ΔH), the valve opening time (t_{op}), the ship weight (W), the initial water depth inside the lock chamber (h), the total area of duct (A_d), the total area of the ports (A_{op}), and the ratio

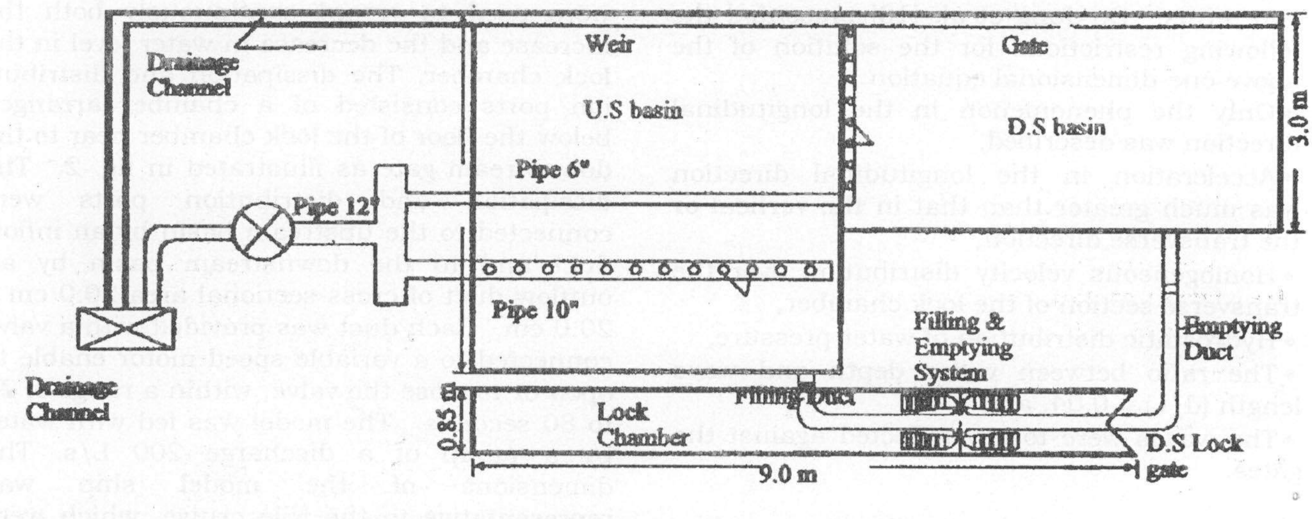

Fig. 1. General layout of the model (plan view).

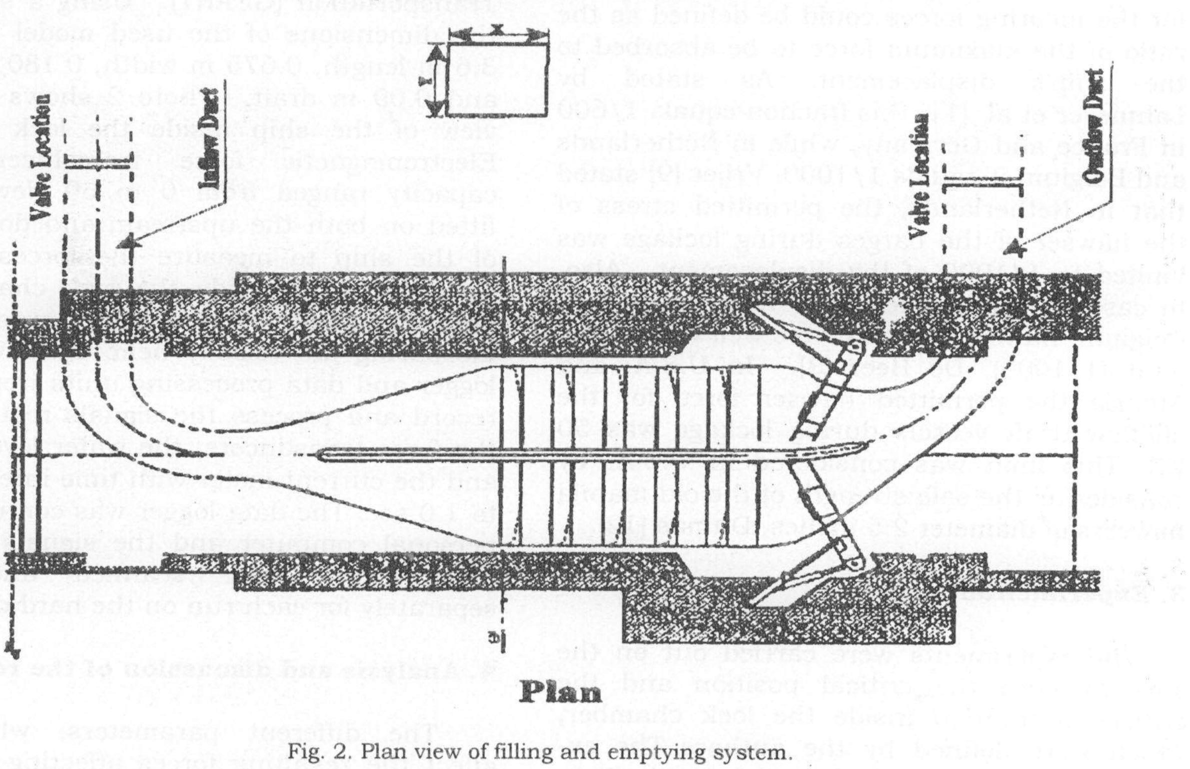

Fig. 2. Plan view of filling and emptying system.

of the chamber length to the chamber width (L/B). These parameters can be expressed in the dimensionless terms $\Delta H/h$, V_g/c, A_d/A_{op} and L/B. The effects of the different parameters on the relative force (F/W) affecting upon the ship inside the lock chamber are studied through 1442 runs. For each dimensionless parameter two cases, which represent both the minimum and the maximum values of the relative force are only selected.

Photo 1. General view of the lock chamber.

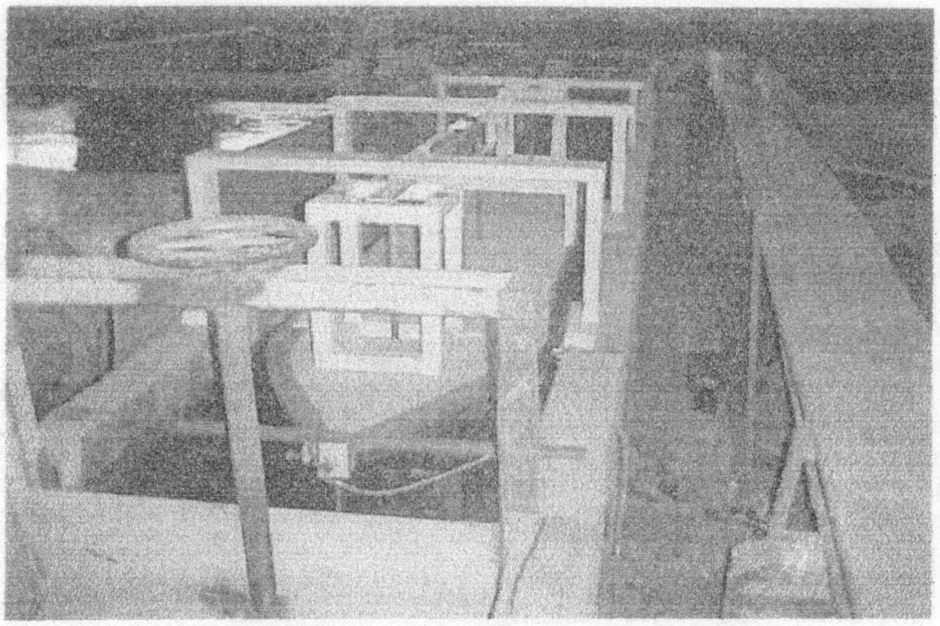

Photo 2. General view of the ship inside the lock chamber during filling and emptying.

4.1. Effect of the relative head difference (ΔH/h) on the relative force (F/W)

Fig. 3 illustrates the variation of the relative force (F/W) versus the relative head difference (ΔH/h) for the different values of A_d/A_{op}, with considering constant values of both V_g/c= 0.0028 and L/B=10. The figure shows that at A_d/A_{op} = 0.15 and ΔH/h = 1.67, the value of F/W= 0.00029. When ΔH/h was increased to 3.33, the value of F/W increased almost three times. The same trend was investigated for the different values of A_d/A_{op}. Also, fig. 4, which represents the maximum values of the relative force shows the variation of F/W versus ΔH/h for a constant values of

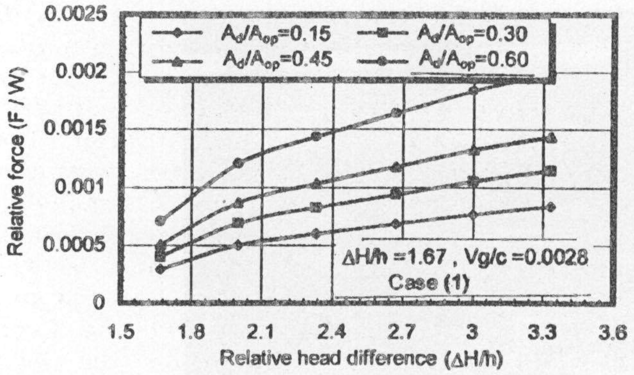

Fig. 3. The effect of the relative head difference on the maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

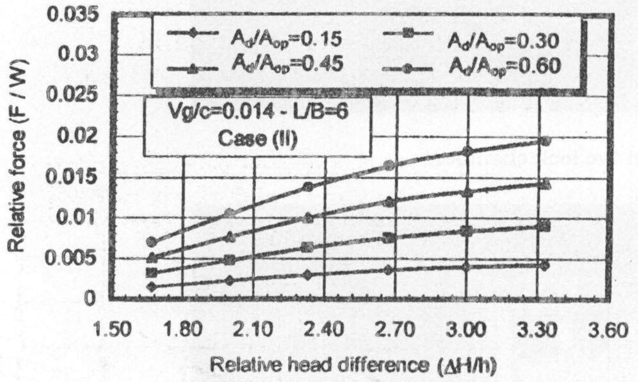

Fig. 4. The effect of the relative head difference on the maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

both $V_g/c = 0.014$ and $L/B=6$. From the figure, it was found that, when $A_d/A_{op} = 0.60$ and $\Delta H/h = 1.67$, the value of F/W reached to 0.007, while at $\Delta H/h = 3.33$ the value of F/W was 0.02. This means that the value of F/W was directly proportional to the $\Delta H/h$. This can be explained, as the head difference increases the velocity of the flowing water from the filling openings increases, which consequently increases the wave celerity inside the lock chamber. The increase of the wave celerity inside the lock chamber increases the kinetic energy upon the ship, which leads to an increase of the affecting force upon the ship. Using of the analytical regression, the relationships between the relative force (F/W) and the dimensionless parameter $\Delta H/h$ were:

$F/W = 0.0003\ (\Delta H/h)^{0.56}$ with a regression 0.97 for lower values; and
$F/W = 0.0007\ (\Delta H/h)^{0.60}$ with a regression 0.99 for higher values.

4.2. *Effect of the relative speed of the valve opening (Vg/c) on the relative force (F/W)*

The effect of the dimensionless speed of the valve opening (Vg/c) on the relative force (F/W) affecting upon the ship inside the lock chamber was studied for both the minimum and the maximum cases as shown in figs. 5 and 6. Fig 5 shows that, the value of F/W=0.0003 when $V_g/c = 0.0028$ and $A_d/A_{op} = 0.15$. When the value of V_g/c was increased to 0.014 (i.e. the value of V_g/c increased 400%), the value of F/W was increased by 230%, which represented the minimum measured value of F/W for the range of V_g/c. As the value of A_d/A_{op} was increased from 0.15 to 0.60, the value of the relative force (F/W) was also increased for the range of V_g/c. Fig 6. shows the variation of the highest values of the relative force (F/W) versus the dimensionless velocity of the valve opening (V_g/c). The figure illustrates that the value of F/W=0.0083 when $V_g/c=0.0028$. When the value of V_g/c was increased from 0.0028 to 0.014 (an increase ratio 400 %), the value of F/W was then increased by 250%. It can be concluded that the value of the relative force (F/W) affecting upon the ship inside the lock chamber was directly proportional to the value of the relative speed of the valve opening (V_g/c). This can be attributed to the increase of the filling velocity, which increases the kinetic energy affecting upon the ship inside the lock chamber. From the shown figures for the lowest and the highest values of the relative force, the following relationships were deduced:

$F/W = 0.0002\ (V/c)^{0.68}$ with a regression 0.90 for lower values; and
$F/W = 0.0083\ (V/c)^{0.54}$ with a regression 0.97 for higher values

4.3. *Effect of the dimensionless parameter (A_d/A_{op}) on the relative force (F/W)*

To indicate the effect of the cross-sectional area of the filling duct (A_d) and the openings

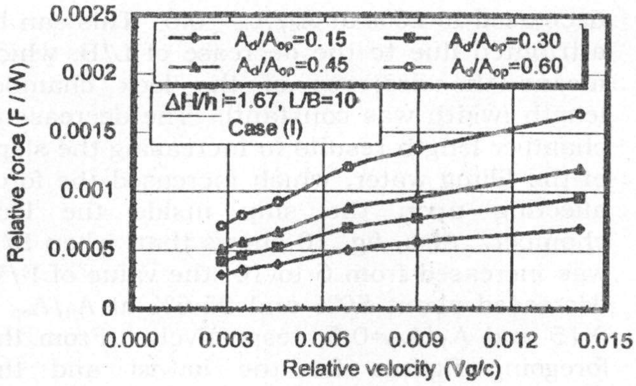

Fig. 5. The effect of Vg/C of the valve opening on the maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

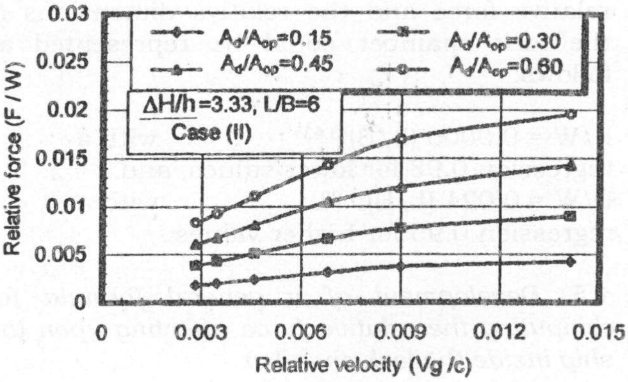

Fig. 6. The effect of Vg/C of the valve opening on the maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

area in the floor of the lock chamber (A_{op}) on the relative force (F/W) affecting the ship inside the lock chamber, two cases were selected. The first case represented the low values of the relative force (F/W) within the range of A_d/A_{op}=0.15-0.6 under specific values of the other dimensionless parameters as shown in fig. 7. The second case represented the high values of the relative force (F/W) as shown in fig. 8. From fig. 7, it was found that, when the value of A_d/A_{op} was increased from 0.15 to 0.6 (300%) the value of F/W was increased about 366% and 130% at L/B =6 and L/B=10, respectively. This can be *Explained,* as follows, as the increasing value of A_d/A_{op} means a decreasing in the openings area, which results in increasing the velocity of the filling water inside the lock chamber. The increase of the filling velocity means an increase of the kinetic energy affecting upon the ship inside the lock chamber. Also, fig. 8 shows that the increase of the value of A_d/A_{op} from 0.15 to 0.6 (300%) results an increase for the value of F/W by 364% and 138% at L/B= 6, and L/B=10 respectively. From the aforementioned figures for both the lowest and the highest values of F/W, it can be concluded that the value of the relative force (F/W) is directly proportional to the value of the relative filling duct area (A_d/A_{op}). Also, it can be concluded that the value of the force affecting upon the ship inside the lock chamber is very sensitive to the area of the filling openings. The relationships between F/W and A_d/A_{op} can be represented as follows:

$F/W = 0.0003\ (A_d/A_{op})^{0.54}$ with a regression 0.95 for lower values; and
$F/W = 0.0044\ (A_d/A_{op})^{1.08}$ with a regression 0.98 for higher values.

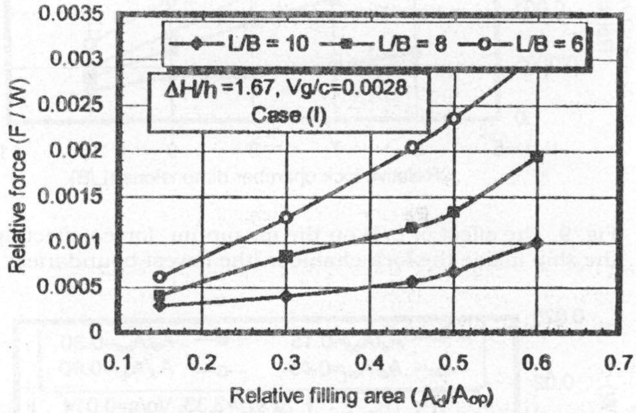

Fig. 7. The effect of A_d/A_{op} on maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

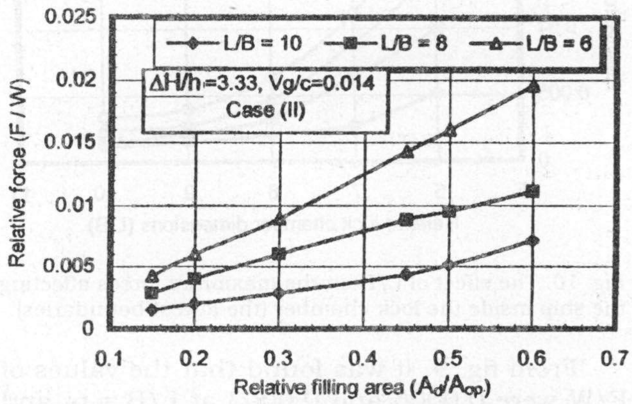

Fig. 8. The effect of A_d/A_{op} on maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

4.4. Effect of dimensionless parameter lock length / width (L/B) on the relative force (F/ W)

The effect of the dimensionless parameter, L/B on the relative force (F/W) affecting upon the ship inside the lock chamber was analyzed for two cases. The first case represents the low values of F/W at the minimum values of $\Delta H/h$ and V_g/c, under different values of A_d/A_{op} as shown in fig. 9. The second case represents the high values of F/W at the maximum values of $\Delta H/h$ and V_g/c under different values of A_d/A_{op} as shown in fig. 10.

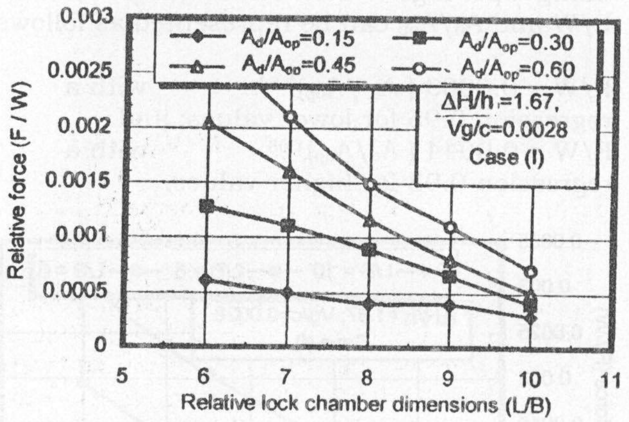

Fig. 9. The effect of L/B on the maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

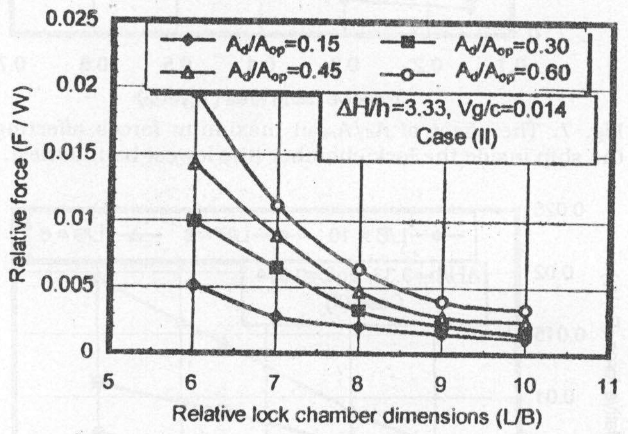

Fig. 10. The effect of L/B on the maximum forces affecting the ship inside the lock chamber (the lowest boundaries).

From fig. 9, it was found that the values of F/W were 0.0006 and 0.0003 at L/B = 6, and L/B =10, respectively. This means that, when L/B was increased 67% the value of F/W was decreased to 50% at A_d/A_{op}=0.15, while it was decreased to 25% at A_d/A_{op} =0.6. This can be attributed due to the decrease of L/B, which means the decrease of the lock chamber length (width was constant). The decrease of chamber length results in increasing the slope of the filling water, which increased the force affecting upon the ship inside the lock chamber. Also, fig. 10 shows that, when L/B was increased from 6 to 10, the value of F/W decreased about 50% and 25.6% at A_d/A_{op} = 0.15 and A_d/A_{op}=0.6, respectively. From the foregoing figures for the lowest and the highest values of F/W, it can be concluded that F/W is inversely proportional to the values of L/B. Using of the analytical regression, the relationships between the relative force and the relative dimensions of the lock chamber could be represented as follows:

$F/W = 0.0006\,(L/B)^{-0.63}$ with a regression 0.98 for lower values; and
$F/W = 0.021\,(L/B)^{-1.20}$ with a regression 0.95 for higher values.

4.5. Development of a general formula for computing the relative force affecting upon the ship inside the lock chamber

The results of the experimental runs were used to obtain a general formula for determination of the longitudinal force affecting the ship inside the lock chamber. The aforementioned analysis showed that the relative force was a relationship in the following dimensionless parameters:

$$F/W = f\,(\Delta H/h,\ V_g/c, L/B,\ A_d/A_{op}). \tag{4}$$

Based on the experimental results (1442 run), a data-fitting computer program was used to obtain the following dimensionless equation:

$$F/W = a\,(\Delta H/h)^b\,(A_d/A_{op})^c\,(V_g/c)^d\,(L/B)^e, \tag{5}$$

in which: a = 9.92, b = 1.485, c = 0.866, d = 0.53, e = -2.3.

then:

$$F/W = 9.92\,(\Delta H/h)^{1.485}\,(A_d/A_{op})^{0.866}\,(V_g/c)^{0.53}\,(L/B)^{-2.3}. \tag{6}$$

The measured values of the relative force (F/W) resulted from the experimental study, which were plotted against the corresponding calculated values by using eq. 6 as shown in fig. 11. The figure shows that the maximum difference between the measured and calculated values of F/W was about 7%. Also, the calculated values from the developed formula were regressed versus all the experimental values of F/W in this research paper. It was found that the relationships had a regression coefficient of 0.93, which could be considered a fairly good result.

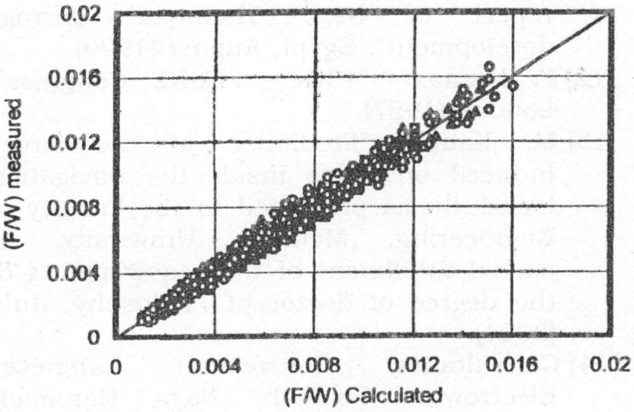

Fig. 11. The measured and calculated values of the maximum relative forces affected upon the ship inside the lock chamber.

5. Conclusions

From this research the following can be concluded:

1. There is a directly proportional relationship between the relative head difference and the relative force affecting upon the ship inside the lock chamber.
2. The increase of wave celerity inside the lock chamber causes an increase for the force affecting upon the ship inside the lock chamber.
3. The values of the relative force affecting upon the ship inside the lock chamber are directly proportional to the relative filling velocity (V_g/c).
4. The force affecting upon the ship inside the lock chamber is very sensitive to the area of the filling openings, as the relative force (F/W) is directly proportional to the value of the relative filling duct area (A_d/A_{op}).
5. The force affecting the ship inside the lock chamber is inversely proportional to the chamber length.
6. Based on the 1442 experimental runs, the following equation was developed by using a best-fitting computer program:

$$F/W = 9.92\,(\Delta H/h)^{1.485}\,(A_d/A_{op})^{0.866}\,(V_g/c)^{0.53}\,(L/B)^{-2.3}$$

7. The calculated values of the relative force (F/W) from the developed equation were regressed versus the experimental results of this research, which had a good regression coefficient value reached a value of 0.93.

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Nomenclature

The following symbols are used in this paper:

- A_d is the transverse section of chamber,
- A_{op} is the opening area of the orfice,
- A_s is the transverse section of the ship,
- b is the ship width,
- b_k is the width of the lock chamber,
- B is the lock chamber width,
- C is the Chezy coefficient,
- C is the wave celerity,
- d is the draft of the ship,
- e is the draught at distance x and time t,
- F_s^- is the dimensionless longitudinal force = F_s/W,
- g is the gravity acceleration,
- h is the water depth in chamber at , distance x and time t,
- ΔH is the difference between the upstream and the downstream head,

Q is the discharge,
R is the hydraulic radius,
l is the ship length,
L is the lock length,
m is the mass of the ship = v.ρ,
W is the weight of the ship = m.g,
ρ is the water density ,
v is the submerged volume of the ship, and
V_g is the speed of the valve opening .

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