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Theoretical and Experimental Measurements of Bollard Pull with Emphasis on Propeller Dimensions

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Abstract

The Bollard Pull (BP) is very important for safe operation of the tugboats. The propeller types and dimension has a significant influence on the measured BP. In this paper the BP is calculated for ideal propellers and compared with the measured using a test rig with motor driven of propulsion system, the exerted thrust was measured for different propellers of different diameters and different blade area ratios (BAR). Experimental results are provided shows the effect of the rpm, the propeller diameter and BAR on the measured thrust.

Keywords: *Bollard Pull, Propeller Dimensions, Exerted Thrust.*

Nomenclature

A	Area of propeller
BA	Blade area
BAR	Blade area ratio
BHP	Brake horse power
BP	Bollard Pull
CPP	Controllable pitch propeller
CT	Thrust coefficient
D	Diameter
G	Shear modulus
F	Spring force
f	Spring deflection
FPP	Fixed pitch propeller
K	Spring stiffness
t	Metric ton
T	Thrust
WP	Input power
τ	Shear stress
V_s	Speed of advance
Z	number of blades

1. Introduction

Bollard Pull is a term often used to describe the pulling capability of the tug boats. Bollard pull trials are conducted to determine the static pull that a tug boat is able to employ in operating conditions.

Bollard Pull is expressed in metric tons (t) or KN. It is not determined by mathematical methods, therefore it must be evaluated for each tug by a “Bollard Pull - Test“. The BP is really important as it is used to obtain the pre-planned towing-speed and provide sufficient power-reserve to ensure safety of the tow also in unfavorable current- and weather conditions.

2. Factors Affecting the Bollard Pull

The following factors are directly related to tug’s generated BP [**1**].

- Tug’s engine output expressed in BHP
- Maximum Continuous Rating.
- Propeller type and size.
- Kort- nozzle.
- Shape of the hulls submerged part.
- Draught.
- Trim.
- Max.Wind
- Max. Waves
- Max. Current

Bollard Pull test is carried out by steaming into a towrope which is fixed ashore and connected to a measuring device, successively with three different performance-level part load (80%), full load (100%), and overload (110%) [**2**].

3. Classifications of the Bollard Pull

The Bollard Pull is classified into Sustained BP, maximum static BP and maximum BP as shown in the following subsections [**3**].

3.1 Sustained Bollard Pull

Mean value of the pull during a specific period of time, often 5 to 10 minutes [**4**].

3.2 Maximum static Bollard Pull

Maximum static BP is always higher than sustained bollard pull as it is the measure of the highest 30 seconds measured during the test.

3.3 Maximum Bollard Pull

The single highest measured value. This value is substantially higher than sustained BP and should not be referred to as BP.

4. The Effect of Propeller System on Bollard Pull

For an approximate conversion from BHP to "t" of the effective available BP, the following formulas may apply [**5**].

a) Tug equipped with fixed pitch propeller:
(Freewheeling) BHP x 0.9 x 1,10 / 100 = (t)

b) Tug equipped with fixed pitch propeller
and kort-nozzle: BHP x 0.9 x 1.20 / 100 = (t)

c) Tug equipped with controllable pitch propeller
(Freewheeling) BHP x 0.9 x 1.25 / 100 = (t)

d) Tug equipped with controllable pitch propeller and kort-nozzle: BHP x 0.9 x 1.40 / 100 = (t)

Example:

Tug boat with main engine of two machineries 1900 BHP at 750 RPM.
Bollard pull (fixed pitch propeller) = 3800 x 0.9 x 1.10 / 100 = 37.62(t)
Bollard pull (fixed pitch propeller and Kort-nozzle) = 3800 x 0.9 x 1.20 / 100 =41.04 (t)
Bollard pull (controllable pitch propeller) = 3800 x 0.9 x 1.25 / 100 =42.75 (t)
Bollard pull (controllable pitch propeller and Kort-nozzle) =3800 x 0.9 x 1.40 / 100 =47.88 (t)

It is noticed that the increase of the bollard pull with the different type of propeller system max- with controllable pitch propeller and kort-nozzle for the same main engine and BHP (see Table(1).

Table 1: propeller type and measured bollard pull

No.	Prop Type	Bollard Pull (t)
1	FPP	37.62
2	DUCTED FPP	41.04
3	CPP	42.75
4	DUCTED CPP	47.88

The BP of CPP is increased by 13.6% than the FPP. The Kort-nozzle has an effect in improving of the BP. The BP is increased by approximately 10% and 12%for the FPP and CPP respectively.

5. Measurement of Bollard Pull

Values for BP can be determined in two ways, practical trial and simulation.

5.1 Practical Trial

Practical trial tests involve suspending a strain gauge on a marine cable that is attached on one end to an immovable object and on the other to the test craft. Mooring bollards are often used as anchor points where the tests get their name. When maximum thrust is applied to the boat's engines, the amount of pulling power exerted on the cable is read off the gauge. See Fig. (1).

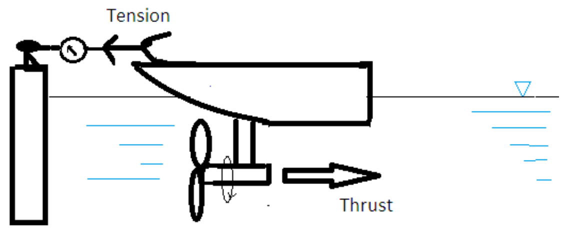

Figure 1: Bollard Pull trial.

5.2 Simulation

These are pure mathematical calculations executed by highly sophisticated and accurate marine simulation software. The high costs of simulated bollard pull tests make this a more suitable option for larger shipyards producing ship lines. As accurate as they are, simulated pull tests are, however, often backed up by practical trial test results.

5.3 Bollard Pull Trials

The bollard pull trails are carried out for the tug boats to determine the maximum static pull that ship can exert [**6**]. The actual bollard pull trail is carried as follows:

a- Maximum bollard pull for 1 min- at max input of ship's engine power.
b- Steady BP over a period of 5 min.
C-Effective BP in open water conditions .this usually approximated to 78% of the steady bollard pull due to the weather conditions **[7].**

For costal tugs the typical BP is in range of 15- 30 tons.
For ocean tugs the typical BP is in range of 30- 110 tons.

6. Experimental setup

An experimental test rig was built to measure propeller model bollard pull. The rig is also capable of assessing the effect of different propeller geometrical configuration (e.g. pitch, blade area ratio, number of blades, ducts.) on the generated BP. The rig was set in the mechanical laboratory in college of engineering and Technology (AASTMT) as shown in Figure (2).

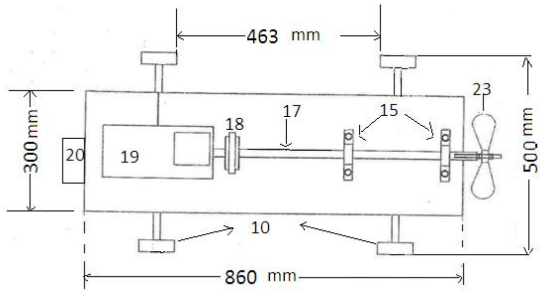

Figure 2: Test Rig

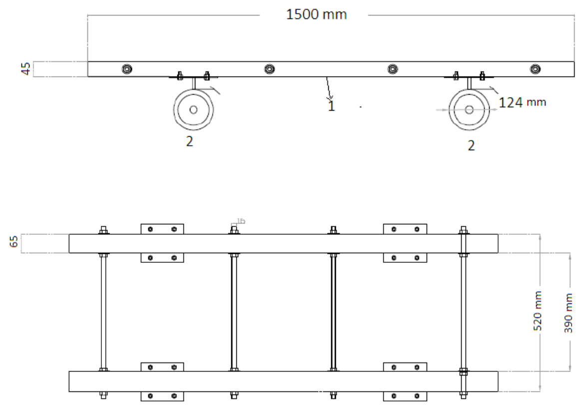

Figure 3: Test rig main chassis

Table 2: Test rig, Item No, Description and Quantity.

No	item	quantity
1	Steel C-Section beams	2
2	Heavy duty swivel casters with brakes	4
3	Casters' base steel plates	4
4	Main chassis power screws	4
5	Teflon barrier plates	2
6	Teflon barrier's slotted sliding stays	4
7	Teflon barrier's sleeves	8
8	Steel barrier's l-angle supports	8
9	Barrier's steel power screws	2
10	Teflon carriage wheels	4
11	Carriage wheels ball bearings	4
12	Carriage wheels' aluminum axles	2
13	Carriage wheels' axles Teflon supports	4
14	Teflon carriage base plate	1
15	Roller bearings unit	2
16	Roller bearings units' Teflon sleeves	4
17	Aluminum propeller shaft	1
18	Mechanical flexible coupling	1
19	Electric 1 hp AC-Motor	1
20	AC-Frequency inverter	1
21	Teflon aft. barrier's spring holder	1
22	Teflon motor side spring holder	1
23	Fixed pitch propeller (diameters of 46 cm,40 cm&36 cm)	3
24	24- Compression steel coil spring 1(1.5 mm D , 20.8 cm length steel)	1

6.1 Calculation of the spring stiffness (K)

The spring stiffness could be measured using two methods as shown in the upcoming section.

6.1.1 Spring Creator Calculator

By entering the spring dimensions and spring type to the calculator for the round helical spring, the spring stiffness *K* is obtained [8] (See Fig (4).

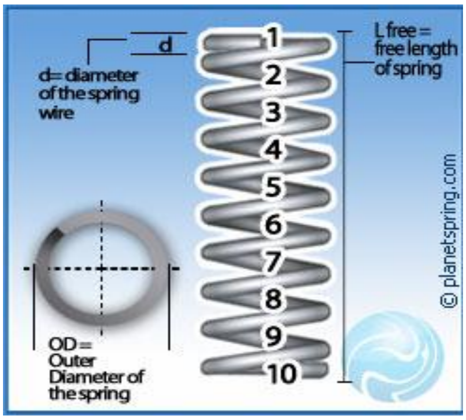

Figure 4: Spring description

Table 3: Spring dimensions

Diameter of spring wire. (d)	1.5 mm
Outer diameter of spring. D.out.	58 mm
Mean coil diameter. (D)	56.5 mm
Spring radius r = D / 2	28.25 mm
Free length of spring. L free	208 mm
Number of active coil.(n)	8
Material	Carbon valve
Spring type	Closed &ground
Shear modulus G = E / (2 (1+v))	79.9 10^9 Pa
Spring force F	5.75 N
Spring deflection (f)	0.164 m
Shear stress (τ)	245.12 10^6 Pa

The program used the following equations:

$$F = \frac{\pi}{16} \cdot \frac{d^2}{\gamma} \cdot \tau \qquad (1)$$

$$f = \frac{64nr^3F}{d^4G} \quad (2)$$

Spring stiffness $k = \frac{dF}{df} = \frac{F}{f}$ (3)

Calculated spring stiffness K = 40 N/m [8].

6.1.3 Spring Calibration

The spring is calibrated at the laboratory by applying axial force and measuring the corresponding deflection. The results are given in (Table 4) and plotted in figure (5).

Table 4: Spring deflection with related forces

Force (N)	deflection (m)
2.52	0.08
3.11	0.097
4.36	0.13
4.48	0.14
5.74	0.165

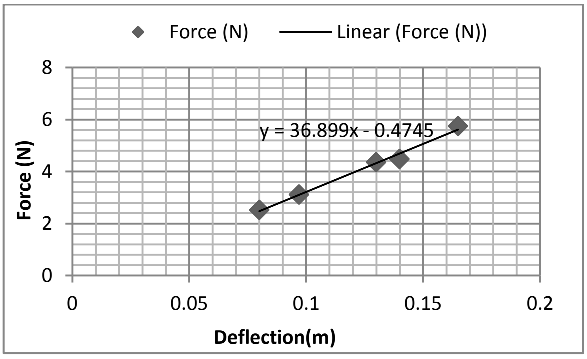

Figure 5: Relation between forces and spring deflection

The slope of the equation represents the spring stiffness (K), in this case ***K*= 36.899 N/m**.

Figure 6: Test rig (set up)

6.2 Test Procedure

The propeller to be tested is mounted on the shaft and secured in place. The test is carried out by running the motor at different rpm which displayed on the AC-frequency inverter and measuring the compression of the spring (x) as shown in fig (6).

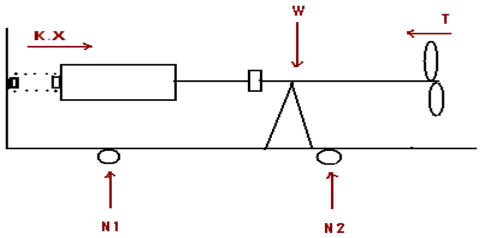

Figure 7: Test rig force analyses

From Fig (7) the thrust can calculated as follows
For equilibrium

∑ F y =0 (4)
∴ W= N1 + N2 (5)

Take N1+N2 = μ.N

W= μ.N (6)

∑ F x =0 (7)

∴ T - k. x = 0 (8)

From eqn. 4,7
∑ F x = ∑ F y (9)

∴ T – k. x = μ.N (10)

T = μ.N + ***k***. x (11)

The thrust can calculated from the following equation:

T=μ.N + ***k***. x (*)

N: Normal force of the wheels which equal to the total weight = (Carriage weight (19 kg) + prop weight) * 9.81 (N).

Propeller no. 1 weight = 0.250 kg

μ: friction coefficient Teflon on aluminum=0.19 [9].

K: spring stiffness = 40 N/m.

x: spring compression (meter).

T: thrust (BP).

Table 5: Propeller No.1dimensions

Z	3
A	0=.166m^2
P	0 .254cm
D	0.46m
BA	0=.03056m^2
BAR	0.184
weight	0.250 kg

Figure 8: Propeller No. 1

6.3 Test Results

Table 6: Test results of No.1 FPP 46cm D. 3 blades

R.P.M	Scale Reading (cm)	X (m)	Thrust-T Equation * (N)
300	44.5	0.005	36.08
400	45	0.01	36.28
500	45.5	0.015	36.48
600	48	0.04	37.48
700	48	0.04	37.48
800	48	0.04	37.48
900	52.5	0.085	39.28
1000	53	0.09	39.48
1100	55.5	0.115	40.48
1200	55.5	0.115	40.48
1300	55.5	0.115	40.48
1400	60	0.16	42.28
1450	61	0.17	42.68

The results on Table 6 are plotted on figure (9).

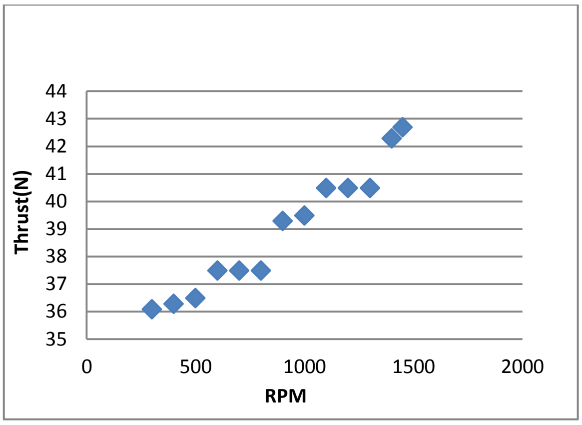

Figure.9: Relation between RPM and extracted thrust of FPP.46cm D

Table 7: Propeller No.2 dimensions

Z	3
A	0.1256 m^2
P	0 .22cm
D	0.40 m
BA	0. 1104 m^2
BAR	0.878
weight	0. 20 kg

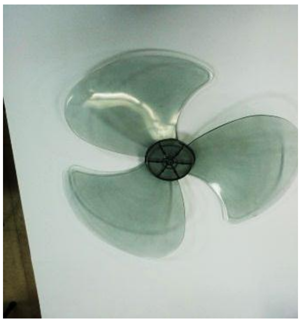

Figure10: Propeller No.2

6.3.1 Thrust calculation for Ideal propeller

Propeller efficiency at static condition

Since $V_s = 0$

η= output / input = T V_s / WP = 0 (12)

$$\eta = \frac{2}{[1+\sqrt{1+C_T}\,]} \quad (13)$$

$$W_p = \frac{\tau.\gamma}{2}[1+\sqrt{1+C_T}\,] \quad (14)$$

Let $[1+\sqrt{1+C_T}\,] = C_T$ (15)

Since,

$$C_T = \frac{T}{0.5\rho V^2} \quad (16)$$

Substitute 4, 5 in 3

$$W_p = \frac{T.V}{2}\sqrt{\frac{T}{0.5\rho V^2}} = \frac{T^{1.5}}{\sqrt{2\rho A}} \quad (17)$$

$$T^{1.5} = \sqrt{2\rho A}.W_p \quad (18)$$

For ideal propellers the bollard pull can calculated from equation (18).

$T^{1.5} = \sqrt{2\rho.A}$. WP.

Where ρ: the density of air = 1.18 kg/m^3

A: area of the propeller $(\frac{\pi}{4}D^2)$ = 0.166 m^2

WP: the input power. = 745.66 Watt

$T^{1.5} = \sqrt{2*.1.18*.0.166}$ * 745.66 (19)

T=61.436 N

Compared with max thrust measured in the test

(42.68N) found is higher by 30.5 %, this difference is due to the friction and that the max input power of the electric motor is measured at 1500 rpm.

Table 8: Test results of No.2 FPP 40cm D. 3 blades

R.P.M	Scale Reading (cm)	x (m)	Thrust –T Equation* (N)
700	47.6	0.003	35.907
800	47.6	0.003	35.907
900	50	0.027	36.867
1000	50	0.027	36.867
1100	52	0.047	37.667
1200	52	0.047	37.667
1300	55.5	0.082	39.067
1400	55.5	0.082	39.067
1450	55.5	0.082	39.067

The results on table (8) are plotted on Fig. (11).

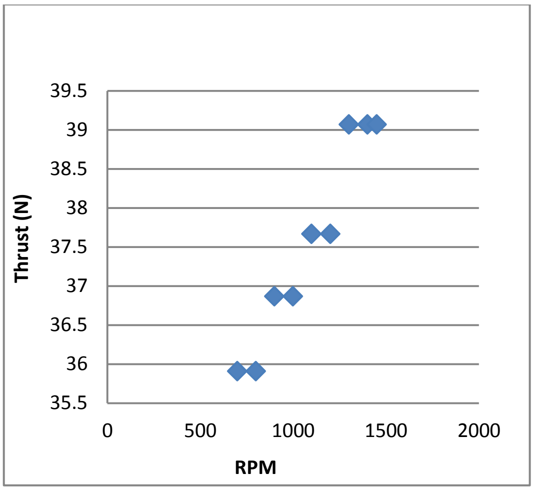

Figure 11: Relation between RPM and thrust of FPP. 40 cm D

For ideal propeller the bollard pull can calculated from the following formula:

$T^{1.5} = \sqrt{2\rho.A}$ .WP

A: area of the propeller $(\frac{\pi}{4}D^2)$ = 0.125 m^2

$T^{1.5} =$ * 745.66 (20)

T =54.739 N

Table 9: PropellerNo.1dimensions

Z	3
A	0.10173 m^2
P	0 .2088 cm
D	0.36 m
BA	345.69 cm^2
BAR	0.3398
weight	0.120 kg

Figure: 12Propeller No.3

Table 10: Test results of No.3 FPP 36cm D. 3 blades

R.P.M	Scale Reading (cm)	X - (m)	Thrust-T Equation* N
1200	48.2	0.002	35.717
1300	48.2	0.002	35.717
1400	51	0.03	36.837
1450	51	0.03	36.837

The results on table (10) are plotted on Fig. (13).

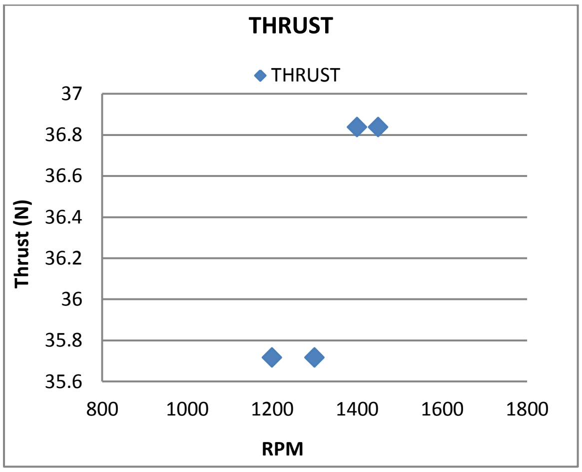

Figure 13: Relation between RPM and the extracted thrust of No.3 FPP 36cm D.

For ideal propeller the bollard pull can calculated from the following formula:

$T^{1.5} = \sqrt{2\rho.A}$ .WP

A: area of the propeller $(\frac{\pi}{4}D^2)$ = 0.101 m^2

$T^{1.5} = \sqrt{2*.1.18*.0.101}$ * 745.66 (21)

T = 50.98N.

Table 11: Test results summary

propeller diameter (m)	No. of blades	propeller type	Max Measured BP (N)	Max Ideal BP (N)
0.46	3	FPP screw	42.68	61.43
0.40	3	FPP screw	39.067	54.739
0.36	3	FPP screw	36.837	50.98

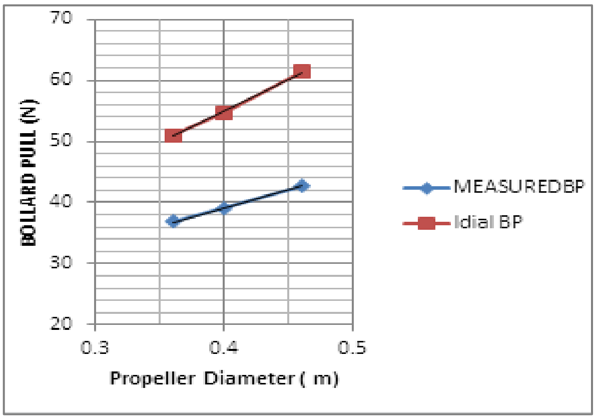

Figure14: Relations between measured and ideal BP with propeller D

Table 12: Effect of BAR on the BP

Propeller no.	BAR	Max exerted thrust (BP)
1	0.184	42.68
2	0.878	39.067
3	0.3398	36.88

7. Discussion of results

1-Exprimental measurements show that the increase of the exerted thrust with the increase of the rpm.

2- In the 46cm diameter propeller (largest diameter) the thrust is constant for early rpm (100,200) and started to increase with rpm increasing (300 RPM)
3- In the 36 cm diameter propeller (smallest diameter) the exerted thrust is constant for large rpms (100- 1100) compared with 46cm propeller diameter.
4- The exerted thrust(BP) increases with the increase of the propeller diameter for the same out- put power and same load i.e by increasing the diameter with 21.73% the thrust improved by 13.69% as shown in Fig. 14 .
5- There is an effect of BAR on the exerted thrust BP
The increase of BAR decreases the BP.
6- The test rig can be used to measure the BP for small propellers diameter.

Recommendations for extended work

It is recommended to measure the thrust for the same test rig after installing ducted propellers to find out the effect of ducted propellers in improving the generated BP.

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