Microbubble Drag Reduction WAIP, another way in air lubrication

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SUMMARY

The Author has invented WAIP: Winged Air Induction Pipe. WAIP essence is as follows; 1 WAIP, drag reduction by turbulence modulation realizes even some 25% with least possible additional power.. 2..Prime mover is negative pressure generated at the wing when ship advances. 3.Microbubble is generated by Kelvin Helmholtz Instability, for which co-existance of air phase and water phase above wing is essential. 4.Drag reduction is supposed to be carried out when ship advances amidst tightening cloud of microbubble.5.WAIP can reduce drag of any kinds of ships. whatever ship type, ship hull form, ship speed etc. it may be .6.Practical drag reduction amount calculation way has been shown and actual examples from small ship to large containership. 7.Microbubble is named compared with boundary layer thickness.

CONTENT

1. Introduction

: Pursuit of another way of in air lubrication: Microbubble Drag Reduction

Since advent of wave making resistance reduction theory, there remained only frictional resistance reduction(from here on Drag Reduction) has become the sole problem to be solved in modern ship technology.

Since when I entered into IHI in 1965, this problem has been hanging in my mind to be solved.

In 1991, the chance has come to me and the order from my chief to investigate and to learn more the Drag Reduction of ship.

Then the author began to investigate by aid of Professor emeritus of University of Tokyo: Dr. Hiroharu Kato and submitted a paper[1] to 22nd Naval hydrodynamics symposium held at Washington D.C. August 1998.

Since this submission, I wondered if I should change my course of research and development direction from conventional bubble making by air compressor or not and found out that extremely low bubble making theoretical efficiency by air compressor.

And then I have begun to find out another way of drag reduction other than air film way in conventional air lubrication.

Finally WAIP have the author established as Microbubble Drag Reduction, as a very effective way, usually up to some 25%over drag reduction possible and almost completely maintenance free technology once WAIP installed.

WAIP is said drag reduction by turbulence modulation/modification [3][4] other than air film [5] way of conventional air lubrication.

The content of this paper is the history of author's R&D and Engineering from 1998 to now 2011. aiming at acual application of WAIP technology to all kinds of ships independently from ship type, hull form and ship speed etc.

WAIP drag reduction is supposed to be carried out ship advancement through tightening cloud of Microbubble.

Microbubble Drag Reduction is composed of WAIP hardware and air compressor if needed.

Bubble making by air compressor is of too much energy consumed,71.1% of total energy for internal energy raise only (see formula below), for pressurizing air.

Then it was conceived to find out essentially another way in air lubrication. It means another way of bubble generation.

$$\frac{\Delta \mathrm{U}}{L_{total}} = \frac{\alpha C_V}{\beta R \,\kappa / (\kappa - 1)} = 0.711$$

$\alpha : 1.3596$

$\beta : 0.0133$

$R : 29.5$

$C_V : 0.718$

$\kappa : 1.4$

This internal energy raise means temperature raise of compressed air and the temperature will be instantaneously lost once it touches with sea water, infinitely large heat sink.

Then adiabatic process efficiency can be said theoretically only about 29% for generating bubble.

In addition to this extremely low theoretical efficiency, air compressor needs also acquisition cost of the machine and its driving power.

Of paramount importance is a discovery of another efficient way to generate bubble less expensively, first of all.

2. WAIP system invented for drag reduction for all kinds of ships:

The author acknowledged before that any injected air into water forms bubble.

For air injection to water, low static pressure portion of a ship, bottom, was considered first of all.

And then increase of this negative pressure were tested like Kikumaru[2] by attaching prism like protrusion on the bottom. This prism generated fog like microbubble as shown below.

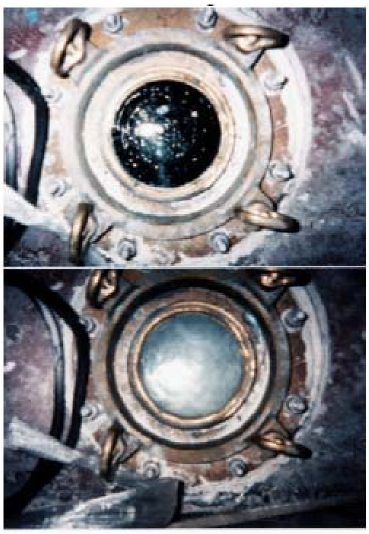
2.1 Kikumaru case and Yayoimaru case: （August 1998 and April 2001）

Photo1.Kikumaru

Lpp*Bmd*Dmd=11.20*2.94*0.74m

Photo 2. Kikumaru bottom photo through peeping hole at the stern

Above: without microbubble, Under: with fog like microbubble [2]



But increased negative pressure at the rear side of the prism has not so many design parameters except prism height and total prism length.

Then invented wing attached to the bottom Yayoimaru case (see Photo 3.) in which prototype of WAIP was born), above which light fluid, air in this case, comes down directly from atmosphere through AIP: air induction pipe and heavy fluid, water in this case, goes very fast to the stern direction.

Photo3. Yayoimaru

Lpp*Bmd*Dmd=8.9*2.1*0.52m,

100ps*2800rpm

Usually light fluid on heavy fluid is very stable as they are when there is no speed difference at the interface. But once any speed difference occurs at the interface, then comes instability and generates microbubble. This phenomenon is called Kelvin Helmholtz Instability the(KHI).

This phenomenon is called Kelvin Helmholtz Instability (KHI).

Above the wing, this phenomenon occurs.

This wing has many design parameters such as wing shape (ogival, aerofoil etc.), size (chord length and width) , aspect ratio, protrusion height and attack angle. By these parameters the best configuration shall be selected. Generated microbubble is shown in Photo ４(Adventure2 case).

Photo ４. Generated microbubble

(Adventure2 case)

7/

2.2 Experiments in the facility at FEL (West Japan Fluid Engineering Laboratory in Sasebo, Japan 2001/2002)

Combinations of wing parameters were selected through facility tests at FEL.

CWC (Circulating Water Channel: Max. homogenious flow velocity is 5.5m/sec) at FEL was used for these tests:

Variation and combinations of wing shape, aspect ratio, protrusion height and attack angle were tested.

Photo 5. CWC at FEL

Photo 6.Improved WAIP

Here conceived was Compensation Distance (C/D) concept as a criteria for the best selection of these parameters combination.

This C/D means distance of which Drag Reduction of the plate covered with microbubble is equal to the Drag caused by the wing (protruding part) itself.

At this CWC, Drag Reduction and wing drag itself should be measured at the same time.

The wing for these tests is of actual size.

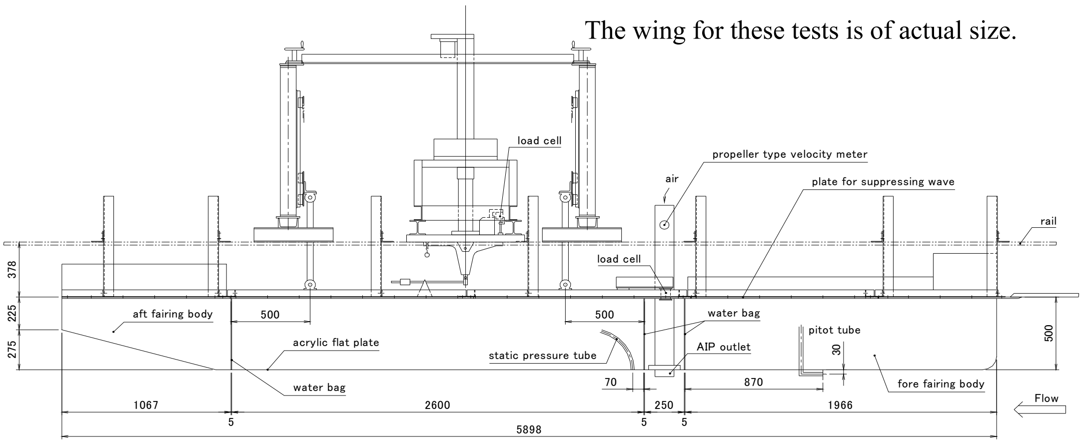


Fig.1A CWC measurement devices

Dt : total drag, Do : drag on wing part, Db : drag on 2.60m acrylic box [=Dt-Do]

ΔDo : wing drag increase [=Do (with WAIP) – Do (with Bare Plate)]

ΔR : drag reduction of 2.60m flat plate [=Db(with WAIP) – Db(with Bare Plate)]

type	attack angle (deg.)	V (m/s)	Dt (Kgf)	Do (Kgf)	Db (Kgf)	ΔDo (Kgf)	ΔR (Kgf)	Ps (mAq)	Vair (m/s)	Q (m^3/mi.)	Xc (m)
Bare Plate		5.562	19.706	1.190	18.516			0.010			
NACA12	12.0	5.579	20.865	3.807	17.058	2.617	-1.458	-0.044	0.110	0.0348	8.5
NACA16	16.0	5.569	21.603	4.561	17.042	3.371	-1.474	-0.210	0.140	0.0442	11
NACA20	20.0	5.567	22.550	5.998	16.552	4.808	-1.964	-0.307	0.135	0.0427	12

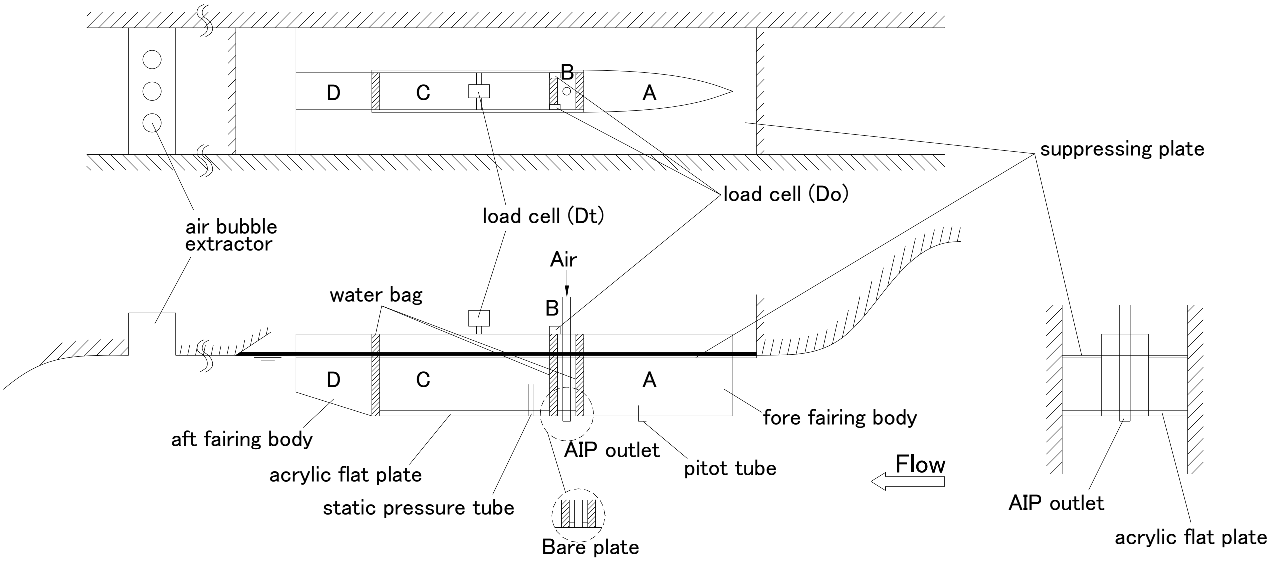


Fig.1B Actual measured data Examples

2.3 Actual sea tests: Advenrure2: WAIP independent test July and December 2002

Photo 7. Adventure2

Lpp*Bmd*Dmd=12.62*2.7*0.83m, 500ps

When I observed microbubble generated at WAIP, it did not diverge so much Athwartship direction. Then at the next step, parallel allocation of WAIPs was tested onboard Santander Ferry1.

About 4% drag reduction by one(1) WAIP at each side was shown at Imari Bay, Nagasaki prefecture, Japan, in December 2002.

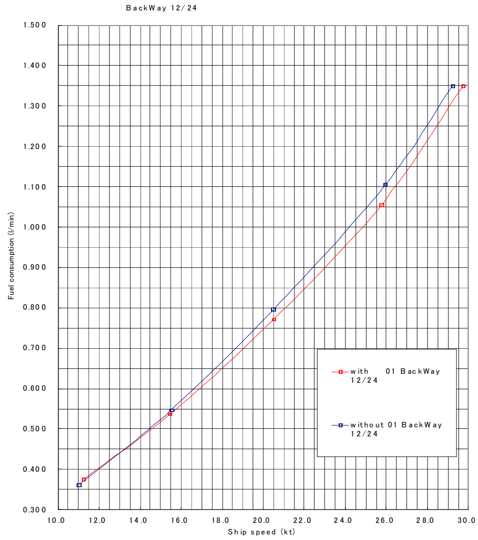


Fig.2 Adventure2 measured data

2.4 Actual sea tests: Santander Ferry 1 case: WAIP parallel application test; September 2004,February 2005

Photo 7. Santander Ferry 1

Lpp*Bmd*Dmd*ps=28.8*5.45*1.55 m*700ps

Actual sea test were carried out in September 2004 and actual fuel consumption was measured in February 2005.as shown in the following table. About over 14% Drag Reduction was measured by direct fuel flow measurement.

Strictly speaking, this "off" case does not correspond to without WAIP case, but roughly looks the same..

Photo 8

Photo 9

燃費計測結果:2005年2月19･20･21日
回転数:1，700rpm
Go: from Santander to Dumaguete
Back: from Dumaguete to Santander

		All closed		No.2 only open		No.1 only open		All open	
		Go	Back	Go	Back	Go	Back	Go	Back
Starboard side Engine	Date	on19th Feb.	ditto	ditto	ditto	ditto	ditto	ditto	ditto
	Time	7:41～8:15	9:01～9:35	10:28～10:59	11:56～12:29	13:30～14:03	15:08～15:42	16:35～17:10	18:04～18:35
	Weather/Sea state	Fine/Calm	Fine/Calm	Fine/Calm	Fine/Calm	Fine/W.wave	Fine/W.wave	Fine/W.wave	Fine/Calm
	Elapsed time seconds	550	534	537	513	545	517	517	543
	Total Variable weight tons	3.776	4.231	4.946	3.126	2.801	3.191	2.866	3.451
	Fuel remained on board	1.566	1.501	1.436	1.371	1.306	1.241	1.176	1.111
	Persons including passengers	2.210	2.730	3.510	1.755	1.495	1.950	1.690	2.340
	Speed measured knots	11.455	11.798	11.732	12.281	11.560	12.186	12.186	11.602
	Fuel consumption measured littre/hou	101.1	80.5	79.6	72.6	72.2	66.4	77.2	70.9
	Weight corrected with 3.776 tons	–	–	–	–	–	–	–	–
	Speed knots		11.817	11.780	12.252	11.519	12.160	12.146	11.589
	Fuel consumtion littre/hour		80.9	80.6	72.1	71.5	66.0	76.5	70.7
	Averaged fuel consumtion littre/hour		91.0		80.6		71.5		76.5
Portside Engine	Date	on 20th Feb.	ditto	ditto	ditto	ditto	ditto	ditto	ditto
	Time	6:05～6:35	7:10～7:45	8:59～9:30	10:54～11:29	12:04～12:36	13:10～13:45	15:00～15:32	16:07～16:40
	Weather/Sea state	Fine/Swell	Fine/Swell	Fine/W.B'ze	Fine/W.waves	S.cloudy/Cal	S.Cloudy/Cal	Fine/Calm	Fine/Calm
	Elapsed time seconds	549	506	528	522	528	518	501	515
	Total Variable weight tons	3.190	2.553	2.500	3.422	3.044	2.146	2.159	2.951
	Fuel remained on board	1.045	0.993	0.940	0.887	0.834	0.781	0.729	0.676
	Persons including passengers	2.145	1.560	1.560	2.535	2.210	1.365	1.430	2.275
	Speed measured knots	11.475	12.451	11.932	12.069	11.932	12.162	12.575	12.233
	Fuel consumption measured littre/hou	39.0	37.1	40.3	38.7	36.7	27.2	32.9	28.0
	Weight corrected with 3.190 tons	–	–	–	–	–	–	–	–
	Speed knots		12.422	11.902	12.079	11.926	12.117	12.528	12.223
	Fuel consumtion littre/hour		36.8	40.0	38.8	36.6	26.9	32.5	27.9
	Averaged fuel consumption littre/hour		37.9		40.0		36.6		32.5

3.Drag Reduction amount calculation process based on tests at FEL.

3.1 Cf/Cf$_0$ approximation by a rational function

After microbubble emitted into water, its behavior in drag reduction, in other words, Cf/Cfo alongside with down flow should be known. Here ship is supposed standstill and microbubble only to flow down to the stern.

Once microbubble emitted into water, no one can control its behavior.

In whatever way microbubble generated, its behavior can be considered the same.

Then IHI 40m long*0.6m wide flat bottom ship model test [6] (See below Fig.12 cited from [1]) was referred.

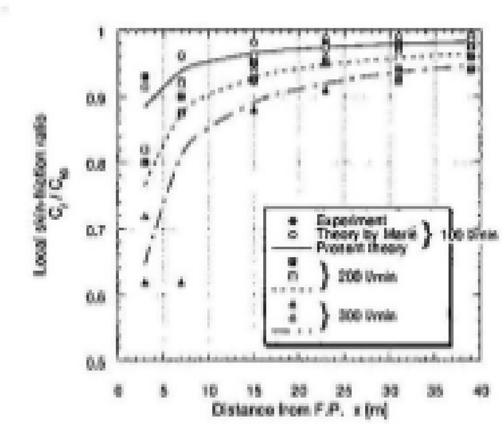


Fig. 12 Local skin-friction ratio obtained on IHI 40 m long flat-bottomed model

The author tried Cf/Cf$_0$ curve, this shearing stress distribution, to be approximated by a rational function.

This function should be satisfied up to 40m down flow as in the above graph.

x : the distance from test body edge to down flow direction in m.

y : Cf/Cf$_0$

Assuming that following form rational expression;

$$y = 1 - \frac{a}{x+b} \quad \text{-------------------------(1)}$$

Here, "a" and "b" shall be fixed so at to satisfy IHI 40m flat ship model.

3.2 "b" fixing

Assuming that b = 2.9, by setting a = 0.7 for air volume 100l/min.

a = 1.3 for air volume 200l/min.

a = 2.0 for air volume 300l/min.

As shown in Fig. 3 approximation curve, "b"=2.9 can be fixed for every air volume case.

This "b"=2.9 fixing was considered also available for every WAIP case.

3.3 “a” fixing

“a” shall be determined for every test case by fitting this function with 2.6m test body reduced drag quantity itself.

What we can measure is only the integrated reduced drag of 2.6m flat plate

from x_1=2.216m(fore edge of acrylic box of 2.6m long) to x_2=4.816m(aft edge of acrylic box of 2.6m long).

From Fig. 4, following amount should be equal to 2.6m plate reduced drag.

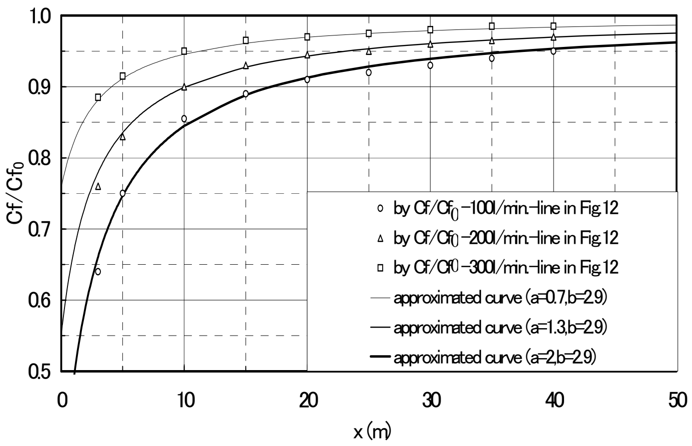


Fig 3.Approximation curve

x Here, we define that x_1 is the point where drag reduction by microbubble starts.

Then, drag reduction of plate from x_1 to x_2 shall be expressed by the following equation.

$$\Delta R_{x_1,x_2} = \int_{X1}^{X2} \frac{1}{2}\rho V^2 C f_0 (1 - \frac{Cf}{Cf_0}) B \cdot dx \quad (2)$$

Here, local friction factor Cf_0 should be calculated by Prandtle-Schlichting's equation as follows.

$$Cf_0 = (2\log_{10}Re_x - 0.65)^{-2.3} \text{----}(3)$$

$$Re_x = \frac{Vx}{\nu}$$: Reynolds number

ν : kinematic viscosity of sea water at 15 degrees(centigrade)

Then, equation of Plandtle-Schlichting applies where Re_x is larger than 10^5. And,

$$1 - \frac{Cf}{Cf_0} = 1 - (1 - \frac{a}{x+b})$$

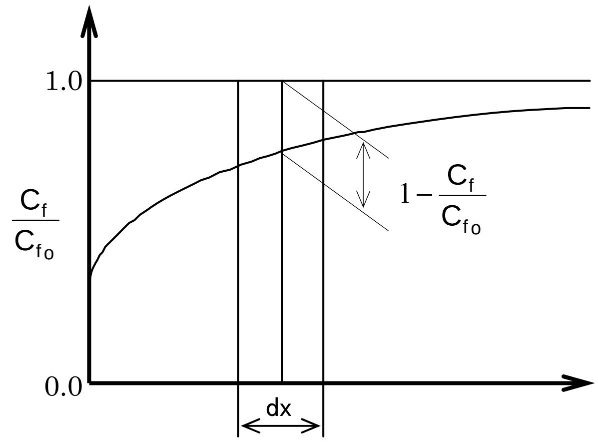


Fig.4 Integrated reduced drag

$$= \frac{a}{x+b} \text{---------------------}(4)$$

When integrating equation (2), we can obtain reduced drag from x_1 to

x_2 as follows.

$$\Delta R_{x_1,x_2} = \int_{x_2}^{x_1} \frac{1}{2}\rho V^2 C f_0 (1 - \frac{Cf}{Cf_0}) B \cdot dx$$

$$= \{\frac{1}{2}\rho V^2 B \int_{x_2}^{x_1} (2\log_{10}Re_x - 0.65)^{-2.3} (\frac{1}{x+b}) dx\} \cdot a$$

(5)

This can be set as follows:

$$= F(x_1, x_2) \cdot a$$

Here, we define,

$$F(x_1, x_2) = \frac{1}{2}\rho V^2 B \int_{x_2}^{x_1} (2\log_{10}Re_x - 0.65)^{-2.3} (\frac{1}{x+b}) dx$$

---(6)

$F(x_1,x_2)$ can be calculated with "quadrature (measuration) by parts".

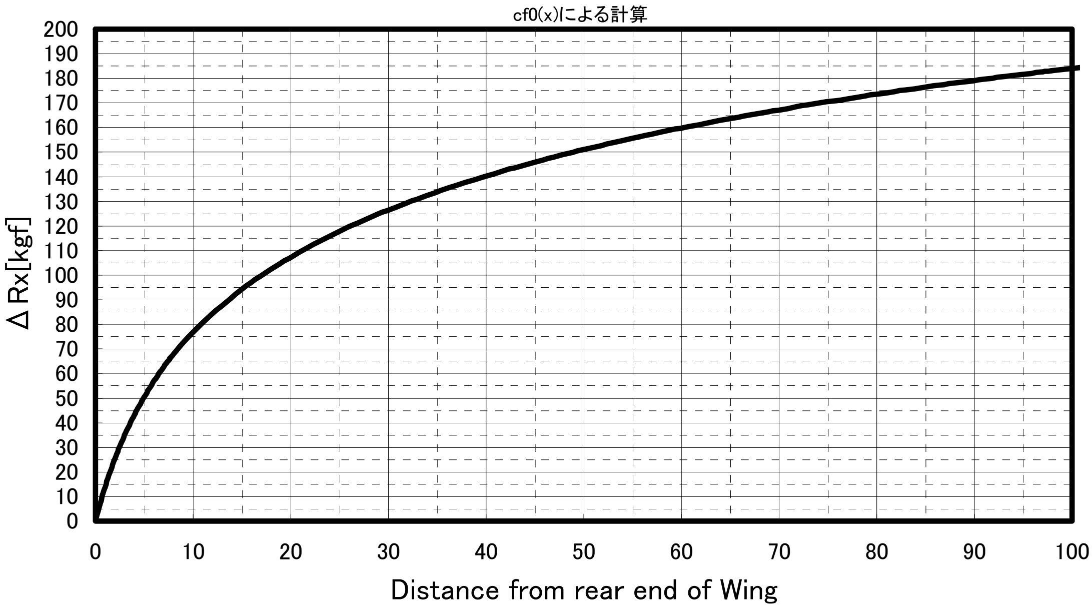


Fig.5 Drag reduction curve per WAIP piece

3.2 Compensation Distance definition

WAIP (see Photo 6) is composed of a protruding wing to generate Air/Liquid Boundary portion (where Kelvin Helmholtz Instability occurs) above it and a pipe through which air is induced to the portion and generates microbubble

WAIP performance should have to be evaluated from the viewpoint of lesser wing drag increase and larger D/R at the same time. For this evaluation, a definition of **Compensation Distance**: C/D (Xc) was conceived.

Physical meaning of C/D is a distance of the WAIP subsequent 500mm wide plate covered with microbubble, by which reduced drag is equal to drag increase by the wing itself. Therefore, the better WAIP should have the shorter C/D.

Any kind of variation of WAIP can be evaluated by this C/D criteria.

Compensation distance x is defined as the distance from the point where the effect of drag reduction starts x_1 to the point to be compensated for wing drag increase x_2. Namely,

$$x = x_2 - x_1$$

Here, we assumed that x_1 is 2.0m.

3.3 Drag reduction curve per WAIP piece

In the same manner, once measured data is available, drag reduction curve per WAIP piece can be drawn as Fig.5.

3.4 Correction Factor of calculated data by actual ship sea trial data

As already described in 2.2,at CWC of FEL the author could measure ΔDo and ΔR of all kind of WAIP in only up to about 5.5m/sec flow because of restrictions of the facility.

Then for higher speed than this about 5.5m/sec, the author could not help taking into consideration of the results of Adventure2 test data (See Fig.2 Performance curve with only two(2) WAIPs)

Physically speaking, the author estimated ΔDo changes proportionally with 1.5 powered speed and ΔR changes proportionally with 3 powered speed.

Usually wing drag changes proportionally with 2 powered speed but in WAIP case upper portion of the wing is considered vacuum enough and then the author estimated ΔDo to change proportionally with 1.5 powered speed.

For ΔR, 2 powered speed shows that air intake volume changes with 2 powered speed and microbubble diameter looks to become smaller with speed because the higher the speed, the shorter time water passes over the wing.

While air stays on the upper portion of the wing, microbubble is supposed to be generated. Then the author estimated ΔR to change proportionally with 3 powered speed.

But these are only assumptions based on CWC measured data.

Therefore all these ΔR values were corrected by Adventure 2 data. This corrected data is called Correction factor. So far maximum value of this Correction factor is about 2.0 and for higher speed more than 28 knots looks less than 1.0.

This like correction is very important for more exact D/R calculation of higher speed performance as a whole of a ship by a rational function approximation curve.

3.5. Actual drag reduction % calculation

By above described preparations, Actual drag reduction % calculation should be proceeded as follows;

(1) Target saving amount X should be fixed based on definite condition
such as;
/MCR
/NOR or MCR/NOR ratio or RPMmcr/RPMnor
/Lpp*B*D*d
X (in kgf):Target saving amount X can be fixed in kgf.

(2) EHP/BHP ratio should be defined, if not known, its ratio should be handled as a variable parameter.
BHP*(EHP/BHP) shows EHP of the ship.

(3) Choice of WAIP/ WAIP with air compressor;
$H=1/(2g)*V^2$
Here, H is in m, V: Ship speed in m/sec, g: gravity acceleration in m/sec^2
When H is larger than d, WAIP can be chosen and otherwise WAIP with air compressor.

(4) Drag reduction curve per WAIP piece should be drawn and figure at 0.75*Lpp (this length is called **effective length** up to this length drag reduced can be taken into consideration) should be defined...

(5) Δ Do should be extracted from this figure. And the remained amount should

be multiplied by Correction factor. The last figure corresponds to actual Drag Reduction per WAIP piece.: Y(in kgf)

(6) X(in kgf)/Y(in kgf) shows number of WAIP/ WAIP with air compressor to be installed for the ship.

(7) Detail allocations of WAIP/ WAIP with air compressor should be investigated.
If the number is smaller than X/Y, another WAIP/WAIP with air compressor should be added. If not, lower saving amount should be satisfied.
Actual distance for each allocated WAIP/ WAIP with air compressor from rear end of the wing shall be examined for final calculation.

(8) Actual drag reduction % should be calculated as X/required PS/KW of main engine at the speed

(9)Assumptions:
/ Correction factor be as per Adventure 2.
/ Each WAIP allocated athwartship at the same frame No. should work independently, that is, No overlap of microbubble.

3.6 Compressed air system design for WAIP with air compressor

A typical example of compressed air system design for WAIP with air compressor should be processed as following example;

1. Ship name:Ormoc Star:
2. Principal Particulars
   Lpp*Bmd*Dmd*draft=48.0*8.3*3.8*3.23m
   Ship Speed: 2,000ps at 310rpm
   Now running 14knots at 255rpm(calculated at 1,113ps)
3. Target saving amount shall be 10%ps of NOR running condition.
4. Selection of WAIP with airc compressor:
   H=(14*0.5144)**2/(2*9.8) =2.646<3.23
   WAIP with air compressor: is chosen.
5. Compressed air required (independently calculated):0.060 m^3/min. for one WAIP with air compressor

6. Total 29 WAIP with air compressor should be installed.

Then, total required amount of air can be calculated as follows;

0.06*29=1.74 m^3/min.at 1.0kgfG/cm^2

7.Compressor used specification: Type MT-23P; 8kgGf/$cm^{2,}$ 260litter/',min.,2ps

PV=Constant,

Required V at 1.323 kgfA/cm^2 is

1.323/9*1.74= 0.256 m^3/min.

8. For allowance, 2 sets of MT-23P required.

This ship aims at 10% saving, in other words, 111ps, out of which 4ps shall be used for compressed air supply.

4. Pressurizing down air/water interface to upon wing of WAIP to begin KHI was discovered at FEL on 15th July 2004

At the beginning of 2004,almost all knowledge about WAIP has turned out clear .but for large ships whose draft is very large nothing could not yet be known.

In July 2004,the author tried in the facility at FEL to slow flow velocity down to 3.5m/sec and found out air/water boundary exists amidst AIP: air induction pipe. Then the air water boundary was pressurized by air compressor down to upon the wing.

To much surprise, the author has found out KHI occurred.

First air phase and water phase began to mix up and then transformed into microbubble (KHI).

This is a process of microbubble generation.

Just by a little too much air pressure air balloon was made at WAIP wing, and the tip of the balloon began to break into microbubble.

Then the author realized pressurization by a little too much doesn't make nothing severe.

The author has recognized that air water simultaneous existence upon the wing is of paramount importance to initiate KHI.

Later air water mixture flow has been turned out one of Bistable flows.

From this time, for large ships, WAIP with air compressor is essential for Microbubble Drag Reduction.

Actual application of WAIP with air compressor was realized on board New Ferry Misaki August 2005 for the first time in the world.

5. Actual applications to various ships

5.1 New Ferry Misaki (August 2005.August 2006)

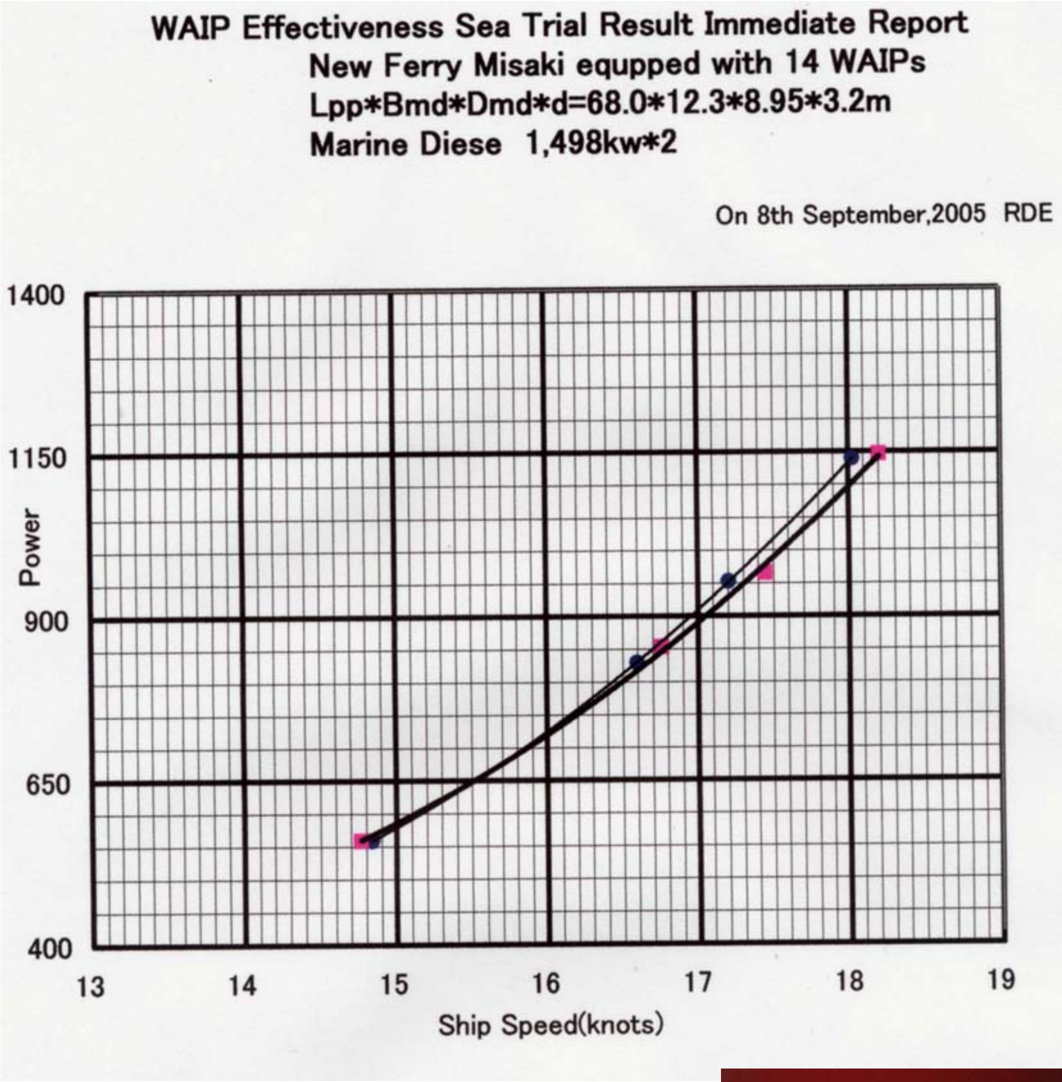
（1）New Ferry Misaki equipped with 14 WAIPs (Cast Iron)

Photo 10. New Ferry Misaki

Lpp*Bmd*Dmd*d=68.0*12.3*8.95*3.2m, 4,076ps

In August 2005, New Ferry Misaki with 14 WAIP onboard sea trial was carried out by one of the governmental authorities

in Japan and showed 5.8% Drag Reduction, which was very close to estimated calculation result.



Another 20 WAIPs were ordered from New Ferry Misaki owner and fitted to the ship in August 2006.

Photo 10. Another 20 WAIPs fitting

Photo 11. NK is surveying

Photo 11

"Summary: Main engine FO consumption change from without WAIP to 34 WAIP"

Photo 10

(1) NO WAIP 4,106Liter/day <100>

: 4,558.8Liter/Day,Average FO consumption for 77 days since Oct 2004 to August 2005.From this figure FO consumption of

G/E and thruster engine consumption data :852.9Liter/Day is extracted

4,958.8-852.9=4,105.9Liter/Day,4,106Liter/day

(2) 34WAIP recorded on 28th Apr.2007 3,733Liter/Day Average speed 14.71knots <90.9>

:Route: Shimogotou(133SM), NagasakiNewPort-Fukue-Naru-Wakamatsujima

Main engine average FO consumption data for 148 days from Sept 2007 to Mar 2008

(3) 34WAIP recorded on 27th Aug.2009 3,676Liter/Day Average speed 15.77knots <89.5>

:Route Kamigotou(122SM): sasebo-Enokidu-Onega-Uku

Recorded data: 3,615.3Liter/day, main engine FO consumption data taken from 53days June 2009 to Jul 2009 is adjusted as follows;

Route distance difference:12 to 133SM

Usually speed difference inflences FO consumption by 3 powers,but inthis case,to becomes too much low FO consumption,then here speed difference is supposed to apply by only linearly,

3,815.5*(133/122)*(14.71/15.77)=1.676.047 say 3,676 Liter/day

For reference

14.71/15.77=0.9327

(14.71/15.77)**3=0.8116

Later by claim from Chief Engineer, too much microbubble in sea chest, two(2) WAIPs on both sides was blanked.

Later by claim from chief engineer Mr. Kubo, two(2) WAIPs on both sides which look to flow above this sea chest were blanked. See Photo 12(August 2009).

This shows plenty microbubble comes along around sea chest.

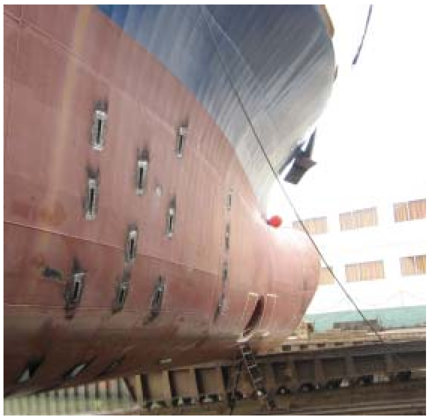
Photo 12 Partially blanked(August 2009)

5.2 Filia Ariea（June 2008）

52 WAIPs were installed to 85m coaster Filia Ariea, see Photo 13.

Photo13 Filia Ariea side view

Lpp*Bmd*Dmd*Output=84.95*13.75*5.55*1440 kw



Filia Ariea one of her sister ships

About 10% drag reduction was realized.

Onboard Filia Ariea, air blowers were installed by mistake instead of compressors. But thanks to shallow forward draft and to small capacity of air blowers, drag reduction by WAIP was carried out as calculated.at about 14knots,about 10% drag reduction was realized.

See next page Fig 6 report by Belkoned, famous Netherland measurement company.

5.2 Olivia Maersk(January 2009,not yet completed 2011)

In January 2009, 124WAIP were installed on board Olivia Maersk (Lpp=224m) as shown in Photo 14.

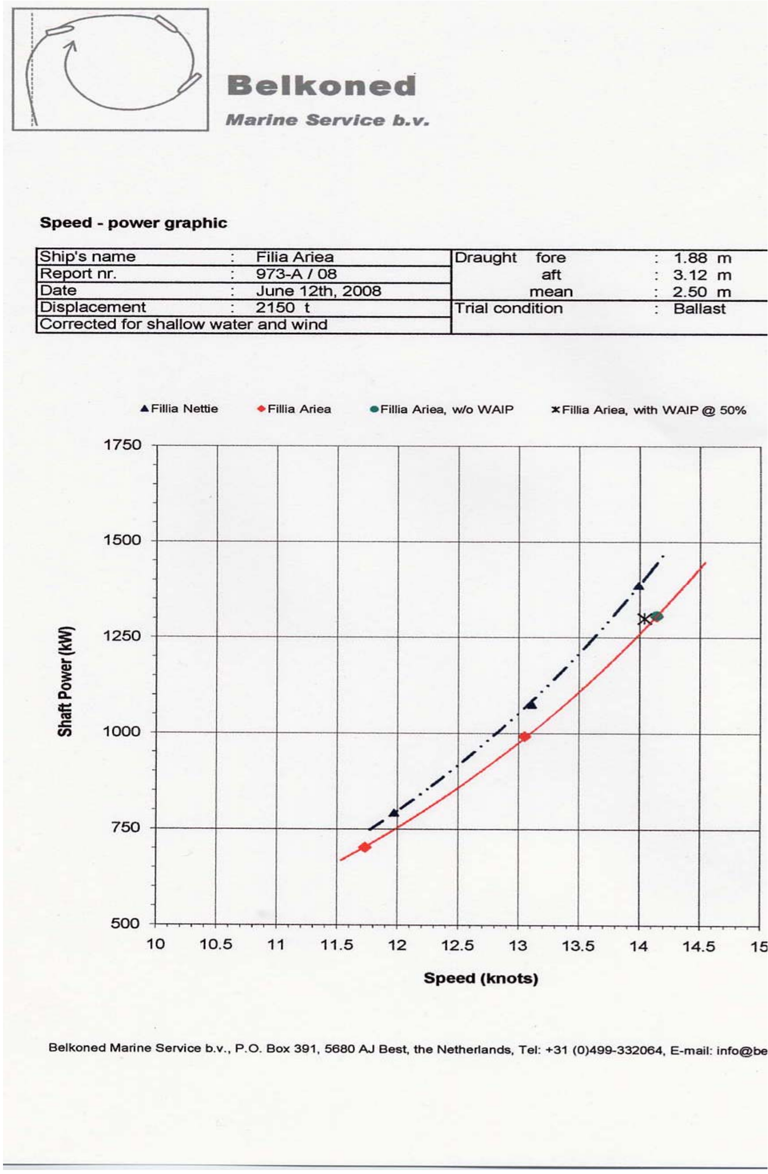


Fig 6 Filia Ariea trial report by Belkoned

Air blowers were mistaken as prime movers of WAIP, but, instead, prime mover of WAIP system is negative pressure generated above wing of WAIP whenever the ship advances. As of August 2011,the test of drag reduction is not completed yet.

Photo 14 Olivia Maersk

Lpp*Bmd*Dmd*Output=224*32.16*18.15*38,430kw

6. Observed microbubble behavior at sea(1999 to 2009) and others

6.1 Microbubble stays pretty long time as it being generated.

Once microbubble being emitted from WAIP, it stays in water pretty long time as it is.

This microbubble phenomenon was first discovered by Adventure2 actual sea trial at Imari bay in July 2002.

Speed test at the second run on the same course of the first run supersedes always previous run by staying microbubble in water.

In August 2008, Kiikaze(tested with WAIP,24m FRP boat) showed this phenomena about 1m deep stayed microbubble looked dark gray from far away at Tanabe bay in August 2008.

Microbubble whenever emitted in water stays aside hull as if clinging to the hull by negative pressure of wing of WAIP.

Next instant ship advances and another microbubble is generated by inflow water.

Likewise microbubble is generated in cloud around the hull, among through the cloud of microbubble, ship advances.

In this way drag reduction is carried out by the cloud of microbubble around the hull.

Negative pressure is generated on the wing of WAIP when ship advances.

Even if WAIP is exposed in air, as is often the case of slamming and large rolling and pitching, the next instant when WAIP is immersed in underwater ,it produces negative pressure and generates Microbubble

Generally speaking, hull wetted surface should be covered with microbubble as large as possible when aiming at maximum drag reduction of the ship.Frictional drag of any microbubble covered area is much less by 40 to 45% compared with that of non covered area.

6.2 Microbubble generation with least possible additional power:

Air phase and Water phase mixture at first and then transformation

into Kelvin Helmholtz Instability as of Microbubble generation mechanism;

Air is pressurized at corresponding water head of location of WAIP, which pressure is supplied by reservoir of compressor.

New Ferry Misaki needs only one step compressor (2.2kw*2 total) and Olivia Maersk needs 5 steps of compressor (1.5kw*5*2 total).

7. Assumption: Actual Drag Reduction way

In the preceeding chapters, especially empirical expression of drag reduction, the author has supposed the ship stands still and water goes around ship down to the stern.

But actually, negative pressure influences only WAIP wing portion and behavior of microbubble described above, has showed me real drag reduction way by WAIP microbubble is assumed to be carried out by tightening cloud of microbubble through which the ship advances.

Then this microbubble drag reduction will not depend on ship type, ship hull form, ship speed and so on.

This Microbubble Drag Reduction by WAIP is applicable to all kinds of ships in the world.

８． Conclusion

WAIP another way in air lubrication, one of the drag reduction by turbulence modulation/modification, this paper has summed up practical application except detail improvements and theoretical consideration so long as practical application is concerned.

Fortunately RDE has acquired an order from a catamaran operator in Philippines to install WAIP system to a catamaran.

A separate report which can prove assumption made in this report will be described in the future.

9.Acknowledgement

I would like to express my sincere thanks to Professor Dr. Yuichi Murai, University of Hokkaido who has taught me two phase (Air/water) flow and various matters in physics for more than 10(ten) years and his fellows; Associate professor Dr. Ichiro Kumagai and Associate professor Dr. Yuji Tasaka.

My discussions with those people were quite precious and my thanks to them is beyond description.

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