ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Performance Prediction Method for Unequally Loaded, Multiple Propeller Vessels

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Performance Prediction Method for Unequally Loaded, Multiple Propeller Vessels

1. PURPOSE OF PROCEDURE

The procedure gives a general description of an analytical method to predict delivered power and rate of revolutions for multiple propeller ships having unequal loading from model test results.

2. DESCRIPTION OF PROCEDURE

2.1 Introduction

The powering prediction (7.5-02-03-01.1) method is generally based on that for single or twin screw ships. This procedure describes only the difference from the original ITTC1978 procedure for single or twin screw ships.

Multiple propeller ships, having unequal loading, are defined as ships having multiple propulsion devices that intentionally have different levels of propulsion characteristics. This could be due to each propeller having different geometry or inflow conditions (mainly due to installation position). This definition could also include twin shaft vessels on which the two propellers rotate in the same direction.

Some good examples of this configuration are presented in Figure 1. Along with different geometry and inflow conditions, each propeller has unequal loading and different interactions with the hull, and this effect should be taken into account in the analysis method. By this definition, twin propeller ships (identical design and symmetric position) are treated as single propeller ships. As an example, an analysis method for triple shaft vessels having one propeller in the centre position and two propellers in the wing side position (where the propeller geometry of the two groups is not necessarily same) will be presented and this description can be extended to more multiple propeller ships.

The method requires respective results of a resistance test, a self-propulsion test and the open water characteristics of the model propellers used during the self-propulsion test. (Note that the characteristics of side propellers may be averaged, since the two side propellers are used in a pair and we don't need to distinguish them in propulsion test)

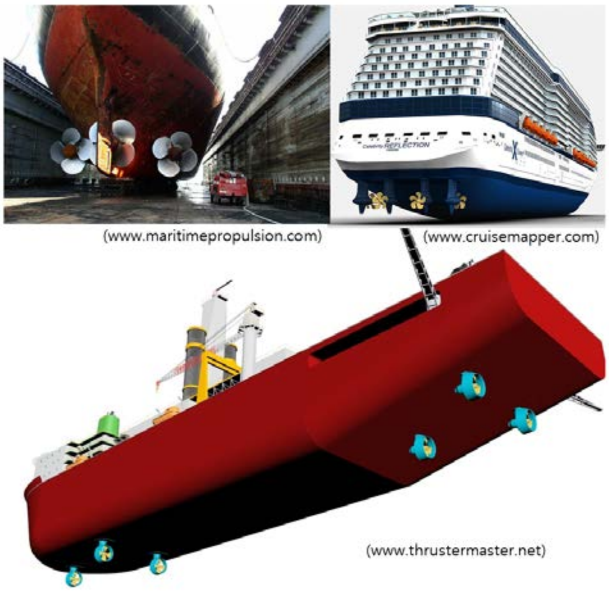

Fig. 1 Unequally loaded, multiple propeller vessels

At the initial design stage, the power distribution of the prime mover of each group is selected carefully and this design value of power ratio is taken into account in the model test by controlling the revolution ratio of each propellers.

As for a self-propulsion test, load variation test (LVT) results are also required to decide the self-propulsion point and the resistance fraction (load ratio) of the centre and side propellers. The details are described in section 2.3 of this procedure.

For the prediction of powering performance of triple shaft vessels, this procedure and guideline presents a new formula for the thrust deduction factor of each propeller. This formula was introduced to consider the interaction effects for the different levels of loading.

Following the general description of the model test and analysis procedure, an example calculation is presented to make this procedure more comprehensive and traceable.

2.2 Definition of Variables

The symbols not defined in the original ITTC1978 procedure are listed below:

R_C resistance of the model at each speed, corrected for temperature differences between resistance and propulsion tests

F_D tow force expected at each speed for the propelled ship self-propulsion point condition

ΔF change of towing force in load variation test

ΔT change of thrust in load variation test

Δt change of thrust deduction factor in load variation test

τ_i thrust deduction sensitivity for one propeller

γ_i resistance fraction for one propeller

t_i thrust deduction factor for one propeller.

Subscript "*i*" is to distinguish propellers. (For example, *i*=1, 2 and 3 correspond to center, port and starboard)

2.3 Model Test Procedure

The triple shaft self-propulsion test described herein incorporates the load variation test (LVT) process covered by 7.5-02-03-01.1 (Propulsion/Bollard Pull Test) and 7.5-02-03-01.4 (ITTC1978 Performance Prediction) methods. The application of the LVT procedure for a triple shaft vessel and the required data are described in the following sections.

In the case of a triple shaft vessel, the centre and side propellers can be controlled independently and can have different powering characteristics. Therefore, at each speed the load ratio of the centre and side propellers is not unique for the ship self-propulsion point (SSPP) where the tow force equals F_D. This means that the power distribution between the centre and side propellers must be determined to satisfy the particular requirement (i.e. efficiency, rate of revolution, acoustics, etc.). Since the power distribution is generally determined at the initial design stage with the selection of prime movers and propeller designs, the ratio of the revolution rates between the centre and side propellers is generally planned. The power ratio between the centre and side propellers during the model test is generally controlled by the propeller revolution ratio for the self-propulsion test. The initial test in this procedure uses this planned revolution rate ratio. Subsequent tests will then vary the revolution rates independently as described below.

This procedure requires the following three load variation tests for the performance predictions of a triple shaft vessel:

These tests are conducted at each desired speed to find the ship self-propulsion point and performance parameters across the desired speed range.

Before performing the LVT 1, the power ratio/revolution rate ratio is decided and the tests are conducted according to the ship self-propulsion point for that ratio. Tests can be conducted at alternate power/revolution rate ratios to determine the optimum power distribution for each speed.

Table 1: Classification of load variation tests

Test	Centre	Side
LVT 1: for all propellers (maintaining the desired revolution ratio between the center and side propellers)	Variable (with constant ratio)	
LVT 2: for center propeller (maintain the revolution rate of the side propellers from the LVT for all propellers at SSPP)	Variable (around SSPP rate)	Constant (SSPP rate)
LVT 3: for side propellers (maintaining the revolution rate of the center propeller from the LVT for all propellers at SSPP)	Constant (SSPP rate)	Variable (around SSPP rate)

To draw a total power & thrust curves for each ship speed as illustrated in Figure 2, multiple series of this procedure are required with different power/revolution rate ratios.

During the LVT 1 for all propellers the approach follows a standard powering test with the exception that the revolution ratio between the centre and side propellers is maintained at the predetermined design ratio corresponding to the planned power distribution. During this test, the ship self-propulsion point is defined when the revolution rates produce the total thrust necessary to achieve the required tow-force (F_D) for the specific speed and the chosen revolution ratio.

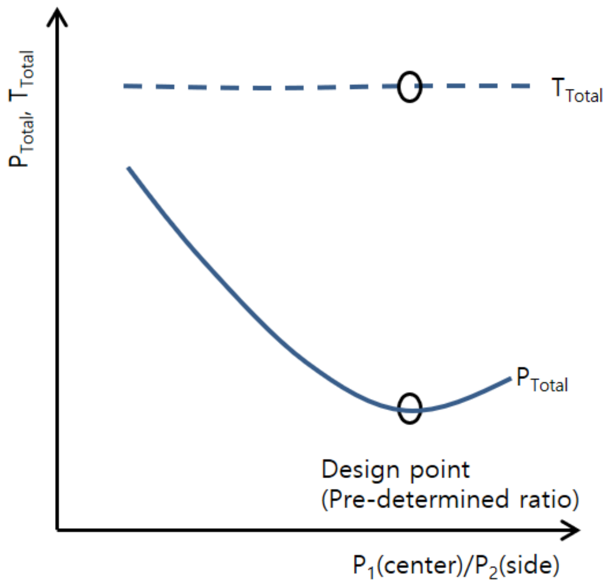

Fig. 2 Total Power & Thrust curves which represents several self-propulsion points at a single speed/various power ratios

Following the LVT 1 to determine the ship self-propulsion points for each speed, tests LVT 2 and LVT 3 are conducted. These tests are conducted to determine the thrust deduction values for the individual propellers used in the prediction process.

The LVT 2 is conducted to determine the centre propeller thrust deduction. During this test the side propeller revolution rate is held constant at the value corresponding to the ship self-propulsion point, found during LVT 1, and the centre propeller revolution rate is varied around its ship self-propulsion point value, also from LVT 1. This generates the horizontal red lines in Figure 3 corresponding to the specific speed and revolution rate ratio/power ratio.

Conversely, during LVT 3, the centre propeller revolution rate is held constant while the side propeller revolution rate is varied. This data represents the vertical purple lines in Figure 3 and provides the thrust deduction for the side propellers.

Figure 3 is an example schematic sketch for test planning where multiple speeds and power/revolution rate ratios are conducted. Each box represents the conduct of this procedure. Considering that the thrust is not actually the independent variable, the diagram is to be based on the power characteristics (i.e. revolution rate).

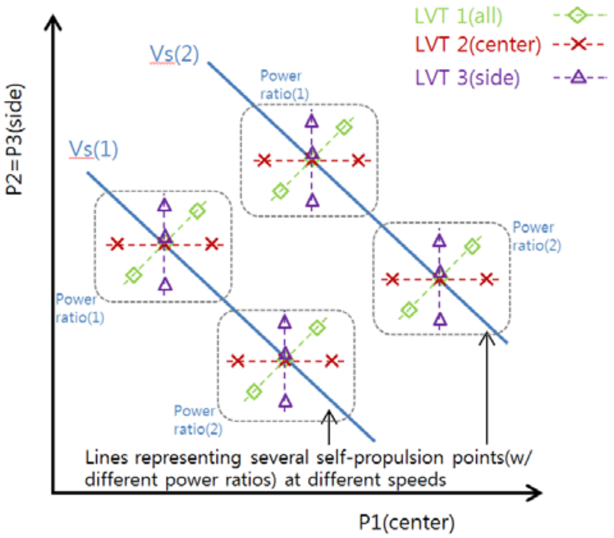

Fig. 3 Schematic sketch of LVT planning

In the case of a ship with n (n>3) propellers, subsequent LVT can be conducted as explained.

2.4 Analysis of the Model Test Results

The analysis methods of resistance for a triple shaft vessel are the same as the original procedure 7.5-02-02-01 (Resistance Test).

In the analysis of power and revolution prediction, the self-propulsion factors are derived according to 7.5-02-03-01.1 (Propulsion/Bollard Pull Test) and 7.5-02-03-01.4 (ITTC1978 Performance Prediction) methods. For the triple shaft vessels however, the thrust deduction factor is considered with special attention because different loading of propellers can have different effect on the resistance increase (or conception of thrust decrease). From the LVT for the center (LVT 2) and side (LVT 3) propellers, the effect on the resistance can be evaluated.

With the values of thrust deduction factor of each propeller, the delivered power and revolution of each propeller can be predicted.

The thrust deduction from a LVT is obtained from the original ITTC1978 description as;

$$1-t = 1-\frac{T_M+F_D-R_C}{T_M} = \frac{R_C-F_D}{T_M} \quad (1)$$

During the test for the centre propeller (LVT 2) and side propellers (LVT 3) for a triple shaft vessel the thrust, thrust deduction and towing force slightly change by ΔT, Δt and ΔF respectfully. The thrust deduction relation can then be written as;

$$1-(t+\Delta t) = \frac{R_C-(F_D+\Delta F)}{T_M+\Delta T} \quad (2)$$

Applying eq. (1) to eq. (2)

$$1-(t+\Delta t) = \frac{(1-t)T_M-\Delta F}{T_M+\Delta T} \quad (3)$$

Then eq. (3) can be rearranged to

$$1-\left\{\frac{(t+\Delta t)\Delta T+\Delta t T_M}{\Delta T}\right\} = -\frac{\Delta F}{\Delta T} \quad (4)$$

which can be written as

$$1-\tau = -\frac{\Delta F}{\Delta T} \quad (5)$$

where

$$\tau = t+\Delta t\frac{\Delta T+T_M}{\Delta T} \quad (6)$$

Note that eq. (2) and the following equations can be simplified under the assumption that Δt is negligibly small. Using this assumption, eq. (6) is not useful anymore and eq. (5) becomes the only equation to describe the sensitivity of the thrust deduction of the propeller.

The thrust deduction sensitivity ($1-\tau_i$) for each propeller is then derived from the LVT for the i-th propeller as the linear slope of the change in towing force and the change in thrust $(\Delta F/\Delta T)_i$.

$$1-\tau_i = \left(-\frac{\Delta F}{\Delta T}\right)_i \tag{7}$$

Then the portion of the resistance (load fraction, γ_i) that the i-th propeller is responsible for is determined as follows;

$$\gamma_i = \frac{T_i(1-\tau_i)}{\sum_{j=1}^{3} T_j(1-\tau_j)} \tag{8}$$

$$\sum_{i=1}^{3} \gamma_i = 1 \tag{9}$$

Therefore, the thrust deduction factor for the i-th propeller at the SSPP can be calculated as follows;

$$1-t_i = \gamma_\mathrm{i}\frac{R_\mathrm{TM}-F_\mathrm{D}}{T_i} \tag{10}$$

Usually the load factor of each propeller is a function of speed, therefore a number of self-propulsion points across the speed range should be calculated by the above method. Then a load factor and thrust deduction curves representing the self-propulsion points can be developed by curve fitting as a function of speed.

Similar to all other vessels, the total thrust deduction factor t can be obtained as follows using the sum of all propeller thrust;

$$t = -\frac{R_\mathrm{TM}-F_\mathrm{D}-\sum_{i=1}^{3}T_\mathrm{i}}{\sum_{i=1}^{3}T_\mathrm{i}} \tag{11}$$

Following the original procedure 7.5-02-03-01.4 (ITTC1978 Performance Prediction) the model-scale effective wake ratio for each propeller is obtained by the thrust-identification, w_{TM_i} (or torque-identification, w_{QM_i}) using the propeller open water characteristics. Then the relative rotative efficiency η_{RM_i} can be calculated and the full-scale predictions can be made. The full-scale predictions utilize the assumption that the thrust deduction and the relative rotative efficiency are the same at full-scale as calculated using model-scale values. Therefore;

$$t_{Si} = t_{Mi} \tag{12}$$

and

$$\eta_{\mathrm{RS}i} = \eta_{\mathrm{RM}i} \tag{13}$$

2.5 Full Scale Predictions

As described in the following sections, no full scale data is disclosed up to now and this section only shows the principle idea of extrapolation following procedure 7.5-02-03-01.4 (ITTC1978 Performance Prediction).

2.5.1 Total resistance of ship

Extrapolation method for the resistance is the same as the original procedure.

$$C_{TS} = \frac{S_S+S_{BK}}{S_S}[(1+K)C_{FS}+\Delta C_F+C_A]+C_R+C_{AAS}+C_{APPS} \tag{14}$$

The relation between total resistance and thrust is written as

$$R_{TS} = T_1(1-t_1)+T_2(1-t_2)+T_3(1-t_3) \tag{15}$$

Or, assuming two propulsors are acting similarly;

$$R_{TS} = T_1(1-t_1)+2T_2(1-t_2) \tag{16}$$

2.5.2 Scale effect corrections for propeller characteristics

The prediction method for characteristics of the full-scale propeller is also the same as the original procedure. However, corrections should be done for each propeller independently for the data obtained at the SSPP. The thrust and torque coefficients are computed in accordance with 7.5-02-03-01.1 (Propulsion/Bollard pull Test) and 7.5-02-03-01.4 (ITTC1978 Performance Prediction) methods. The full-scale values use corrected model-scale values as follows;

$$K_{TS} = K_{TM} - \Delta K_T \tag{17}$$

$$K_{QS} = K_{QM} - \Delta K_Q \tag{18}$$

Where

$$\Delta K_T = -\Delta C_D \cdot 0.3 \cdot \frac{P}{D} \cdot \frac{c \cdot Z}{D} \tag{19}$$

$$\Delta K_Q = \Delta C_D \cdot 0.25 \cdot \frac{c \cdot Z}{D} \tag{20}$$

The difference in drag coefficient, ΔC_D, between full and model-scale is;

$$\Delta C_D = C_{DM} - C_{DS} \tag{21}$$

Where

$$C_{DM} = 2\left(1 + 2\frac{t}{c}\right)\left[\frac{0.044}{(Re_{co})^{\frac{1}{6}}} - \frac{5}{(Re_{co})^{\frac{2}{3}}}\right] \tag{22}$$

and;

$$C_{DS} = 2\left(1 + 2\frac{t}{c}\right)\left(1.89 + 1.62 \cdot \log\frac{c}{k_P}\right)^{-2.5} \tag{23}$$

Details are described in the original 7.5-02-03-01.4 (ITTC1978 Performance Prediction) procedure.

2.5.3 Full scale wake and operating condition of propellers

The full-scale wake fraction is calculated by the ITTC1978 formula using the model wake fraction and the thrust deduction fraction for each propeller defined in section 2.4. The number and position of the rudder(s), type of side shaft support(s) (brackets or split stern) should be considered for each propeller. The formulas for the correction are the same as the original procedure but addressed separately for each propeller.

$$w_{TSi} = (t_i + w_{Ri}) + (w_{TMi} - t_i - w_{Ri})\frac{(1+k)C_{FS} + \Delta C_F}{(1+k)C_{FM}} \tag{24}$$

where w_{R_i} is set to zero when the rudder is not located behind the i-th propeller.

The full-scale load is obtained by the same procedure. However, the operating conditions of the centre and side propellers are different and must be computed independently using the individual model-scale load fractions and thrust deductions, and full-scale wake fractions for each propeller.

$$\frac{K_{TSi}}{J_i^2} = \frac{S_S}{2 \cdot D_S^2} \cdot \frac{C_{TS} \cdot \gamma_i}{(1-t_i)(1-w_{TSi})^2} \tag{25}$$

$$n_{Si} = \frac{(1-w_{TSi})V_S}{J_{TSi} D_S} \tag{26}$$

Finally, the delivered power, thrust and torque of each propeller are determined using full-scale parameters and the model-scale relative rotative efficiency as follows,

$$P_{DSi} = 2\pi\rho_S D_S^5 n_{Si}^3 \frac{K_{QTSi}}{\eta_{Ri}} \tag{27}$$

$$T_{Si} = \left(\frac{K_{TSi}}{J_i^2}\right) \cdot J_{TSi}^2 \rho_S D_S^4 n_{Si}^2 \tag{28}$$

$$Q_{Si} = \frac{K_{QTSi}}{\eta_{Ri}} \cdot \rho_S D_S^5 n_{Si}^2 \tag{29}$$

2.5.4 Model-ship correlation factor

The model-ship correlation factor should be based on systematic comparison between full scale trial results and predictions from model scale tests. Thus, the correlation factors for triple shaft vessels may differ from that of single/twin shaft vessels. However, no recommended value exists at present, since there is not enough data for triple shaft vessels.

2.6 Example Calculation

2.6.1 Subject vessel and basic data

A subject vessel, a 1,500 passenger/1,600 lane meters RoPax ferry, is selected. It has one center propeller and two wing-side pods. The ship's main particulars and details of the propulsion system are described in Table 2.

Table 2 Main particulars of the ship and propulsion system

Main Particulars		
Item	Ship	Model
Scale	18.000	
LBP(m)	155.70	8.650
B(m)	24.80	1.378
Td(m)	5.50	0.316
WSA(m^2)	4009.1	12.374
Vs(design)	22.5 kts	2.728 m/s
Ship Propulsion System		
Item	Main,center	Wing-side Pods
Diameter(m)	4.50	3.00
P/D(mean)	1.06	1.35
EAR	0.75	0.60
Power(kW)	10,400	6,500

The normal operation point of the propulsion system has a 20-60-20 power distribution ratio. The centre propeller delivers about 60% and the two wing-side pod thrusters deliver about 40% (each 20%) of the total propulsion power [1]. The corresponding revolution ratio between centre and side propellers is determined in advance as 1:1.293 (centre:side).

2.6.2 Model test data and analysis

The load variation test results for all three test conditions are presented below in Table 3.

From LVT 1 of all propellers, self-propulsion point data for the centre and side propellers is obtained as below;

From LVT of centre propeller and side propellers, the thrust deduction sensitivity, τ_i (i.e., effect of resistance change due to each propeller), resistance fraction γ_i and thrust deduction factor t_i can be calculated. Other propulsion factors are calculated with open water characteristics data of centre and side propellers and finally the delivered power and revolution of each propeller can be calculated based on the same procedure of ITTC78 original. (Details are referred to [1]).

A relatively smaller value of $(1-\tau_i)$ means a larger change in resistance for an increase in thrust at the self-propulsion condition, and this larger interaction effect results in a larger thrust deduction factor sensitivity. Note that the thrust deduction sensitivity is important in the distribution of the interactions not the absolute value of the thrust deduction.

From the model test, the delivered power and revolution of centre and side propellers are calculated separately and these results would be compared with sea trial data if they become available.

Table 3 Model test data for LVT for all/centre/side propellers

LVT 1 for all propellers				
Vs	[knot]	22.5		
Vm	[m/s]	2.728		
Fd	[N]	47.71		
Tf	[N]	47.3	58.1	36.1
n_centre	[Hz]	11.10	10.90	11.30
n_side	[Hz]	14.35	14.09	14.61
T_centre	[N]	102.3	95.3	109.8
T_side	[N]	23.4	21.0	25.8
Q_centre	[Nm]	4.93	4.64	5.25
Q_side	[Nm]	1.26	1.18	1.35
P_centre	[W]	344.0	317.5	372.5
P_side	[W]	114.0	104.1	123.9

LVT 2 for center propeller				
Vs	[knot]	22.5		
Vm	[m/s]	2.728		
Fd	[N]	47.71		
Tf	[N]	47.7	37.3	54.7
n_center	[Hz]	11.09	11.39	10.89
n_side	[Hz]	14.34	14.34	14.34
T_center	[N]	102.1	113.4	94.5
T_side	[N]	23.3	23.3	23.3
Q_center	[Nm]	4.92	5.39	5.08
Q_side	[Nm]	1.26	1.26	1.26
P_center	[W]	343.0	386.0	347.6
P_side	[W]	113.4	113.4	113.4

LVT 3 for side propeller				
Vs	[knot]	22.5		
Vm	[m/s]	2.728		
Fd	[N]	47.71		
Tf	[N]	47.7	50.6	44.8
n_center	[Hz]	11.09	11.09	11.09
n_side	[Hz]	14.34	14.04	14.64
T_center	[N]	102.1	102.1	102.1
T_side	[N]	23.3	20.4	26.3
Q_center	[Nm]	4.92	4.92	4.92
Q_side	[Nm]	1.26	1.15	1.37
P_center	[W]	343.0	343.0	343.0
P_side	[W]	113.4	101.8	125.7

Table 4 Self-propulsion point data

Item	n	T	Q
	[Hz]	[N]	[Nm]
Centre	11.09	102.1	4.92
Side	14.34	23.3	1.26

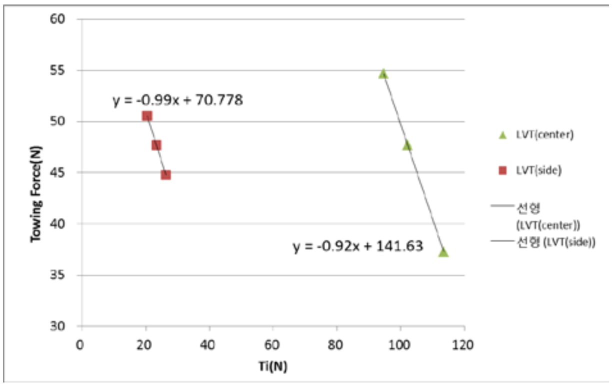

Fig. 4 Data graph for thrust deduction sensitivity for centre/side propeller

Table 5 Self-propulsion factors

Item		Center	Side
$1-\tau_i$ (thrust deduction sensitivity)	[-]	0.92	0.99
γ_i (resistance fraction)	[-]	0.671	0.165
t_i (thrust deduction factor)	[-]	0.173	0.110
W_{TS}	-	0.191	0.045
K_T/J^2	-	0.355	0.131
J_{TS}	-	0.782	1.101
η_H	-	1.023	0.932
η_O	-	0.669	0.591
η_D	-	0.678	0.558
P_E	[kW]	6178	3035
P_D	[kW]	9106	5440
P_D_total	[kW]	14546	
n	[RPM]	159.7	200.8

*Rtm for t_i calculation is 173.6N

3. VALIDATION

3.1 Uncertainty Analysis

General uncertainty analysis procedure for self-propulsion test will be applied.

3.2 Comparison with Full Scale Results

Not yet available

4. REFERENCES

[1] H. Seo, S. Go, S. Lee and J. Kwon(2011), ‘A Study on the Powering Performance of Multi-axes Propulsion Ships with Wing Pods’, SMP’11, Hamburg, Germany