脱炭素船の MBD
MBD of Wind Assistive Ships

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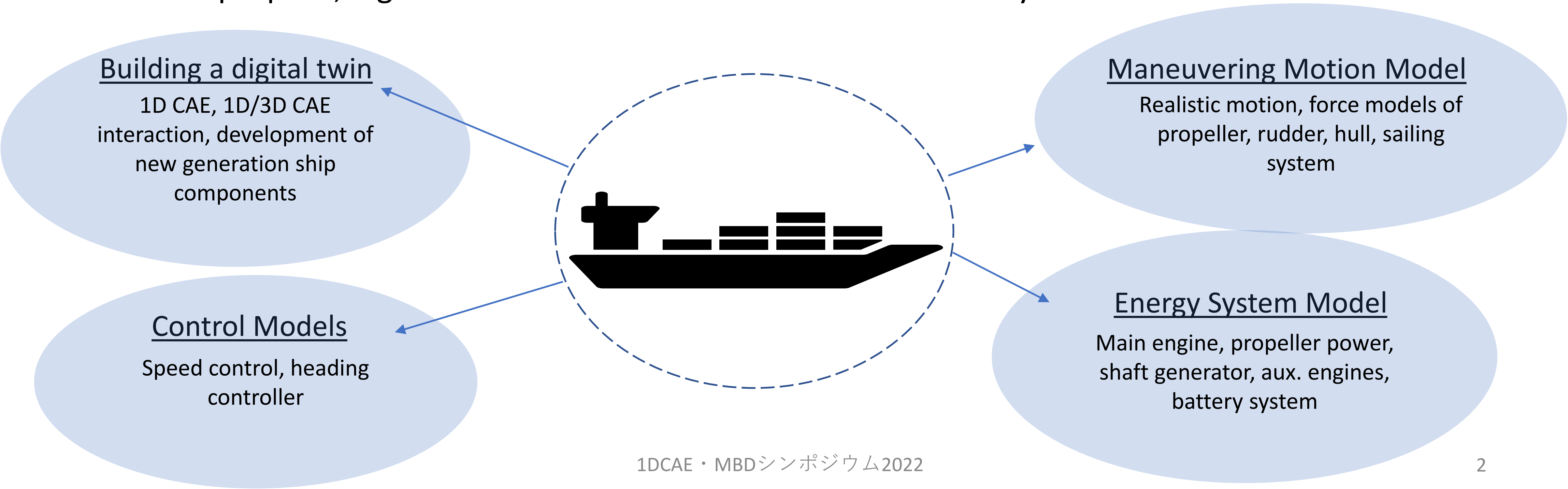
Background

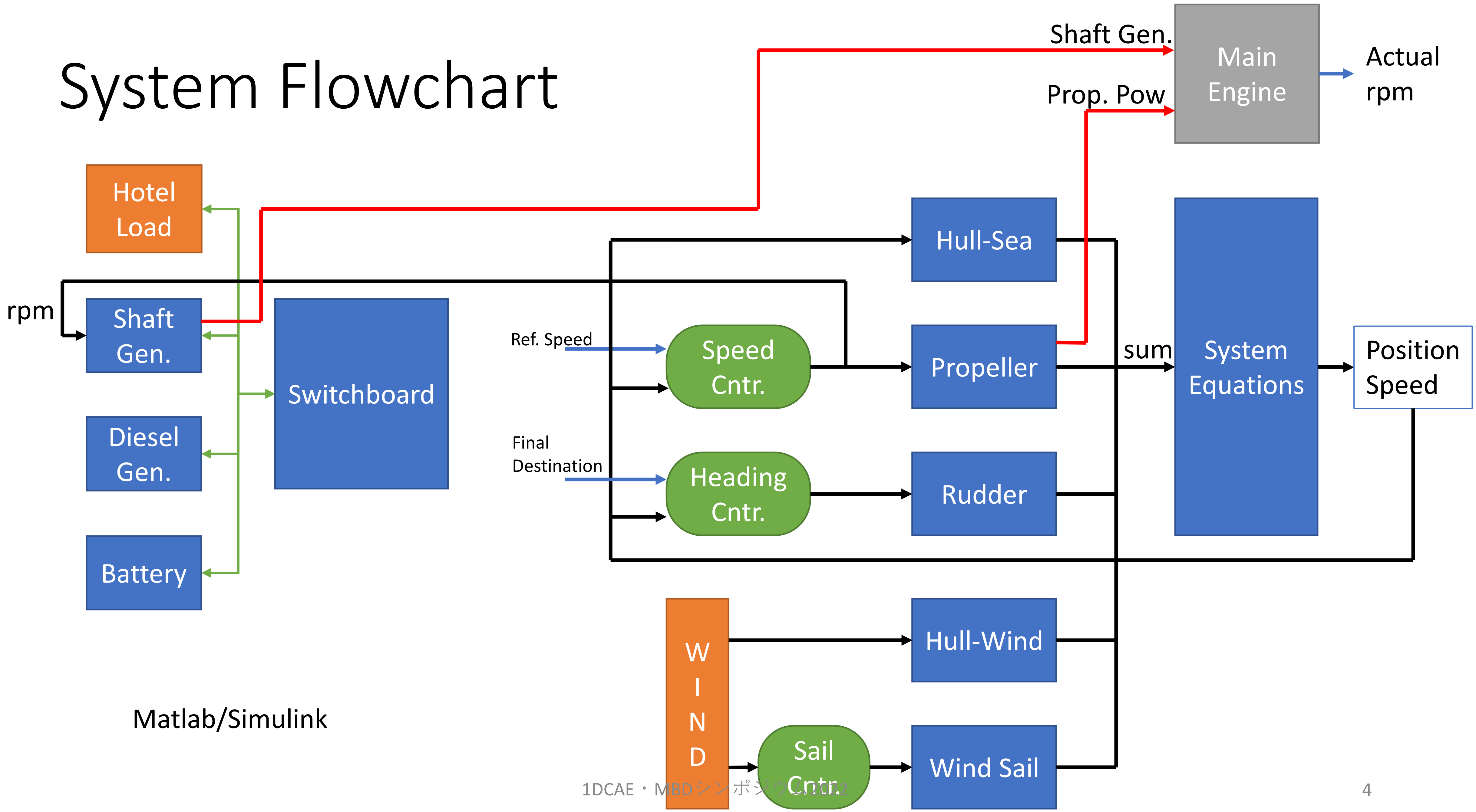
- Increasing fossil fuel consumption lead high level of CO_2 emission and becomes important issue in all industries.
- Reduction of CO_2 emission is the aim for decarbonized societies.
- For this purpose, digitalization of maritime structures is necessary.



Overview

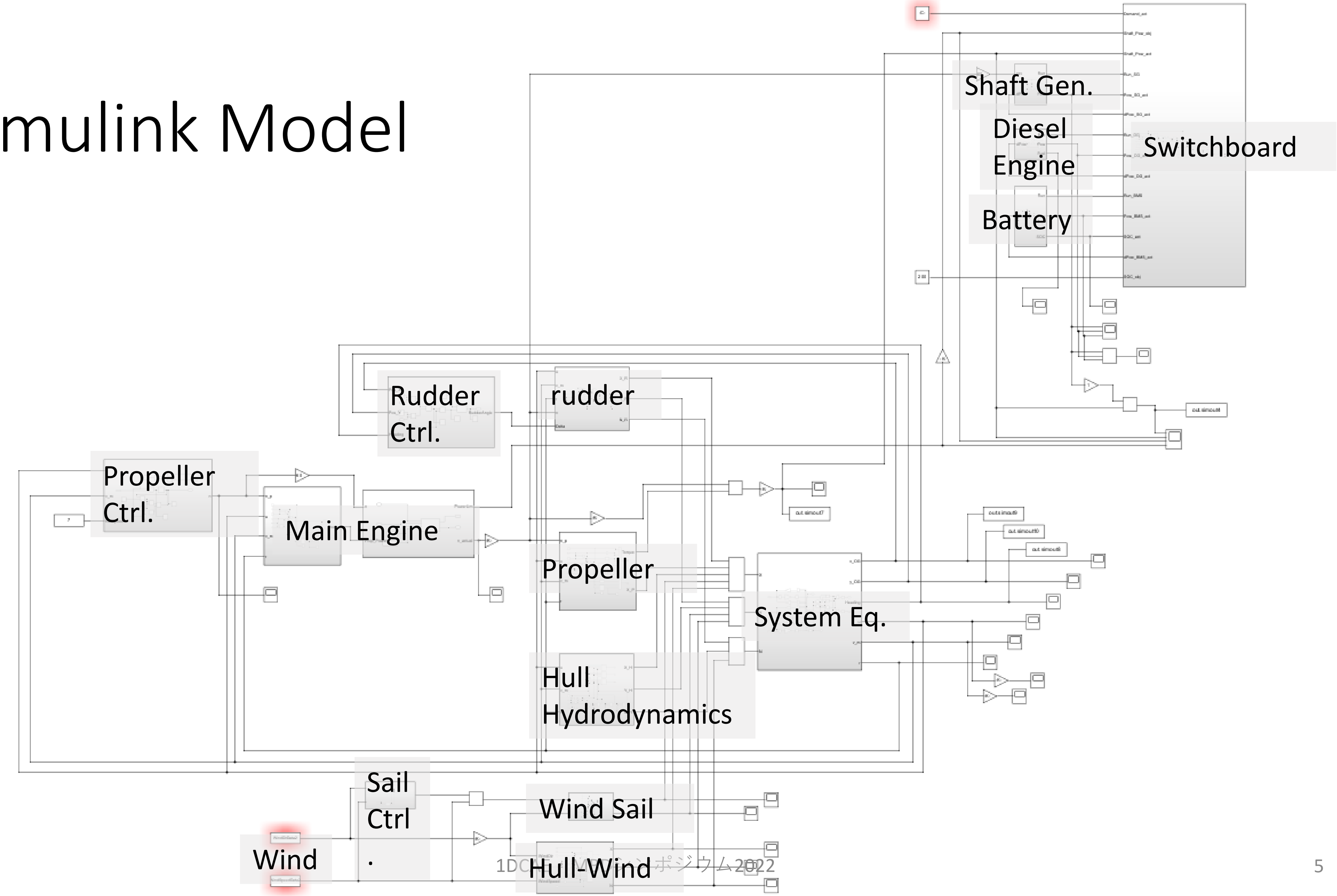
- Aim:
  - To understand ship dynamics, maneuvering, fuel consumption, power management systems
  - To model interaction between subsystems of ship
- Method:
  - MMG model for mechanical systems
    - Hull-Sea interaction, Hull-Wind interaction, propeller, rudder, Wind Sail, etc.
  - Electric/Energy Systems
    - Generators, battery management system etc.

System Flowchart



Matlab/Simulink

Simulink Model



Motion and Maneuvering Model

- Equation of Motion
  - 3 degree of freedom
  - Surge, sway, yaw

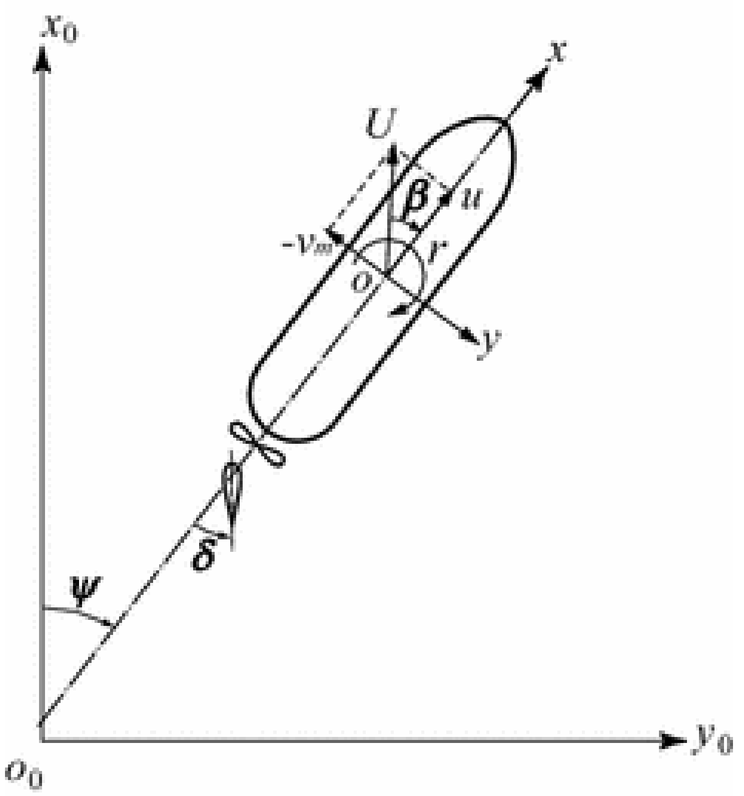
System Equation

$$(m + m_x)\dot{u} - (m + m_y)v_m r - x_G m r^2 = X$$
$$(m + m_y)\dot{v}_m + (m + m_x)ur + x_G m\dot{r} = Y$$
$$(I_{zG} + x_G^2 m + J_z)\dot{r} + x_G m(\dot{v}_m + ur) = N_m$$

- MMG model – based on system modelling approach
  - Consider each source of force generation separately.
  - Hull-Sea, $X/Y/N_H$
  - Propeller , $X/Y/N_P$
  - Rudder , $X/Y/N_R$
  - Hull-Wind , $X/Y/N_A$
  - Wind Sail, $X/Y/N_S$

Forces

$$X = X_H + X_P + X_R + X_A + X_S$$
$$Y = Y_H + Y_P + Y_R + Y_A + Y_S$$
$$N = N_H + N_P + N_R + N_A + N_S$$



Yasukawa, H., Yoshimura, Y. Introduction of MMG standard method for ship maneuvering predictions. *J Mar Sci Technol* **20**, 37–52 (2015). https://doi.org/10.1007/s00773-014-0293-y

Hull-Sea Interaction

$$\left.\begin{aligned} X_H &= (1/2)\rho L_{pp} d U^2 X'_H(v'_m, r') \\ Y_H &= (1/2)\rho L_{pp} d U^2 Y'_H(v'_m, r') \\ N_H &= (1/2)\rho L_{pp}^2 d U^2 N'_H(v'_m, r'), \end{aligned}\right\}$$

$$\begin{aligned} X'_H(v'_m, r') &= -R'_0 + X'_{vv} v'^2_m + X'_{vr} v'_m r' + X'_{rr} r'^2 + X'_{vvvv} v'^4_m \\ Y'_H(v'_m, r') &= Y'_v v'_m + Y'_R r' + Y'_{vvv} v'^3_m + Y'_{vvr} v'^2_m r' + Y'_{vrr} v'_m r'^2 + Y'_{rrr} r'^3 \\ N'_H(v'_m, r') &= N'_v v'_m + N'_R r' + N'_{vvv} v'^3_m + N'_{vvr} v'^2_m r' + N'_{vrr} v'_m r'^2 + N'_{rrr} r'^3 \end{aligned}$$

- Resistive forces acting on ship
- Defined based on normalized velocities, v'_m and r'
- Hydrodynamic coefficients: $X'_{\dots}$, $Y'_{\dots}$, $N'_{\dots}$
- R_0: the resistance during a straight path

Propeller

$X_P = (1 - t_p) \times T$
$Y_P = 0$
$N_P = 0$

$T = \rho\, n_P^2\, D_P^4\, K_T(J_P)$

$J_P = \frac{u(1-w_P)}{n_P D_P}$

w_P is affected propeller position, u, v, and r.

- Propeller only produce thrust in X direction.

- $Thrust\ (T) = \rho\, n_P^2\, D_P^4\, K_T(J_P)$
- $Moment\ (Q) = \rho\, n_P^2\, D_P^5\, K_\theta(J_P)$

Rudder

$$X_R = -(1 - t_R)F_N \sin\delta$$
$$Y_R = -(1 + a_H)F_N \cos\delta$$
$$N_R = -(x_R + a_H x_H)F_N \cos\delta,$$

$$F_N = (1/2)\rho A_R U_R^2 f_\alpha \sin\alpha_R$$

$$U_R = \sqrt{u_R^2 + v_R^2}$$

$$\alpha_R = \delta - \tan^{-1}\left(\frac{v_R}{u_R}\right) \simeq \delta - \frac{v_R}{u_R}$$

$$v_R = U\gamma_R \beta_R$$

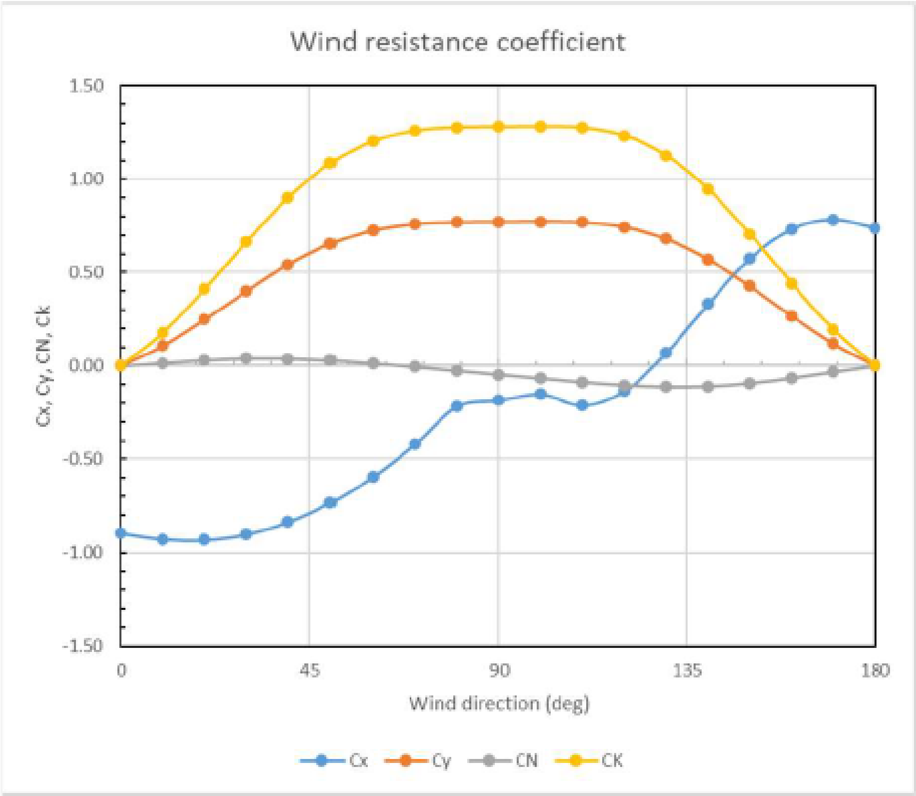
where

$$\beta_R = \beta - \ell'_R r'$$

$$u_R = \varepsilon u(1 - w_P)\sqrt{\eta\left\{1 + \kappa\left(\sqrt{1 + \frac{8K_T}{\pi J_P^2}} - 1\right)\right\}^2 + (1 - \eta)}$$

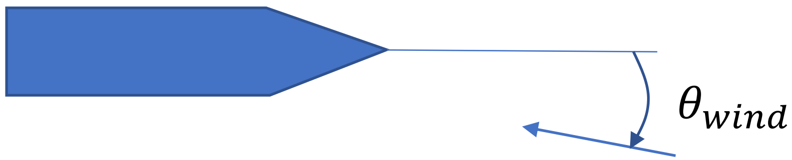
- Forces on rudder module is calculated based on the flow around rudder. (u_R, v_R)

Hull-Wind Interaction



Wind Direction (deg)	Cx	Cy	CN	CK
0	-0.90	0.00	0.00	0.00
10	-0.93	0.11	0.02	0.18
20	-0.93	0.25	0.03	0.41
30	-0.90	0.40	0.04	0.66
40	-0.84	0.54	0.04	0.90
50	-0.73	0.66	0.03	1.09
60	-0.59	0.73	0.01	1.20
70	-0.42	0.76	-0.01	1.26
80	-0.22	0.77	-0.03	1.28
90	-0.18	0.77	-0.05	1.28
100	-0.15	0.77	-0.07	1.28
110	-0.21	0.77	-0.09	1.28
120	-0.13	0.74	-0.10	1.23
130	0.07	0.68	-0.11	1.13
140	0.33	0.57	-0.11	0.95
150	0.57	0.43	-0.09	0.71
160	0.73	0.27	-0.06	0.44
170	0.79	0.12	-0.03	0.20
180	0.74	0.00	0.00	0.00

- C_X, C_Y, C_N
- Frontal, Lateral Areas
- Forces in X, Y, N



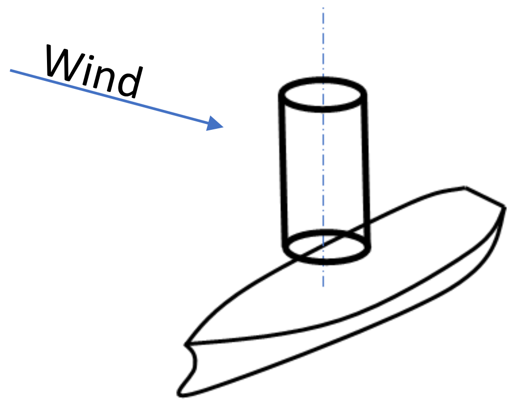
$$C_X = X_A / (q_A A_F)$$
$$C_Y = Y_A / (q_A A_L)$$
$$C_N = N_A / (q_A A_L L_{OA})$$
$$C_K = K_A / (q_A A_L H_L)$$

Estimation method is explained in the reference paper below：

https://dl.ndl.go.jp/view/download/digidepo_10783918_po_ART0006391406.pdf?contentNo=1&alternativeNo=

Wind Sail

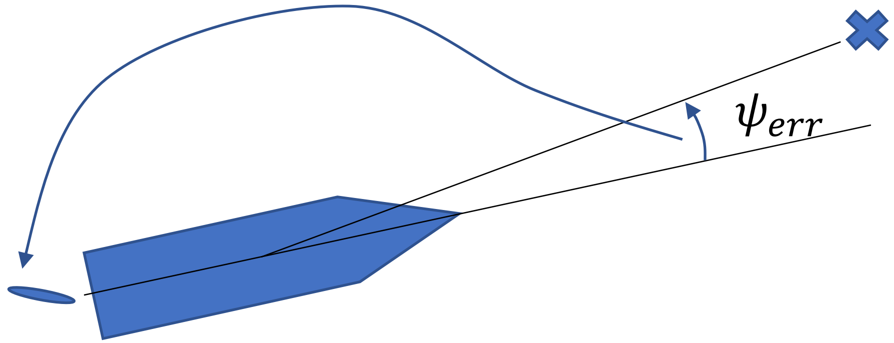
- Sail system is also similar to hull-wind interaction.
- Lift and drag forces were generated due to airflow around rotating cylinder.

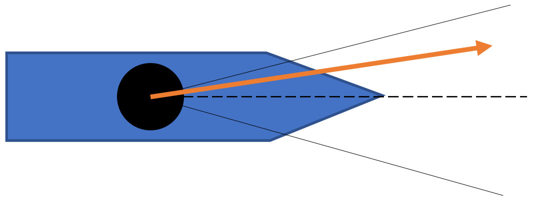


- Generated forces were calculated by using wind speed and wind direction. (Look-up table)

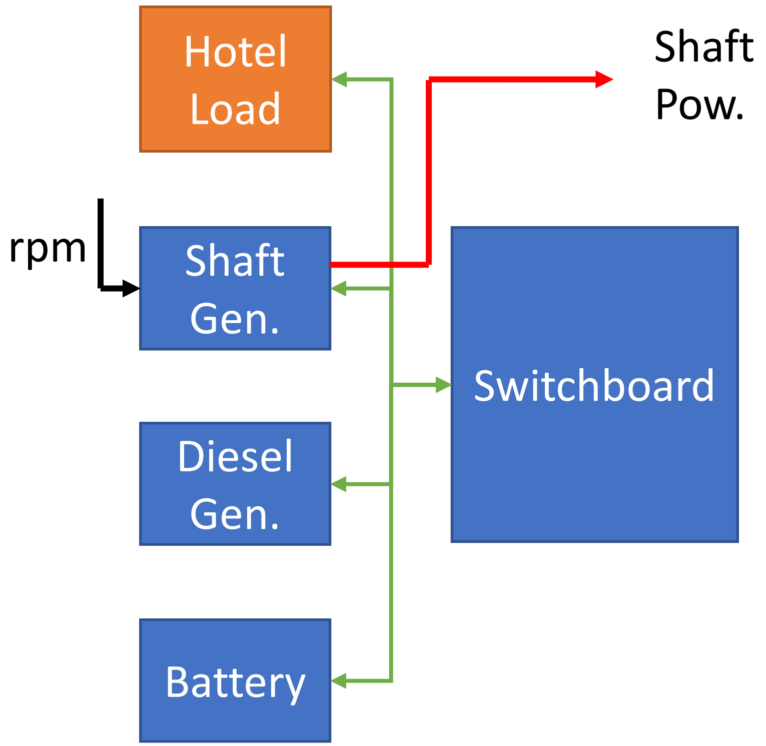
Controllers

- Propeller speed controller
  - Ship speed was set to 15 knots. PID controller was applied to keep speed same by controlling propeller speed
- Rudder angle controller
  - Rudder angle control to set heading angle always towards to destination point
- Wind sail controller (On/Off)
  - If the resultant force coming from wind sail is between +- 15 degree relative to the nose of ship, it is set on, otherwise it is off.

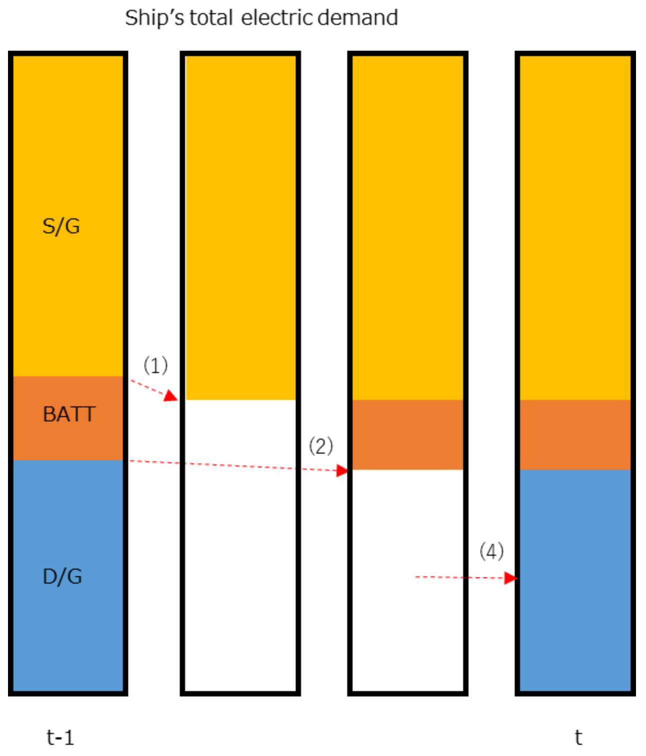




Electric Systems and Power Management

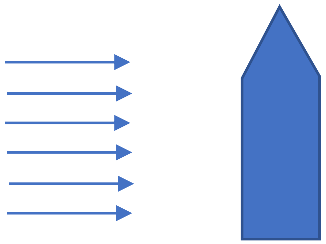


- Simple priority-based energy management
- Switchboard manages devices to store and release energy.
  - First, shaft generator
  - Second, battery due to having a faster response
  - Third, diesel engine as an additional power source

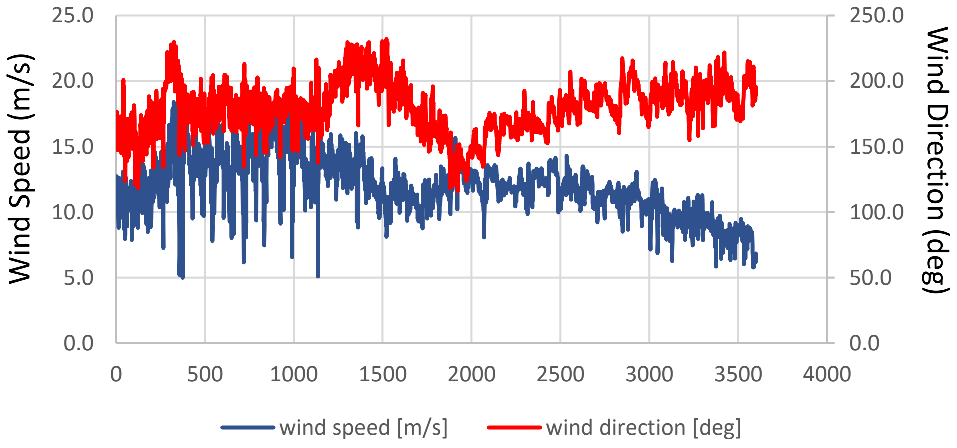


Can wind assistance system reduce fuel consumption?

- First, a constant beam wind is applied.
  - Wind was considered coming at 90 degree
  - Wind speed was also constant.

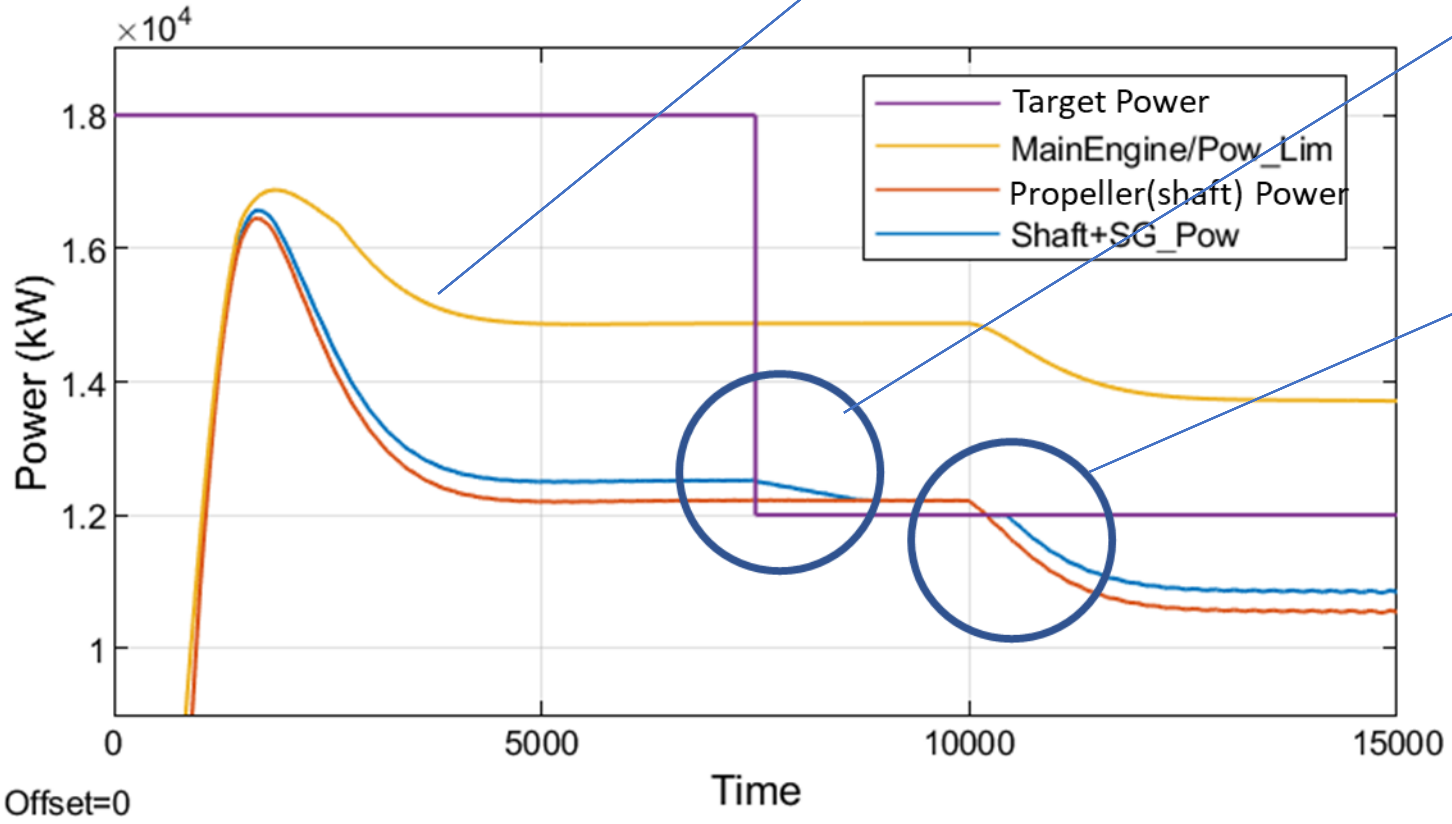


- Then, an experimental data of wind speed and direction was considered.



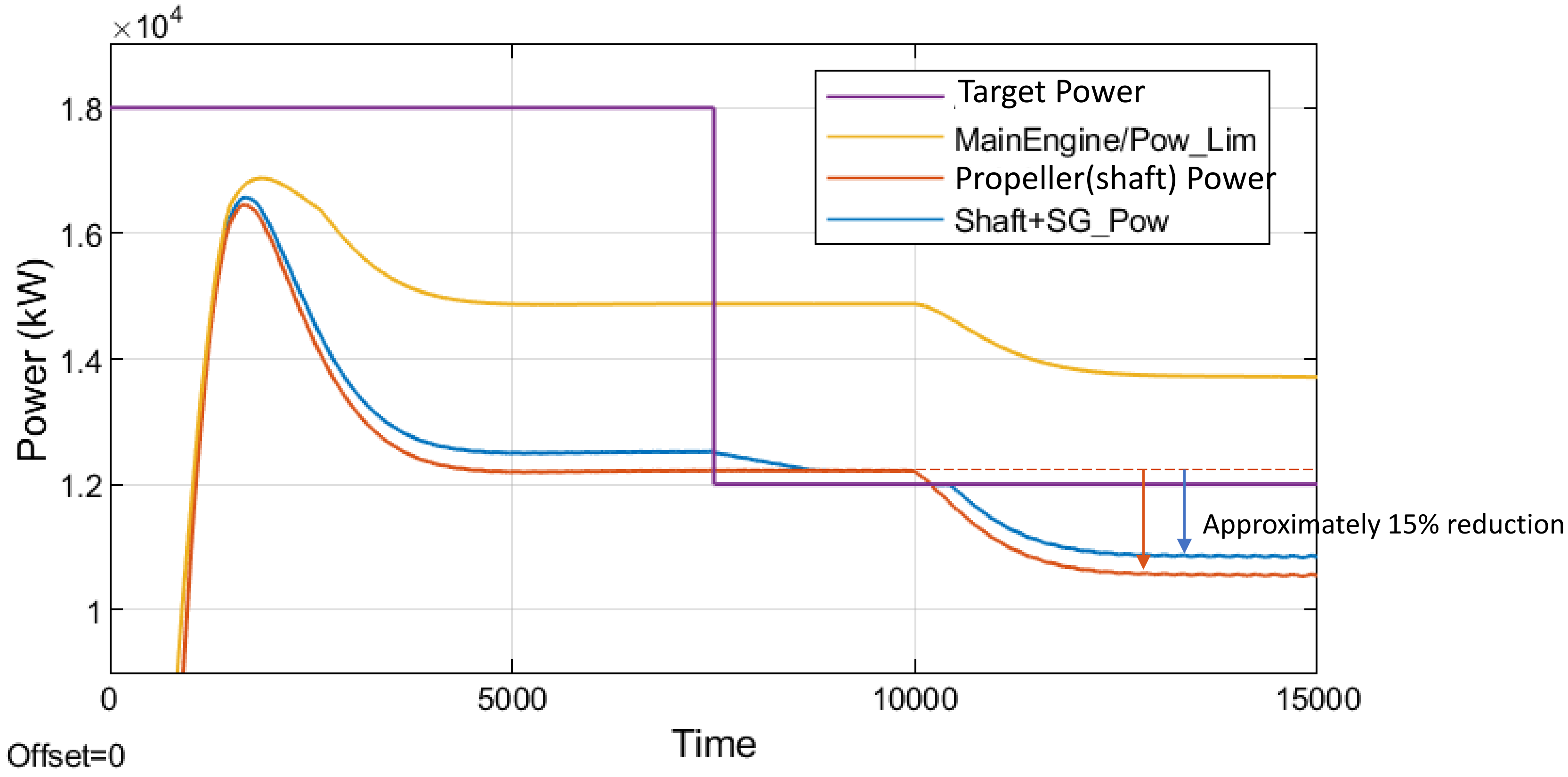
System Behavior under Constant Wind Close-Up

Limiting power of main engine was not exceeded during analyses.



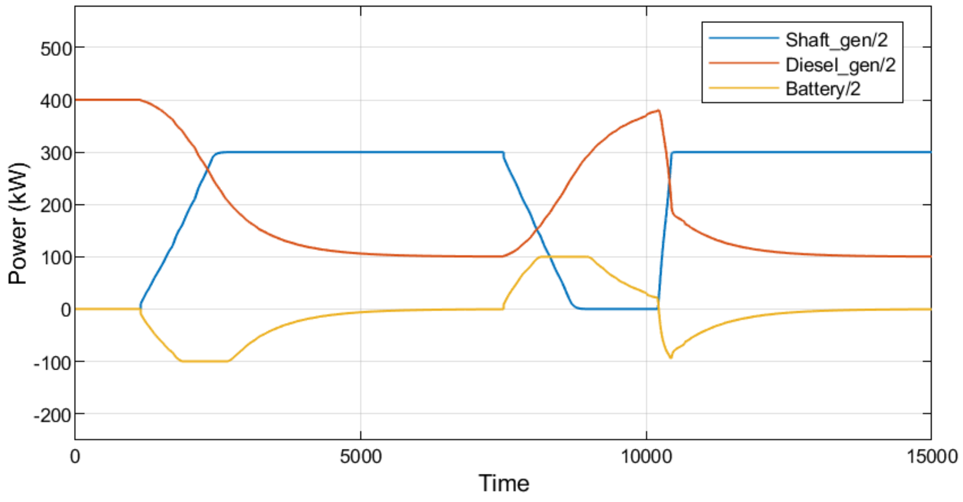
- Target power is reduced at 7500 s.
  - Shaft generator stops
- Wind Sailing System was activated manually at 10000 s.
  - Engine power and propeller power decreased.
  - Shaft generator restarts.

System Behavior under Constant Wind Close-Up



- Main Engine power is basically Shaft+SG power.
- Yellow Line is limiting power for given rpm.
- Purple is the target power.
- We can calculate how much power reduction is provided by using before and after WAD is active.

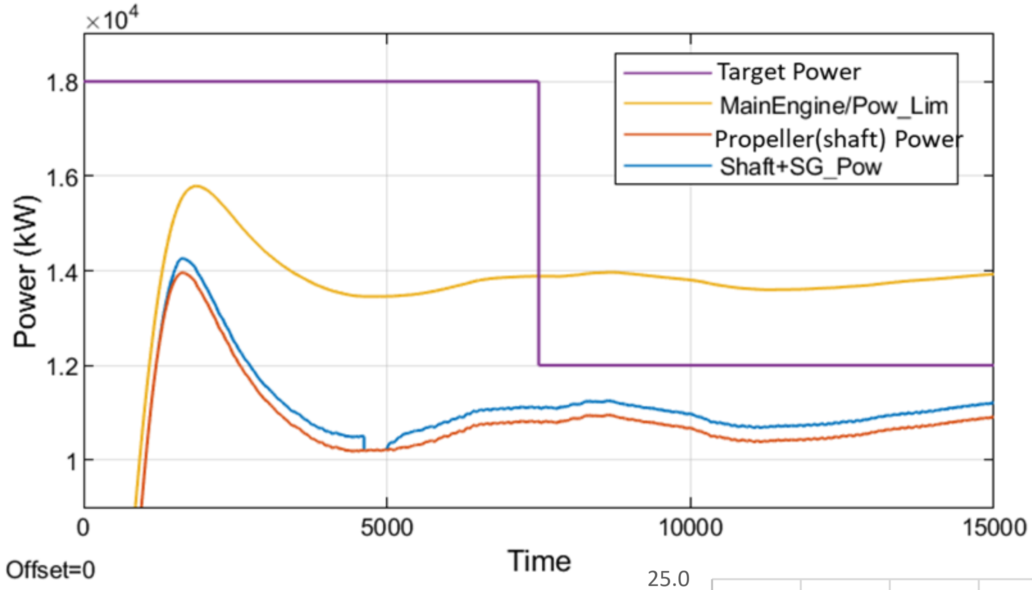
Electric Point of View

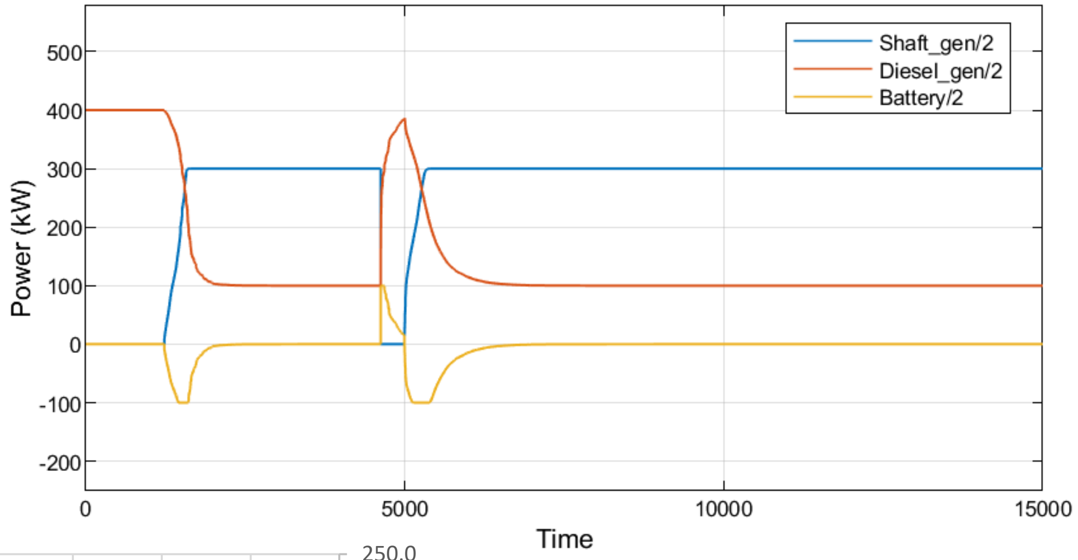


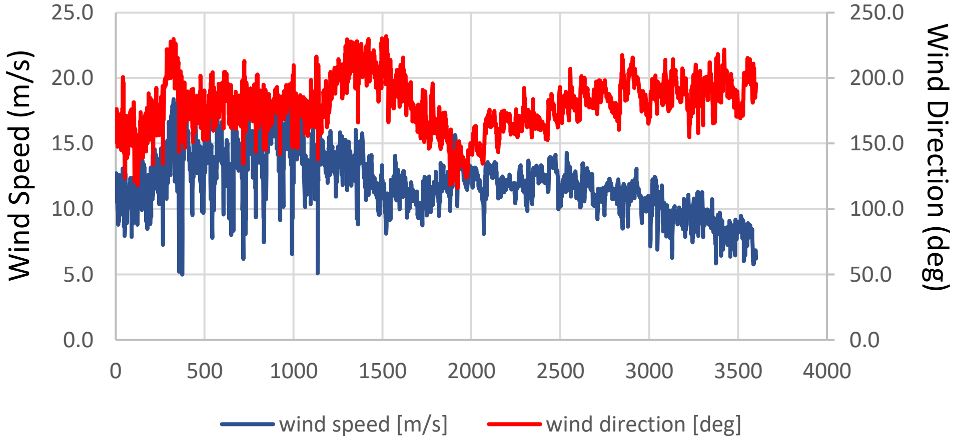
- Engine starts from 0.
  - Diesel engine also works.
- Then, it reaches a stable rotational speed.
  - Shaft generator starts to run.
  - Diesel engine power reduces.
- Optimal power was reduced.
  - Shaft generator stops running.
  - Diesel engine becomes active again.
- Wind Sailing system starts working
  - Total propeller power reduces.
  - Shaft generator starts running again.
  - Diesel engine stops

System Behavior under Real Wind Data

When Sailing system is always active

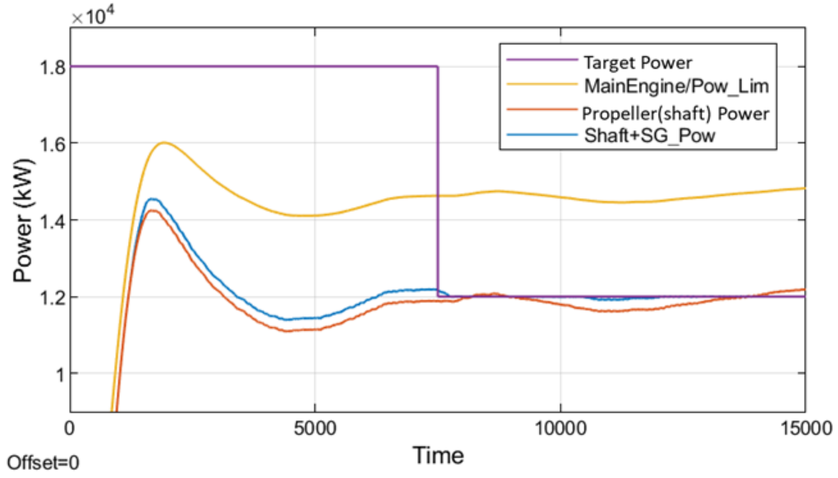


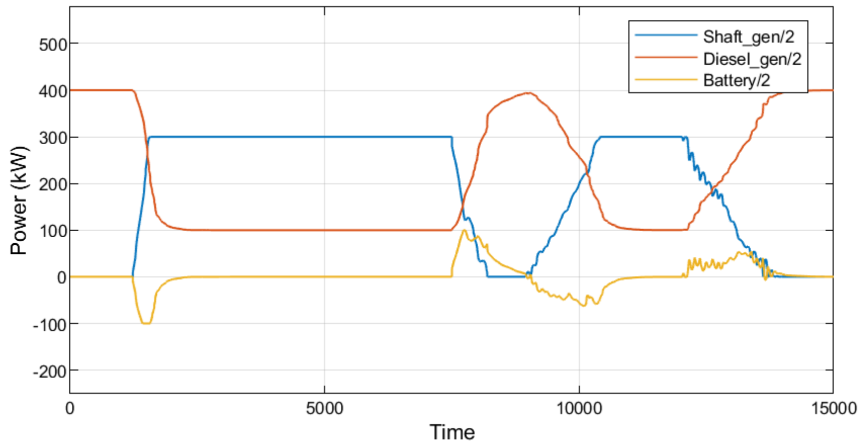




System Behavior under Real Wind Data

When a sailing control system is implemented





- These results show that how energy and power demands changes and system responds based on changing requirements.

Discussion

- 1D/CAE model of ship allows us to understand the potential of wind assistance systems.
- Approximately up to 15% reduction in the power consumption can be achieved and contribute the reduction of fuel consumption, greenhouse gases and CO_2 emission.
- The current study investigates only performance of wind assistance system with specified parameters. The reduction in fuel consumption can be further obtained by optimized wind assistance system.
- The benefit of wind assistance systems can be increased by optimizing the route in the next studies.

Conclusion and Future Studies

- 1D CAE model of ship was built considering mechanics, electrics, power dynamics.
  - Allows developing new designs using hardware-in-loop, software-in-loop systems
  - 1D/3D CAE connected product development
  - Enables the investigation of hybrid propulsion, etc.
- Application of wind assistive technology
  - Rotor sails
  - Wind sails, kites for future studies
- In the future studies, it is also necessary to consider rolling motion for stability calculations.
- Also, the strength and deflection limits should be considered to set a limit for wind assistive systems.