Advanced Propulsion System GEM 423E

Week 6: Propeller-Ship Interaction

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  - Propeller weight
  - Dry propeller inertia
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- Hydrodynamic interaction

General

General

- The propeller and ship interact in a variety of ways.
- This interaction is effected either through the coupling between the shafting system and the vessel or via pressure pulses transmitted through the water from the propeller to the hull surface.
- The interaction forces and moments can be considered to compromise both a constant and a fluctuating component.

- The constant components of the interaction
  - propeller weight, inertia
  - the mean wake field
- The fluctuating interactions
  - The variations in the wake field generated by the ship
  - Propeller out-of-balance forces and moments

1. Bearing forces — The forces and moments transmitted through the shafting system
2. Hydrodynamic forces — The forces experienced by the ship that are transmitted through the water in the form of pressure pulses

Bearing Forces

Bearing Forces

- The sources of the propeller bearing forces are;

Propeller weight and center of gravity

Dry propeller inertia

Propeller forces and moments

Added mass, inertia and damping

Out-of-balance forces and moments

Propeller weight

- The dry weight is the weight of the propeller in air.
- The effective weight of the propeller experienced by the ship's tail shaft is

$$W_E = W_D - U$$

W_D : The weight of the propeller in air

U : Archemedean upthrust

- The dry weight calculation is carried out in two parts;
  - First: the blade including an allowance for fillets
  - Second: the calculation of the weight of the propeller boss or hub.
- The blade weight calculation is essentially performed by means of a double integration over the blade form.
- The first integration evaluates the area of each helicoidal section by integration of the blade thickness distribution over the chord length

- Hence for each section the area of the section is given by,

$$A_x = \int_0^c t(x)dx$$

$t(x)$: *the section thickness at each chordal location*

c : *the section chordal length*

A_x : *the section area at the radial position* $x = r/R$

- The integration can be accomplished by using any numerical integration technique

- The second integration to be performed is the radial quadrature of the of the sectional areas A_x between the boss, or hub radius, and the propeller tip.
- This integration gives the blade volume for conventional blade forms as follows:

$$V' = \int_{r_h}^{R} A_x dr$$

- For non-conventional blade forms it is advisable to evaluate these parameters by means of higher-order geometric definition and interpolation coupled with numerical integration technique.
- The blade volume *V'* calculated needs to be corrected for additional volume of the blade fillets and a factor of the order of 2-5% would be reasonable for most cases.
- The weight of the blade can be determined from

$$W_b = \rho_m Z V$$

Z : The number of blades

ρ_m : The material density

V : The volume of one blade corrected for the fillets

- For CP the blade weight W_b is further corrected for the weight of blade palm.
- The dry propeller weight W_D is the sum of the blade weights and the boss or hub weight.
- The resulting dry weight of the propeller W_D is then

$$W_D = W_b + W_H$$

W_H : The boss or hub weight

- The upthrust U is readily calculated for the blades and the boss of a fixed pitch propeller as

$$U = \frac{\rho}{\rho_m} W_D$$

- Hence the effective weight W_E of the propeller is given by

$$We = W_D \left[1 - \frac{\rho}{\rho_m} \right]$$

- Since the water and nickel aluminium bronze the ratio

$$\frac{\rho}{\rho_m} \approx 0.137$$

- In the case of CP the equation

$$We = W_D \left[1 - \frac{\rho}{\rho_m} \right]$$

- does not apply since the hub does not composed of uniform material. As a consequence the upthrust derives from the following equation

$$U = \frac{\rho}{\rho_m} W_B + \rho V_H$$

External volume of the propeller hub

Dry propeller inertia

- At its most fundamental the mechanical inertia is the sum of all the elemental masses in the propeller multiplied by the square of their radii of gyration.
- So the moment of inertia of a blade tip from the following equation:

$$I_{\mathrm{OX}} = m \times k^2 = Z \int dm \times r^2 = Z \rho_m \int_{r_h}^{R} A_x \times r^2 \times dr$$

- The moment of inertia of the boss I_{H} is relatively straightforward, since it can be approximated by a series of concentric cylinders.
- The dry moment of inertia of the propeller can be found as follows:

$$I_0 = I_{\mathrm{H}} + I_{\mathrm{OX}}$$

Added mass, inertia and damping

- When a propeller is immersed in water the effective mass and inertia characteristics of the propeller when vibrating as part of a shafting system change due to the presence of water around the blades.
- In addition there is also a damping term to consider deriving from the propeller's vibration in water.

- The resulting equation of motion for the propeller is

External excitation force matrix (shaft forces and moments from the engine and transmission)

Excitation forces and moments

$$M + M_a \quad \ddot{x} + C_P\dot{x} - f_s = f_e$$

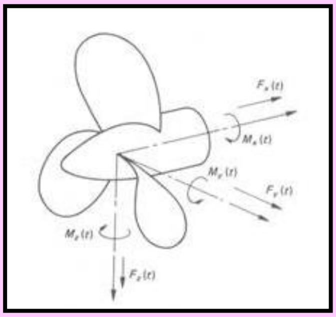
Propeller mass matrix

The added mass matrix

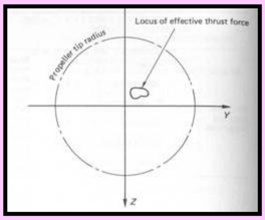
The damping matrix

Propeller forces and moments

- The mean and fluctuating forces and moments produced by a propeller working in the ship's wake field have to be reacted at the bearings, and therefore form a substantial contribution to the bearing forces.
- In the early stages of design the main components of the force F_x and moment M_x are calculated from open water propeller data assuming a mean wake fraction for the vessel.



- The line of action of the effective thrust force will be raised above the shaft axis as a result of the slower water velocities in the upper part of the propeller disk.
- Furthermore, due to the effects of the tangential velocity component, the effective thrust force is unlikely to lie on the plane of symmetry of the axial wake field.
- The thrust eccentricity $e_T(t)$ is the distance from the shaft centre-line to the point through which the effective thrust force acts.

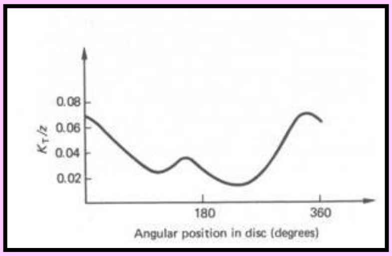


$$e_T^2(t) = e_{Ty}^2(t) + e_{Tz}^2(t)$$

- The forces and moments can be expressed as the sum of Fourier series expansion:

$$F(t) = F_{(0)} + \sum_{k=1}^{n} F_{(k)} \cos(\omega t + \phi_k)$$

$$M(t) = M_{(0)} + \sum_{k=1}^{n} M_{(k)} \cos(\omega t + \phi_k)$$



- Hence the resulting forces and moments can be expressed as a mean component plus the sum of a set of harmonic components

- The expression derived by Sasajima for the fluctuating forces around the propeller disc are given by;

$$\tilde{K}_T(\theta) = \frac{1}{z} \sum_{i=1}^{z} K_T \;\; J(\theta + \theta_t)$$

$$\tilde{K}_Q(\theta) = \frac{1}{z} \sum_{i=1}^{z} K_Q \;\; J(\theta + \theta_t)$$

$$\tilde{F}_y(\theta) = -\frac{2}{z\xi_f} \sum_{i=1}^{z} K_Q \;\; J(\theta + \theta_i) \;\; \cdot \cos(\theta + \theta_i)$$

$$\tilde{F}_z(\theta) = \frac{2}{z\xi_f} \sum_{i=1}^{z} K_Q \;\; J(\theta + \theta_i) \;\; \cdot \sin(\theta + \theta_i)$$

$$\tilde{M}_y(\theta) = -\frac{\xi_f}{2z} \sum_{i=1}^{z} K_T \;\; J(\theta + \theta_i) \;\; \cdot \cos(\theta + \theta_i)$$

$$\tilde{M}_z(\theta) = \frac{\xi_f}{2z} \sum_{i=1}^{z} K_T \;\; J(\theta + \theta_i) \;\; \cdot \sin(\theta + \theta_i)$$

$\tilde{F}_y, \tilde{F}_z$	$= \frac{F_y, F_z}{\rho n^2 D^4}$, $\tilde{M}_y, \tilde{M}_z = \frac{M_y, M_z}{\rho n^2 D^5}$
ξ_f	$= \frac{r_f}{R}$, non-dimensional radius of the loading point
θ_i	$= \frac{2\pi \;\; i-1}{z}$
z	= number of blades
$J \;\; \theta + \theta_i$	= advance coef. at each ang. posn. of each blade
$K_T(J), K_Q(J)$	= open-water char. of the prop.

Out of balance forces and moments

- A marine shafting system will experienced a set of significant out of balance forces and couples if either the propeller becomes damaged so as to alter the distribution of mass or the propeller has not been balanced prior to installation.

- A static balancing requirements have been defined ISO's references (ISO 484/1-D>2.5 meters and 484/2 – 0.80<D<2.5 meters).

- ISO 484/1. *Shipbuilding-Ship Screw Propellers-Manufacturing Tolerances-Part 1: Propellers of Diameter greater than 2.5 m, 1981.*
- ISO 484/2. *Shipbuilding-Ship Screw Propellers-Manufacturing Tolerances-Part 2: Propellers of Diameter Between 0.80 and 2.5 m Inclusive, 1981.*

Hydrodynamic interaction

Hydrodynamic interaction

- The hydrodynamic interaction between the propeller and the hull originates from the passage of blades beneath or in the vicinity of the hull and also from the cavitation dynamics on the surface of the blades.
- The pressure differences caused by these two types of action are then transmitted through the water to produce a fluctuating pressure over the hull surface which, due to its acting over a finite area, produce an excitation force to the vessel.

- The analysis of the hydrodynamic interaction can be considered in three parts;
  - Pressure from the passage of the non-cavitating blade, p_0(t)
  - Pressure from the cavity volume variations on each blade, p_c(t)
  - The effect of the hull surface on the free space pressure signal-termed the solid boundary factor (SBF)

Non-cavitating blade contribution

- The contribution of the total pressure signal on the hull from the passage of the non-cavitating blade is the form of a continuous time series p_0(t) which is

$$p_0(t) = -\rho \frac{\partial \phi\ t}{\partial \phi}$$

ρ = density of fluid

t = time

$\phi\ t$ = velocity potential

Cavitating blade contribution

- The cavitating blade contribution to the hull pressure field is considered to derive from the pulsating of the suction side sheet and tip vortex cavities.
- Hence these types of cavitation may collapse either on or off the blade. The simple relation would be for this;

$$p_c \simeq -\frac{\rho}{4\pi} \frac{1}{R_p} \frac{\partial^2 V\ t}{\partial t^2}$$

ρ = density of fluid

t = time

$V\ t$ = total cavity volume

R_p = distance

Influence of the hull surface

- When a solid boundary is introduced into the vicinity of the propeller then the pressures acting on that boundary are altered significantly.
- For example, if a flat plate is introduced at a distance above the propeller, then the pressure acing on the plate surface is twice the free field pressure which leads to the concept of a solid boundary factor.
- The solid boundary factor is defined as follows:

$$SBF = \frac{\text{pressure acting on the boundary surface}}{\text{free field pressure in the absence of the SB.}}$$

- In the case of the flat plate example, which is of infinite stiffness, the SBF=2.
- However, in the case of a ship form a lesser value would normally be expected due to the real hull form being different from the flat plate and also the influence of pressure release at the sea surface.
- To take SBF around 1.8 gives reasonable values for ship calculations.

Methods for Predicting Hull Surface Pressures

- On essence there are three method for predicting hull surface pressures;
  - Empirical methods
  - Calculations using advanced theoretical methods
  - Experimental measurements

- Holden (*) proposes a method after examination of 72 full-scale results for the estimation of the non-cavitating and cavitating pressures respectively

(*) Holden, K.O., Fagerjord, O., Frostad, R., Early design- stage approach to reducing hull surface forces due to propeller cavitation. *Trans. SNAME*, November, 1980.

$$p_0 = \frac{ND^2}{70}\frac{1}{Z^{1.5}}\left(\frac{K_0}{d/R}\right)(N/m^2)$$

$$p_c = \frac{ND^2}{160}\frac{V_s\, w_{T\max} - w_e}{\sqrt{h_a + 10.4}}\left(\frac{K_c}{d/R}\right)(N/m^2)$$

N = propeller RPM
D = diameter (m)
V_s = ship speed (m/s)
Z = blade number
d = distance from r/R = 0.9 to a position on the submerged hull when the blade is at the TDC position (m)
R = propeller radius (m)
$w_{T\max}$ = the maximum value of Taylor wake fraction in the propeller disc
w_e = the mean effective full scale Taylor wake fraction
h_a = the depth to the shaft center line (m)

- K_0 and K_c are given by the relationships

$$K_0 = 1.8 + 0.4\ d/R \quad \text{for} \quad d/R \le 2$$

$$\text{and} \quad K_c = 1.7 + 0.7\ d/R \quad \text{for} \quad d/R < 1$$

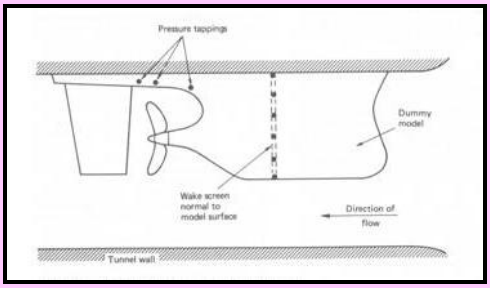
$$K_c = 1$$

The total pressure impulse is then;

$$p_z = \sqrt{p_0^2 + p_c^2}$$

- Theoretical models which would be used in association with this form analysis are those which can be broadly grouped into the lifting surface or vortex lattice categories.

- Experimental methods can be conducted in cavitation tunnel



Calculation Examples

S-E-H-A-M V-5.0 30-Oct- 7 08:34:58 B--M--T

CUSTOMER	:M303/FURTRANS	MODULE	: PROP-EXCITATION
PROJECT	:M303/FURTRANS	OUTPUT	:HULL PRESS. AMP.
		METHOD	: BMT + DNV

TRANSDUCER LOCATION (MM)			HULL EXCITATION PRESSURE (SINGLE AMPLITUDE : K.PASCAL)					
X (+FWD)	Y (+STBD)	Z (+UP)	BMT BRF	BMT 2BRF	DNV BRF		DNV 2BRF
5550	2900	7005	0.5	0.2	2.8		1.2
5550	1933	6862	1.0	0.4	2.9		1.4
5550	967	6719	1.4	0.5	3.2		1.6
5550	0	6577	1.8	0.7	4.1		1.7
5550	-967	6719	1.8	0.7	4.6		1.6
5550	-1933	6862	1.6	0.6	4.1		1.4
5550	-2900	7005	1.2	0.5	3.3		1.2
4100	2900	7225	0.9	0.4	3.2		1.4
4100	1933	7082	1.6	0.6	3.5	***	1.8
4100	967	6939	2.4	0.9	4.4	***	2.4
4100	0	6796	3.2	1.2	7.6	***	3.0
4100	-967	6939	3.3	1.3	7.7	***	2.4
4100	-1933	7082	2.7	1.0	5.7		1.8
4100	-2900	7225	2.0	0.7	4.1		1.4
2650	2900	7445	1.1	0.4	3.3		1.5
2650	1933	7302	1.8	0.7	3.7	***	2.0
2650	967	7159	2.8	1.1	5.5	***	3.1
2650	0	7016	4.1	1.6	11.9	***	4.7
2650	-967	7159	4.3	1.6	10.0	***	3.1
2650	-1933	7302	3.3	1.2	6.5		2.0
2650	-2900	7445	2.2	0.8	4.4		1.5
1200	2900	7665	0.8	0.3	3.0		1.3
1200	1933	7522	1.5	0.6	3.2	***	1.7
1200	967	7379	2.2	0.8	4.0	***	2.1
1200	0	7236	2.9	1.1	6.2		2.5
1200	-967	7379	2.9	1.1	6.3		2.1
1200	-1933	7522	2.4	0.9	5.1		1.7
1200	-2900	7665	1.7	0.7	3.9		1.3
-250	2900	7884	0.4	0.1	2.5		1.1
-250	1933	7742	0.8	0.3	2.6		1.2
-250	967	7599	1.2	0.5	3.0		1.4
-250	0	7456	1.5	0.6	3.7		1.5
-250	-967	7599	1.5	0.6	3.9		1.4
-250	-1933	7742	1.3	0.5	3.6		1.2
-250	-2900	7884	1.0	0.4	3.0		1.1

BLADE RATE VERTICAL EXCITATION FORCE = 173.7 KN
*** :- PRESSURE EXCEEDS RECOMMENDED LIMIT
BRF <= 6.62 OR 2BRF <= 0.5 * BRF