NTNU

Department of energy and process engineering

Examination paper for TEP4200, Mechanical Design, Operation and Maintenance of Hydraulic Machinery

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Examination date: 6th June 2024

Examination time (from-to): 15:00 – 19:01

Permitted examination support material: D

No written and handwritten examination support materials are permitted. A simple calculator is permitted.

Other information:

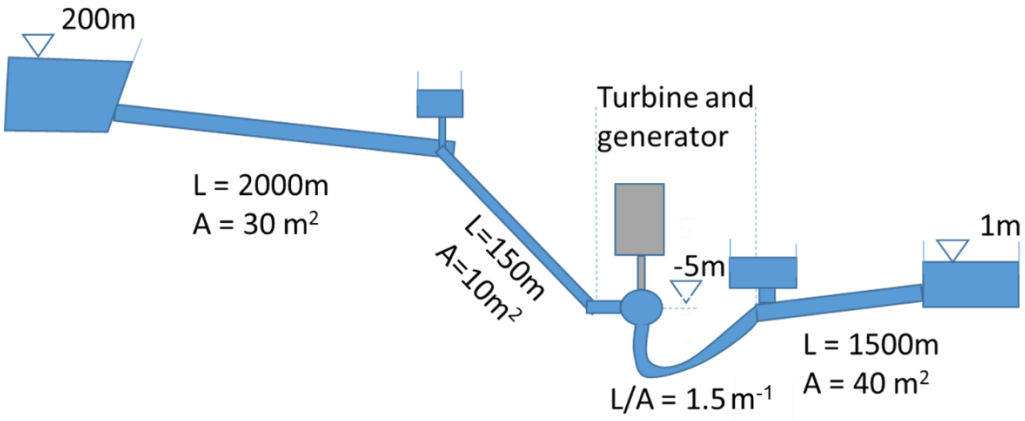
- You have to fill out and deliver all questions pages, 2 to 5, as your solution. No written notes should be delivered.
- For Multiple choice questions there can be more than one marked check box for each question. Correct answers are rewarded with one point (1p.) while incorrect answers give minus one point (-1p.).
- True or false are rewarded with one point (1p.) for correct answer, while incorrect answers give zero point (0p.).

Language: English

Number of pages (front page excluded):

Number of pages enclosed:

Problem 1. Turbine and System dynamics (max. 6 points)



Speed number	$\underline{\Omega} = \underline{\omega} \cdot \sqrt{\underline{Q}}$
Frequency and period of U-tube oscillation	$\omega = \sqrt{\frac{g}{A_{shaft} \cdot {}^{L}/_{A}}}$ $T = \frac{2 \cdot \pi}{\omega}$
Penstock time constant and retardation/acceleration pressure	$T_w = \frac{Q}{g \cdot H} \cdot \Sigma\left({}^{L}/_{A}\right)$ $\Delta H = \frac{1}{g} \cdot \sum \frac{L}{A} \cdot \frac{\Delta Q}{T_C}$
Up- or down-surge in the surge shaft	$\Delta z = \Delta Q \cdot \sqrt{\frac{\Sigma(L/A)}{g \cdot A_{shaft}}}$

1	A power plant is under construction with a lay-out as shown in the Figure above. The flow rate Q = 30 m^3/s, and the generator has 7 pole pairs.	Check box
1A.	Calculate the area of the upper surge shaft if Δz < 10 m. Neglect the head loss. **(**Single-choice question)	
i	The area of the upper surge shaft is: A_{Shaft} = 32 m^2	
ii	The area of the upper surge shaft is: A_{Shaft} = 43 m^2	
iii	The area of the upper surge shaft is: A_{Shaft} = 56 m^2	
iv	The area of the upper surge shaft is: A_{Shaft} = 61 m^2	X

$$\Delta z = \Delta Q \cdot \sqrt{\frac{\Sigma(L/A)}{g \cdot A_{shaft}}} \qquad A_{shaft} = \Delta Q^2 \cdot \frac{\Sigma(L/A)}{g \cdot \Delta z^2} = 30^2 \cdot \frac{2000/30}{9.81 \cdot 10^2} = 61\ m^2$$

1B.	Calculate the change of pressure in the draft tube at turbine level as the turbine closes in T_C = 11 seconds if there is no surge shaft installed. **(**Single-choice question)	
i	The change of pressure in the draft tube at turbine level is: ΔH = 5,9 m	
ii	The change of pressure in the draft tube at turbine level is: ΔH = 9,7 m	
iii	The change of pressure in the draft tube at turbine level is: ΔH = 10,8 m	X
iv	The change of pressure in the draft tube at turbine level is: ΔH = 11,5 m	

$$\Delta H = \frac{1}{g} \cdot \sum \frac{L}{A} \cdot \frac{\Delta Q}{T_C} = \frac{1}{g} \cdot \sum \left(\frac{1500}{40} + 1{,}5\right) \cdot \frac{30}{11} = 10{,}8\ m$$

1C. The surge shaft at the outlet of the draft tube has an area of 150 m^2. Calculate the down surge in surge shaft at shut down from a flow rate Q = 30 m^3/s **(**Single-choice question)		
i	The down surge in surge shaft is: Δz = 3,8 m	
ii	The down surge in surge shaft is: Δz = 4,2 m	
iii	The down surge in surge shaft is: Δz = 4,8 m	X
iv	The down surge in surge shaft is: Δz = 5,2 m	

$$\Delta z = \Delta Q \cdot \sqrt{\frac{\Sigma(L/A)}{g \cdot A_{shaft}}} = 30 \cdot \sqrt{\frac{\frac{1500}{40}}{9{,}81 \cdot 150}} = 4{,}8\ m$$

1D. The surge shaft at the outlet of the draft tube has an area of 150 m^2. Calculate the down surge period at shut down from a flow rate Q = 30 m^3/s **(**Single-choice question)		
i	The surge period is: T = 140 s	
ii	The surge period is: T = 150 s	X
iii	The surge period is: T = 160 s	
iv	The surge period is: T = 170 s	

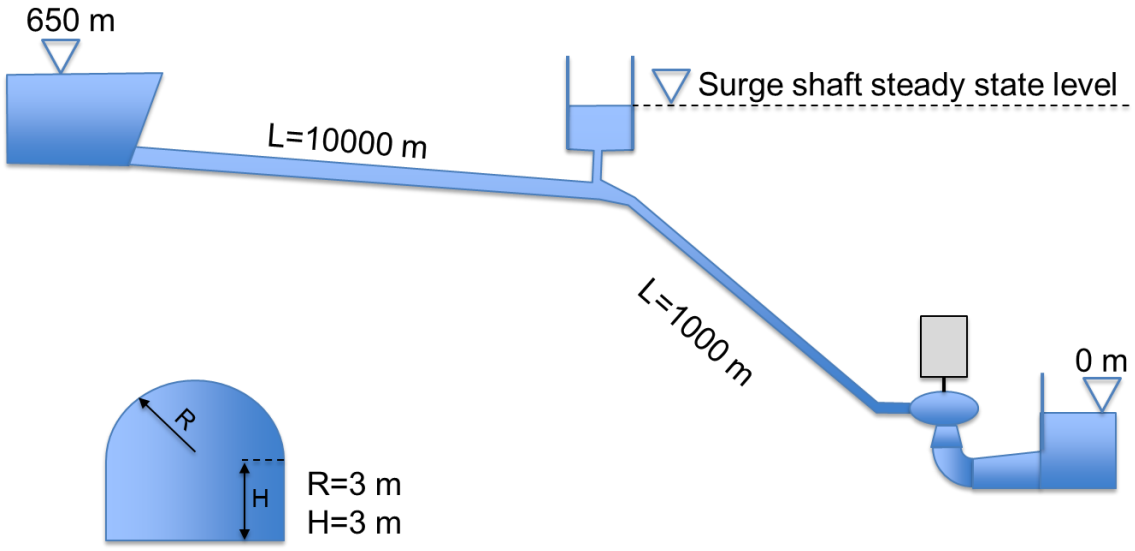
$$\omega = \sqrt{\frac{g}{A_{shaft} \cdot {}^{L}/_{A}}} = \sqrt{\frac{9{,}81 \cdot 40}{150 \cdot 1500}} = 0{,}042\ rad/s \qquad T = \frac{2 \cdot \pi}{\omega} = \frac{2 \cdot \pi}{0{,}042} = 150\ s$$

1E. Calculate the waterhammer upstream the turbine as the turbine shut down from the flow rate Q = 30 m^3/s in T_C = 8 seconds and there is no surge shaft installed. **(**Single-choice question)		
i	The waterhammer is: ΔH = 31 m	X
ii	The waterhammer is: ΔH = 36 m	
iii	The waterhammer is: ΔH = 39 m	
iv	The waterhammer is: ΔH = 41 m	

$$\Delta H = \frac{1}{g} \cdot \frac{\Delta Q}{T_C} \cdot \sum \left(\frac{L}{A}\right) = \frac{1}{g} \cdot \frac{30}{8} \cdot \sum \left(\frac{150}{10} + \frac{2000}{30}\right) = 31\ m$$

1 True-False. The consequence of the change of pressure in the draft tube at turbine level as the turbine closes in T_C = 11 seconds if there no surge shaft will be: **(**True or False question)			
i	The change of pressure will not give any problems for the operation of the turbine		False
ii	The change of pressure will result in cavitation at the outlet of the turbine runner	True	
iii	The change of pressure will result in cavitation at the outlet of the draft tube		False
iv	The change of pressure will result in a water column separation in the draft tube	True	

Problem 2. Head Loss (max. 6 points)



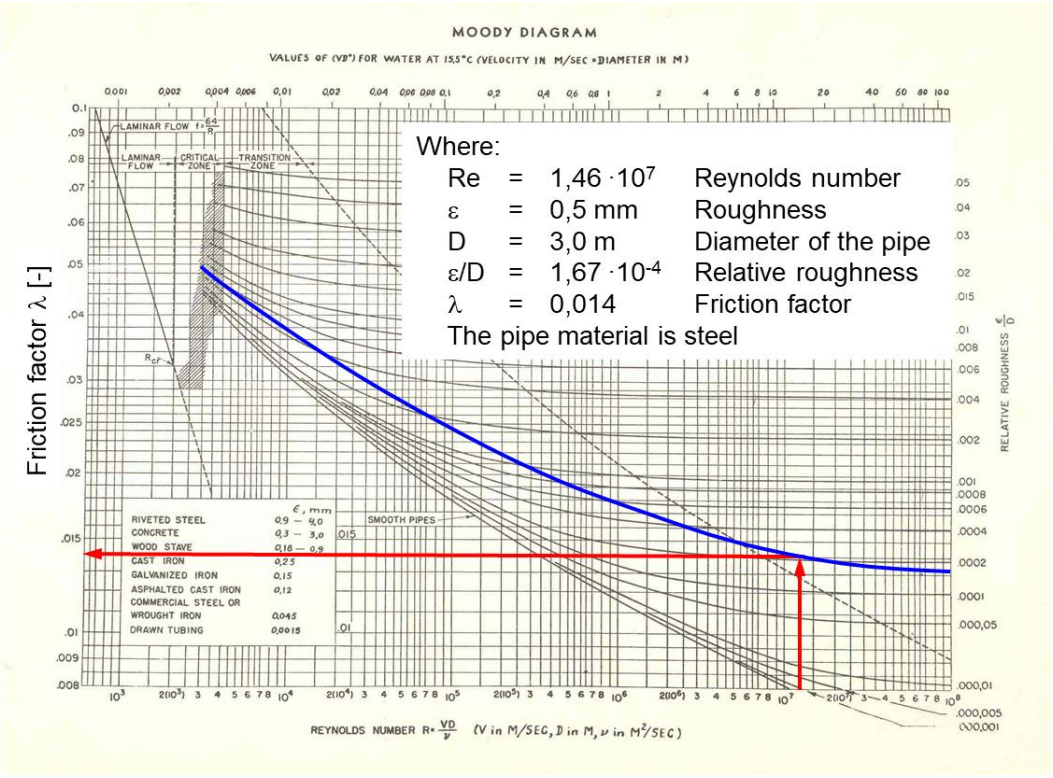
$$h_f = \frac{L}{M^2} \cdot \frac{c^2}{{R_h}^{4/3}} \qquad R_h = \frac{A}{P} \qquad h_f = \lambda \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g} \qquad Re = \frac{c \cdot D}{\upsilon}$$

Given data:

	Symbol		Unit
Gravity constant	g	9,81	m/s^2
Mannings constant	M	34	$m^{1/3}/s$
Kinematic viscosity	ν	$1{,}308 \cdot 10^6$	m^2/s
Turbine efficiency	η_t	94	%
Generator efficiency	η_G	98	%
Transformer efficiency	η_T	98	%
Penstock material roughness	ε	0,5	mm
Diameter of the penstock	D	3,0	m
Flow rate	Q	45	m^3/s

2	Calculate the following for the hydropower plant with tunnel and penstock as shown in the figure above: **(**Multiple-choice question)	Check box
2a	Head loss in the tunnel; $H_f = 9{,}9$ m	X
2b	Head loss in the tunnel; $H_f = 12{,}9$ m	
2c	Head loss in the tunnel; $H_f = 14{,}1$ m	
2d	Head loss in the penstock; $H_f = 9{,}6$ m	X
2e	Head loss in the penstock; $H_f = 10{,}1$ m	
2f	Head loss in the penstock; $H_f = 11{,}3$ m	
2g	Turbine power output; $P_T = 262$ MW	X
2h	Turbine power output; $P_T = 264$ MW	
2i	Turbine power output; $P_T = 267$ MW	
2j	The steady state level in the surge shaft = 630 m	

2k	The steady state level in the surge shaft = 640 m	X
2l	The steady state level in the surge shaft = 650 m	
2m	The net head of the turbine; H_n = 630,5 m	X
2n	The net head of the turbine; H_n = 630,5 m	
2p	The net head of the turbine; H_n = 650,0 m	
If the power plant has a gross head of 700 meter, what is the Generator Power output:		
2q	Generator power output; P_G = 277 MW	X
2r	Generator power output; P_G = 294 MW	
2s	Generator power output; P_G = 300 MW	



Problem 3. Hydro Turbines

3	**The following statements are true or false.** **(**True or False statements)	True	False
3a	Hydropower is the largest source renewable electrical energy in the world	X	
3b	LCOE of hydropower is higher than solar and onshore wind	X	
3c	The reservoir storage of hydropower is the largest battery of the world	X	
3d	Runaway speed will always be lower than rated speed on a Francis turbine		X
3e	Runaway speed will always be higher than rated speed on a Pelton turbine	X	
3f	The relative friction losses in a laboratory scale turbine are higher than for the full scale turbine in a power plant	X	
3g	The speed factor n_{ED} represent a relative relation to a turbine with a head: H=1 m and a diameter D_2=1 m		X
3h	Cavitation occurs only at the outlet of the runner in a Francis turbine		X
3i	Francis turbines are always submerged		X
3j	Pelton turbines are not submerged	X	

Problem 4. Francis turbine performance diagram (max. 7 points)

Given data:

	Symbol		Unit
Inlet pressure on the model turbine	p_{in}	235	kPa
Outlet pressure on the model turbine	p_{out}	95	kPa
Atmospheric pressure	p_{atm}	93	kPa
Flow rate on the model turbine	Q_M	245	l/s
Gravity constant	g	9,8	m/s^2
Density of water	ρ	1000	Kg/m^3
Velocity at the inlet of the turbine	C_{inlet}	3	m/s
Velocity at the outlet of the turbine	C_{outlet}	1	m/s
Level at the inlet	Z_{in}	1,5	m
Level at the outlet	Z_{out}	1	m
Model Turbine Torque	M_T	900	Nm
Model Turbine Speed	n_M	350	rpm
Prototype Turbine Speed	n_P	375	rpm
Generator efficiency	η_G	-	0,99
Model Turbine runner outlet diameter	D_M	0,35	m
Prototype Turbine runner outlet diameter	D_P	1,78	m
Number of runner blades	Z_{runner}	28	-
Number of guide vanes	$Z_{guide\ vanes}$	17	-

4	**(**Multiple-choice question)		Check box
4a	The net head of the model turbine is;	H_n = 14,9 m	
4b	The net head of the model turbine is;	H_n = 15,2 m	X
4c	The net head of the model turbine is;	H_n = 15,7 m	
4d	Model turbine efficiency;	η_T = 89,3 %	
4e	Model turbine efficiency;	η_T = 90,4 %	X
4f	Model turbine efficiency;	η_T = 91,2 %	
4g	Speed factor is;	n_{ED} = 0,16	
4h	Speed factor is;	n_{ED} = 0,17	X
4i	Speed factor is;	n_{ED} = 0,18	
4j	Flow factor is;	Q_{ED} = 0,15	
4k	Flow factor is;	Q_{ED} = 0,16	X
4l	Flow factor is;	Q_{ED} = 0,17	
4m	The flow rate of the prototype is:	Q_P = 32 m^3/s	
4n	The flow rate of the prototype is:	Q_P = 35 m^3/s	X
4o	The flow rate of the prototype is:	Q_P = 38 m^3/s	
4p	The net head of the prototype is:	H_n = 445 m	
4q	The net head of the prototype is:	H_n = 454 m	X
4r	The net head of the prototype is:	H_n = 473 m	
4s	The rotor-stator interaction frequency in the runner is:	RSI = 99 Hz	X
4t	The rotor-stator interaction frequency in the runner is:	RSI = 163 Hz	
4u	The rotor-stator interaction frequency in the runner is:	RSI = 473 Hz	

Given equations:

Head loss: $h_f = \lambda \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g}$

Head loss: $h_f = \frac{L}{M^2} \cdot \frac{c^2}{{R_h}^{4/3}}$

Hydraulic radius: $R_h = \frac{A}{P}$

Reynolds number: $Re = \frac{c \cdot D}{\upsilon}$

Power output; $P = \rho \cdot g \cdot H_n \cdot Q \cdot \eta$

Frequency of U-tube oscillation: $\omega = \sqrt{\frac{g}{A_{shaft} \cdot {}^{L}/_{A}}}$

Period of U-tube oscillation: $T = \frac{2 \cdot \pi}{\omega}$

Penstock time constant: $T_w = \frac{Q}{g \cdot H} \cdot \Sigma\left({}^{L}/_{A}\right)$

Penstock retardation/acceleration pressure: $\Delta H = \frac{1}{g} \cdot \sum \frac{L}{A} \cdot \frac{\Delta Q}{T_C}$

Up- or down-surge in the surge shaft: $\Delta z = \Delta Q \cdot \sqrt{\frac{\Sigma(L/A)}{g \cdot A_{shaft}}}$

Reduced numbers; $\underline{c} = \frac{c}{\sqrt{2 \cdot g \cdot H}}$ $\underline{u} = \frac{u}{\sqrt{2 \cdot g \cdot H}}$ $\underline{w} = \frac{w}{\sqrt{2 \cdot g \cdot H}}$ $\underline{Q} = \frac{Q}{\sqrt{2 \cdot g \cdot H}}$ $\underline{\omega} = \frac{\omega}{\sqrt{2 \cdot g \cdot H}}$

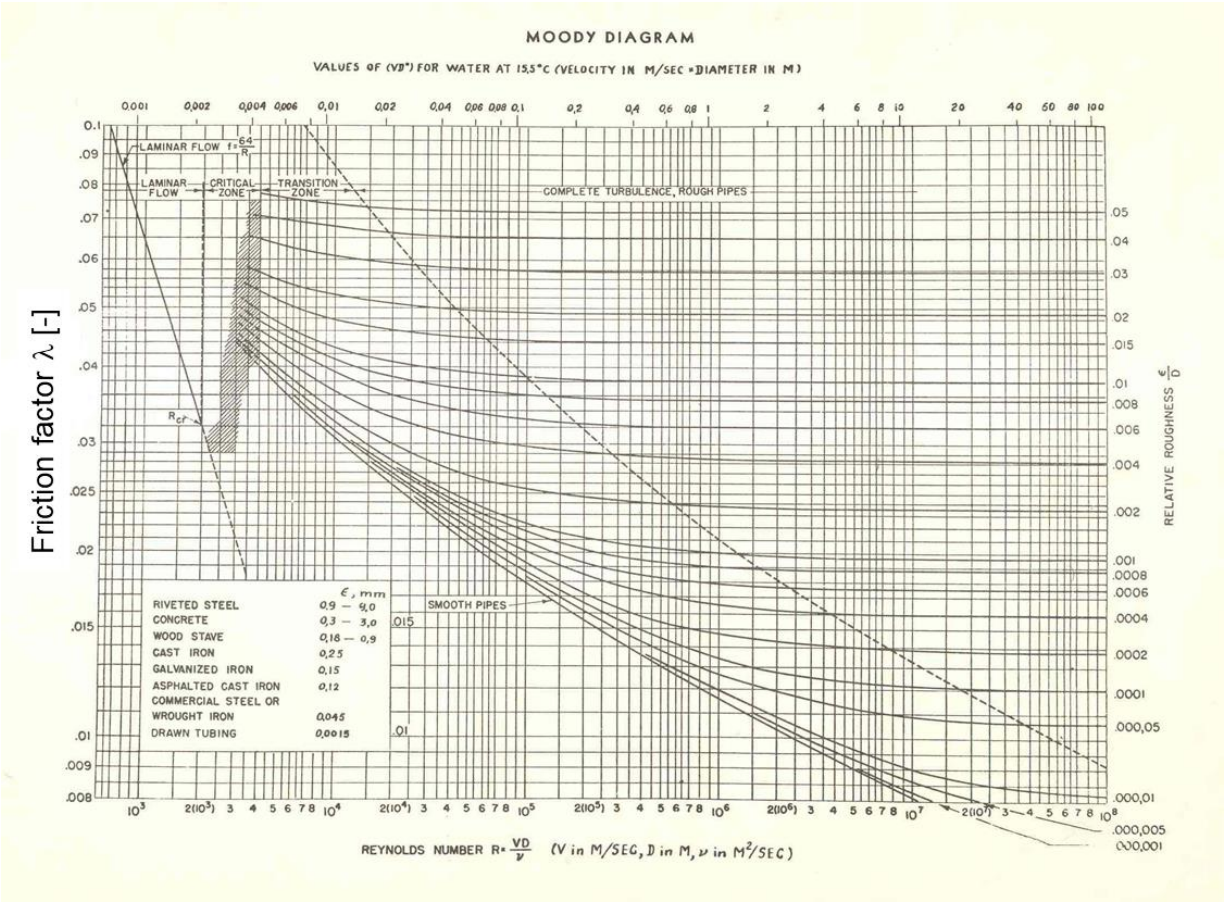
$\underline{\Omega} = \underline{\omega} \cdot \sqrt{\underline{Q}}$ $n_{ED} = \frac{n \cdot D}{\sqrt{E}}$ $n_q = n \cdot \frac{\sqrt{Q}}{H^{0,75}}$ $Q_{ED} = \frac{Q}{D^2 \cdot \sqrt{E}}$

Affinity equations; $\frac{H_1}{n_1^2 \cdot D_1^2} = \frac{H_2}{n_2^2 \cdot D_2^2}$ $\frac{Q_1}{n_1 \cdot D_1^3} = \frac{Q_2}{n_2 \cdot D_2^3}$ $\frac{P_1}{n_1^3 \cdot D_1^5} = \frac{P_2}{n_2^3 \cdot D_2^5}$

Bernoulli's equation on a turbine: $h_{in} + Z_{in} + \frac{C_{in}^2}{2 \cdot g} = H_n + h_{out} + Z_{out} + \frac{C_{out}^2}{2 \cdot g}$

Turbine efficiency: $\eta = \frac{\omega \cdot M}{\rho \cdot g \cdot Q \cdot H_n}$

Rotor Stator Interaction frequency: $RSI = n \cdot Z$


MOODY DIAGRAM
VALUES OF (VD*) FOR WATER AT 15,5°C (VELOCITY IN M/SEC ×DIAMETER IN M)
Friction factor λ [-]
LAMINAR FLOW f=64/R
LAMINAR FLOW
CRITICAL ZONE
TRANSITION ZONE
COMPLETE TURBULENCE, ROUGH PIPES
SMOOTH PIPES
RELATIVE ROUGHNESS ε/D
ε, mm
RIVETED STEEL 0,9 — 9,0
CONCRETE 0,3 — 3,0
WOOD STAVE 0,18 — 0,9
CAST IRON 0,25
GALVANIZED IRON 0,15
ASPHALTED CAST IRON 0,12
COMMERCIAL STEEL OR WROUGHT IRON 0,045
DRAWN TUBING 0,0015
REYNOLDS NUMBER R=VD/ν (V in M/SEC, D in M, ν in M²/SEC)