NATIONAL EXAMINATIONS

May 2018

98-Mar-B5 FLUID MACHINERY

Three hours duration

Notes to Candidates

1. This is a **Closed Book** examination.

2. Examination consists of two Sections: **Section A is Calculative (5 questions)** and **Section B is Descriptive (3 questions).**

3. **Do four (4) questions (including all parts of each question) from Section A (Calculative) and two (2) questions from Section B (Descriptive)**.

4. **Six questions constitute a complete paper.** (Total 60 marks).

5. **All questions are of equal value.** (Each 10 marks).

6. Read the entire question before commencing the calculations and take note of hints or recommendations given. Note that Question 5 is on two pages.

7. If doubt exists as to the interpretation of any question, submit a clear statement of any assumptions made.

8. If any initial parts of a multi-part question cannot be solved the remaining parts may be worked by making appropriate assumptions for the first parts from the technical data given.

9. Candidates may use one of the approved **Casio** or **Sharp** calculators.

10. **Reference data** for particular questions are given in the Attachments on pages 11 to 16. **All pages from which data has been obtained or on which answers have been written are to be returned with the answer booklet to show any working. Candidate's names must be on these sheets.**

11. **Reference formulae and constants** are given on pages 17 to 21.

12. **Drawing Instruments** (scale ruler, protractor and sharp pencil) are required for vector diagrams. While calculation of velocities by trigonometric ratios with reference to a sketch is acceptable it is longer and more time consuming.

SECTION A CALCULATIVE QUESTIONS

Show all steps in the calculations and state the units for all intermediate and final answers.

QUESTION 1 TURBOJET COMPRESSOR

Refer to the Examination Paper Attachments Page 11 **Compressor Velocity Diagram**. Refer also to Page 12 **Single Spool Turbojet** for illustrative purposes only.

The top picture on page 12 shows the core engine (compressor, combustion chamber, turbine), while the bottom picture shows the complete engine including afterburner and nozzle.

Specifications for this small turbojet (without afterburner) are as follows:

Number of stages	8
Pressure ratio	6.8
Flow rate	20 kg/s
Rotational speed	16 500 rpm (revolutions per minute)
Static thrust	12.65 kN

Assume the following additional data:

Blade root diameter = one half blade tip diameter for first stage only

Blade tip velocity for all stages	320 m/s
Air inlet temperature	15°C
Inlet guide (fixed) vane outlet angle α_1	10°
First stage moving blade outlet angle β_2	30°

(a) Calculate the following:

- (i) First stage blade root and tip diameters.
- (ii) Axial air inlet velocity neglecting blade thickness.
- (iii) Mean blade velocity (velocity at mid-height). (5)

(b) Draw to scale, the velocity diagrams for the first stage and determine and show all velocities obtained. (3)

(c) From the velocity diagram determine the power required to drive the first stage. (2)

Note: The scale drawing should be large enough for accurate measurements (a scale of 10 m/s = 4 mm is suggested). While calculation of velocities by trigonometric ratios is acceptable, it is longer and more time consuming.

[10 marks]

QUESTION 2 TURBOJET ENGINE

Refer to the Examination Paper Attachments Page 12 **Single Spool Turbojet** for illustrative purposes only.

The top picture on page 12 shows the core engine (compressor, combustion chamber, turbine), while the bottom picture shows the complete engine including afterburner and nozzle.

Specifications for this small turbojet (without afterburner) are as follows:

Number of stages	8
Pressure ratio	6.8
Flow rate	20 kg/s
Rotational speed	16 500 rpm (revolutions per minute)
Static thrust	12.65 kN (without afterburner)

Assume the following additional information:

Air inlet temperature	15°C
Air inlet velocity	200 m/s

Equal pressure ratio in all compressor stages.
The turbojet engine (or aircraft) is stationary.
Ideal thermodynamic and fluid conditions prevail throughout the turbojet.

(a) From thermodynamic principles, calculate the following:

(i) Pressure ratio for first stage.
(ii) Power required to drive the first stage.
(iii) Power required to drive the whole compressor. (5)

(b) From energy and momentum theory, calculate the following:

(i) Exit jet velocity to give the specified thrust when stationary.
(ii) Power developed by the turbine of the turbojet.
(iii) Equivalent net power developed by the gas flow. (3)

(c) Sketch a temperature versus entropy diagram of the whole thermodynamic cycle and show where power is produced or consumed. Write the values obtained in (a) and (b) on the diagram in the correct places. (2)

[10 marks]

QUESTION 3 STEAM TURBINE BLADE EFFICIENCY

Refer to the Examination Paper Attachments Page 13 **Steam Turbine Velocity Diagram.**

The attached diagram clarifies the nomenclature used in the question below. Use this same nomenclature in your answer

One stage of a steam turbine operating on the impulse principle has the following blade characteristics:

Moving blade velocity	V_B	=	100 m/s
Inlet steam velocity	V_{S1}	=	300 m/s
Nozzle exit angle	θ	=	25°
Steam mass flow rate	M	=	24 kg/s

The moving blades are assumed to be symmetrical and frictionless, that is:

Blade outlet angle γ = Blade inlet angle Φ
Relative velocity V_{R2} = Relative velocity V_{R1}

Draw a velocity (vector) diagram (see note below) to a scale of 1 mm = 2 m/s to show the absolute and relative velocities within the turbine blades. By measuring from this diagram determine the following:

(a)	Absolute exhaust steam velocity.	(5)
(b)	Impulse force on the moving blades.	(1)
(c)	Energy transferred to the moving blades in kJ/kg.	(1)
(d)	Inlet and exhaust kinetic energies in kJ/kg.	(1)
(e)	Blade efficiency.	(1)
(f)	Power developed by the turbine stage.	(1)

Note: While calculation of velocities by trigonometric ratios with reference to a sketch is acceptable it is longer and more time consuming.

[10 marks]

QUESTION 4 PELTON WHEEL

An electrical generator is driven by a small single jet Pelton turbine designed to have the following technical parameters:

Specific speed	0.20
Effective head at the nozzle inlet	120 m
Nozzle velocity coefficient	0.985
Runner rotational speed	880 rev/min
Blade speed to jet speed ratio	0.47
Overall efficiency of the turbine	0.88 (based on shaft output)

(a) Calculate the shaft power output of the turbine. (3)

(b) Calculate the volume flow rate. (2)

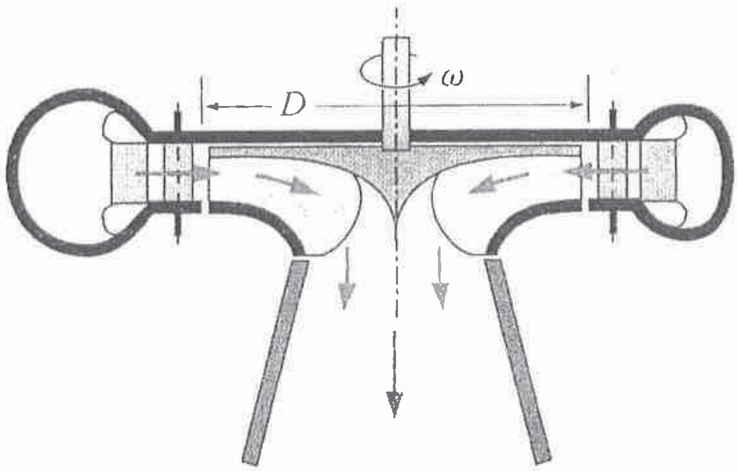
(c) Calculate the jet flow area. (3)

(d) Calculate the ratio of wheel diameter to jet diameter. (2)

[10 marks]

QUESTION 5 HYDRO TURBINE

Refer to the Examination Paper Attachments Page 14 **Hydro Turbine Parameters**. This shows a picture of an actual Francis turbine runner as well as a typical velocity diagram associated with this type of turbine. The diagram below shows how the runner is fitted into the machine.



The specifications, converted to SI units, for the Niagara Falls Francis turbine runners as shown on page 14 are as follows:

Total head	H	=	65.227 m	
Turbine speed	N	=	107 rev/min	
Mechanical power	P	=	54.063 MW	
Turbine efficiency	η	=	0.938	
Runner outer diameter	D_1	=	4.470 m	(at blade entrance)

Measurements from the picture of the runner indicate approximate parameters as follows:

Runner inner diameter	D_2	=	$0.5\ D_1$	(at blade exit)
Runner throat diameter	D_{throat}	=	D_1	(at draft tube entrance)
Runner blade height	h	=	$0.2\ D_1$	(at blade entrance)
Runner blade thickness	t_{total}	=	10% of inlet circumference	
Blade inlet angle	β_1	=	90°	
Blade outlet angle	β_2	=	(180° – 15°) = 165°	

This question is continued on the next page ………

Question 5 Continued

Using the above (on previous page) information do the following:

(a) Calculate the water volume flow rate through the turbine. (1)

(b) Calculate the runner inlet peripheral velocity and radial velocity. (1)

(c) Draw a velocity diagram at the runner inlet and determine the absolute water velocity V_1 entering the runner and the water inlet angle α_1. (2)

(d) Calculate the runner outlet peripheral velocity and radial velocity. Assume that the runner exit area is the same as that of the throat (top of draft tube). (1)

(e) Calculate the hydraulic power developed by the runner. (1)

(f) In order to develop the hydraulic power calculated in (e) above determine the angle α_2 at which the water leaves the runner. Assume that the water leaves the runner in a nearly axial direction to minimise loss that is $V_2 \approx V_{radial}$. (2)

(g) Draw a velocity diagram at the runner outlet and determine the absolute velocity of the water V_2 leaving the runner and the blade exit angle β_2. Compare this value with that given in the data above. (2)

Note: The velocity diagrams should be drawn to a large enough scale (for example at least 2 mm = 10 m/s at the inlet and 4 mm = 10 m/s at the outlet) and be fully labelled.

[10 marks]

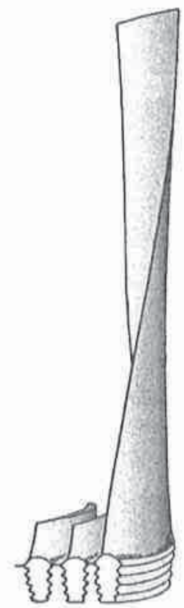
SECTION B DESCRIPTIVE QUESTIONS

Note that each five mark part of each question requires a full page answer with complete explanations with sketches, if appropriate, to support the explanation.

QUESTION 6 COMPRESSOR AND TURBINE BLADE SHAPE

Refer to the Examination Paper Attachments Page 15 **Compressor Inlet Blades**.

Compressor blades at and near the inlet of large compressors have twisted blades as shown in the photograph on Page 15. Similarly turbine blades at or near the exhaust of large turbines also have twisted blades as shown in the adjacent sketch.



(a) Explain why it is necessary to have twisted blades on large machines. (3)

(b) For large steam turbines show with the aid of sketches how the velocity diagrams are different at the base and at the tip of twisted blades. (4)

(c) For large steam turbines explain how the degree of reaction changes from the base to the tip of twisted blades. Clarify what is meant by the degree of reaction. (3)

[10 marks]

QUESTION 7 COMPRESSOR AND PUMP CHARACTERISTICS

PART I STALLING IN COMPRESSORS

Describe stalling in an axial flow compressor as used in a typical gas turbine. Clarify under what conditions stalling can occur. Explain how the phenomenon of stalling affects the design of the compressor especially with regard to the number of stages required.

(5 marks)

PART II CENTRIFUGAL PUMPS

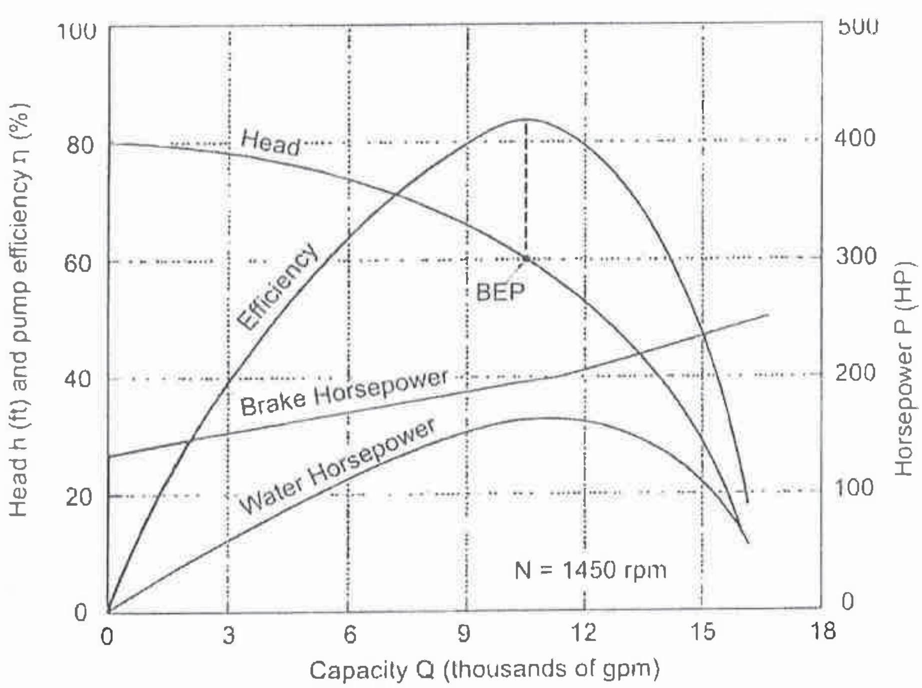
With reference to the figure below explain the following:

(a) Why the hydraulic efficiency (water horsepower) rises from zero to a peak and then declines towards zero

(b) Why the difference between the hydraulic power (water horsepower) and the mechanical power (brake horsepower) decreases to a low value and then increases to a value greater than the initial value.

(5 marks)

[10 marks]



Characteristic curves for a typical mixed-flow centrifugal pump

QUESTION 8 FAN CONTROL

Refer to the Examination Paper Attachments Page 16 **Fan Control Methods**.

The diagrams show (as dotted lines) the system and fan characteristics and operating point for normal design conditions of a typical air flow system.

The volume flow rate through the system can be controlled (reduced) by three methods:

- Dampers in the ducting which may be progressively closed.
- Vanes at the fan inlet which can create increasing pre-whirl.
- Speed of driving motor which can progressively reduce fan speed.

(a) For each of these three methods show on the diagrams how the system or fan characteristics change to give a new operating point.

(i) Control by duct dampers.
(ii) Control by inlet vanes.
(iii) Control by fan speed.

In each case show the new operating point. (5)

Return Page 16 with the examination answer booklet.

(b) Explain, with reference to the diagrams, why and how the flow is reduced in each case.

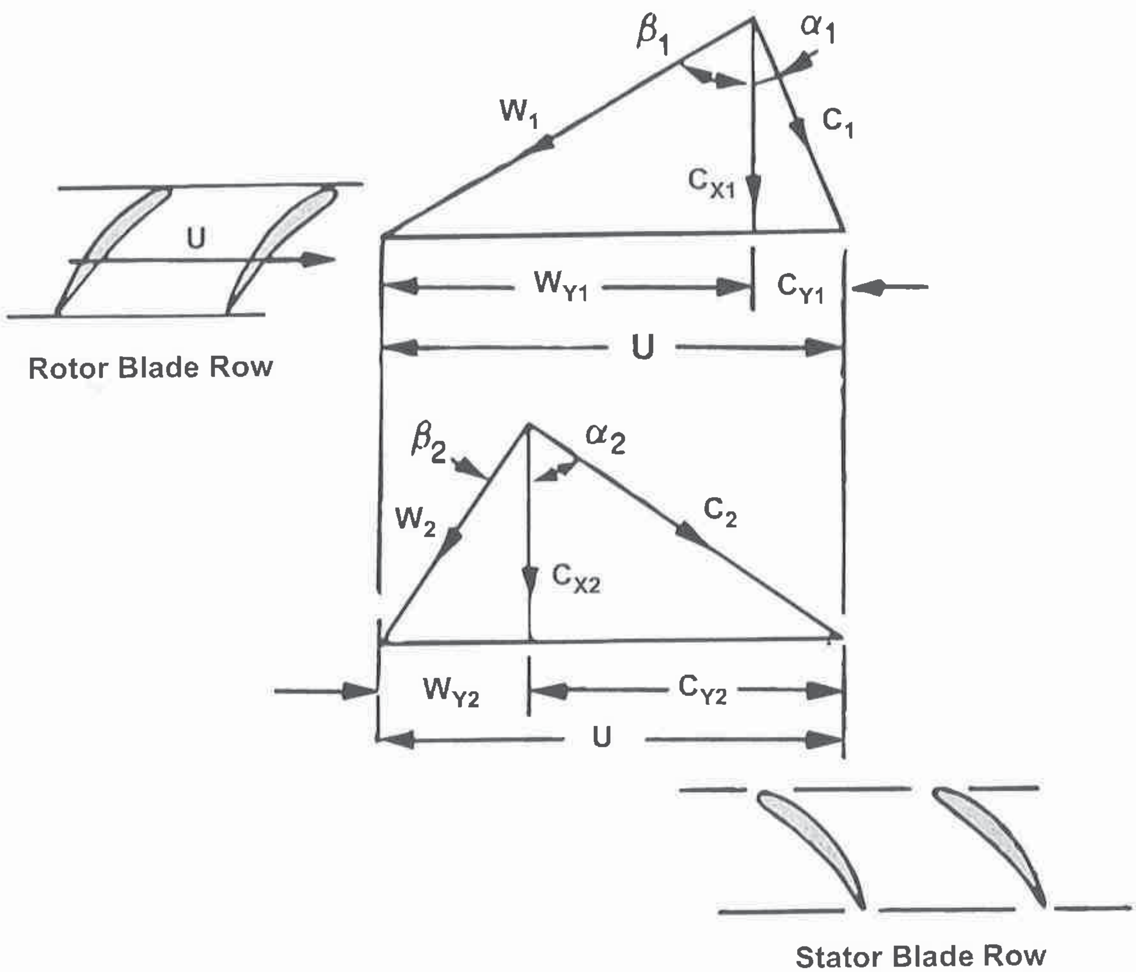
(i) Effect of duct dampers.
(ii) Effect of inlet vanes.
(iii) Effect of fan speed. (5)

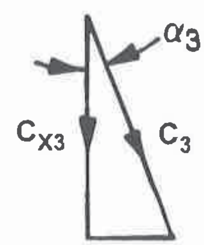
Hint: Sketches of velocity diagrams may be useful in the explanation for (b) (ii).

[10 marks]

EXAMINATION PAPER ATTACHMENTS

QUESTION 1 COMPRESSOR VELOCITY DIAGRAM





U Blade velocity
C_1 Rotor blade absolute inlet velocity
W_1 Rotor blade relative inlet velocity
C_2 Rotor blade absolute outlet velocity
W_2 Rotor blade relative outlet velocity
C_3 Stator blade absolute outlet velocity

QUESTION 1 & QUESTION 2 SINGLE SPOOL TURBOJET

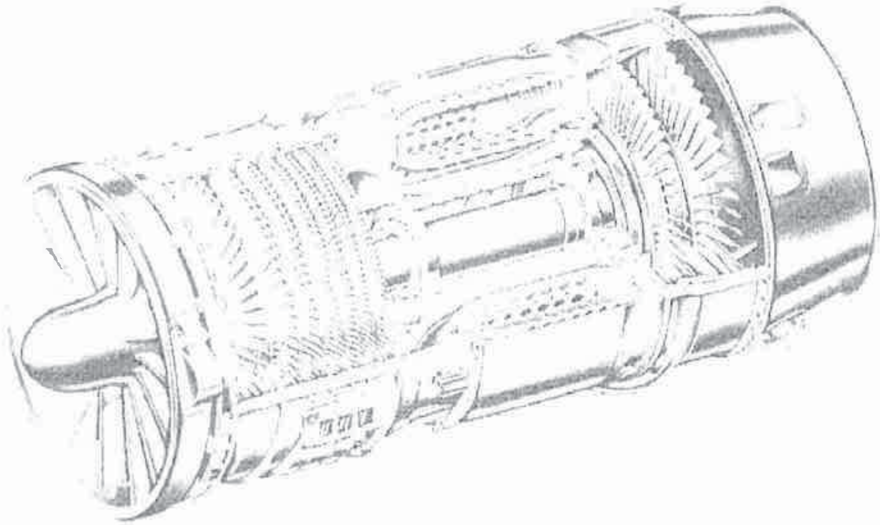
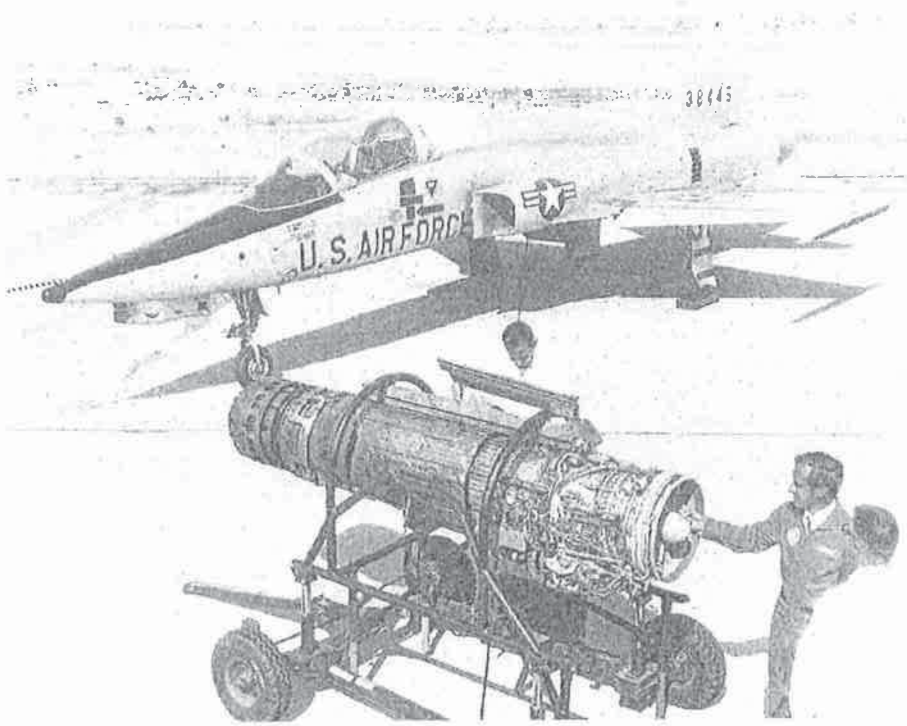


Fig 4-21 Single-spool turbojet with low compression ratio (General Electric CJ-610, 8-stage compressor, compressor pressure ratio p_{t3}/p_{t2} = 6.8, mass flow rate 20 kg/s, rotational speed 16,500 rpm, static thrust 12.65 kN/2800 lb)

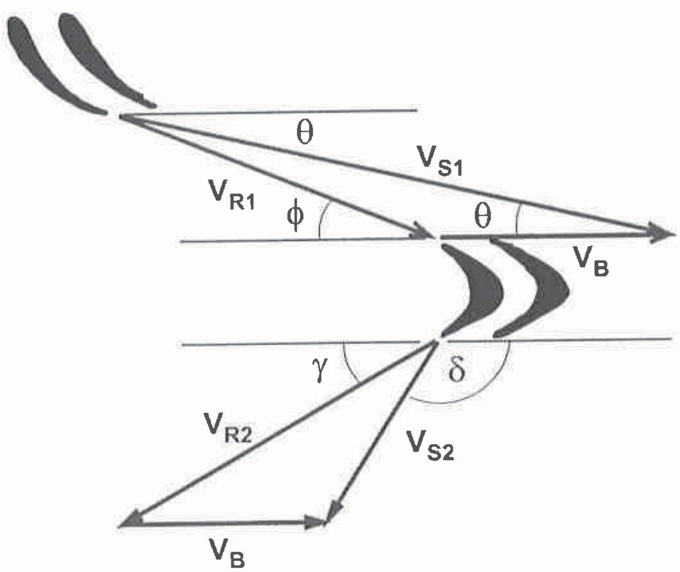


A J85-21 for the F-5E. Weighing 684 lb, this diminutive afterburning turbojet has an airflow of 53 lb/s and gives 5,000 lb thrust. Installed, it fits downstream of the auxiliary inlet doors seen open near the tail! Note GE overalls.

EXAMINATION PAPER ATTACHMENTS

QUESTION 3 STEAM TURBINE VELOCITY DIAGRAM

Nomenclature for velocity vectors and angles



V_{S1}	Absolute steam velocity entering moving blades
V_{R1}	Relative steam velocity entering moving blades
V_B	Moving blade velocity
V_{R2}	Relative steam velocity leaving moving blades
V_{S2}	Absolute steam velocity leaving moving blades

EXAMINATION PAPER ATACHMENTS

QUESTION 5 HYDRO TURBINE PARAMETERS

Francis Turbine Runner

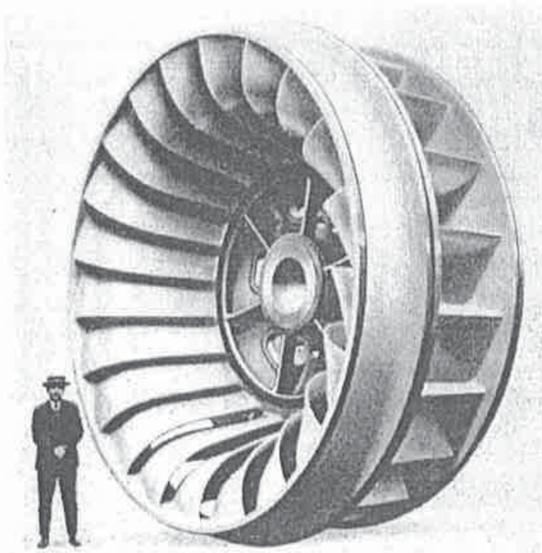
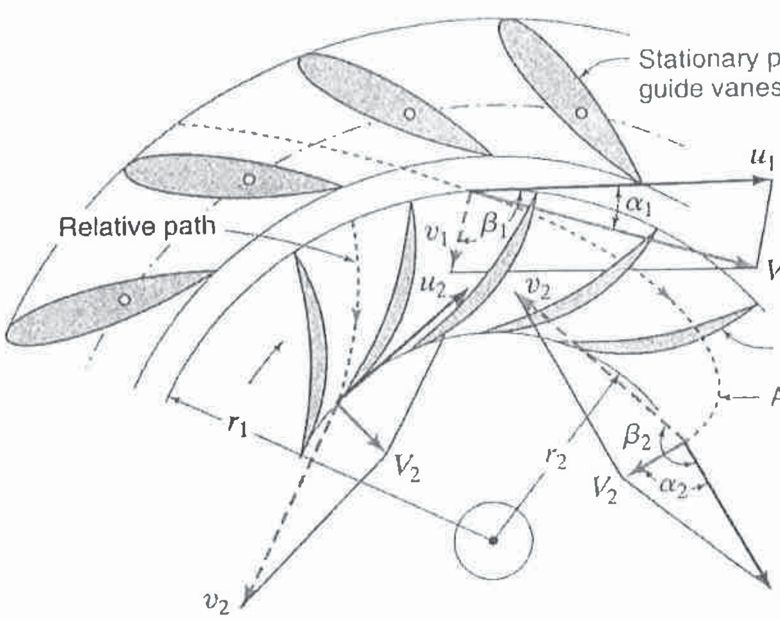


Figure 16.3 Francis runner at Niagara Falls. $h = 214$ ft, $n = 107$ rpm, $\eta = 93.8$ percent at 72,500 hp, diameter = 176 in, overall diameter at band = $183\frac{3}{8}$ in. (*Courtesy of Allis-Chalmers Mfg. Co.*)

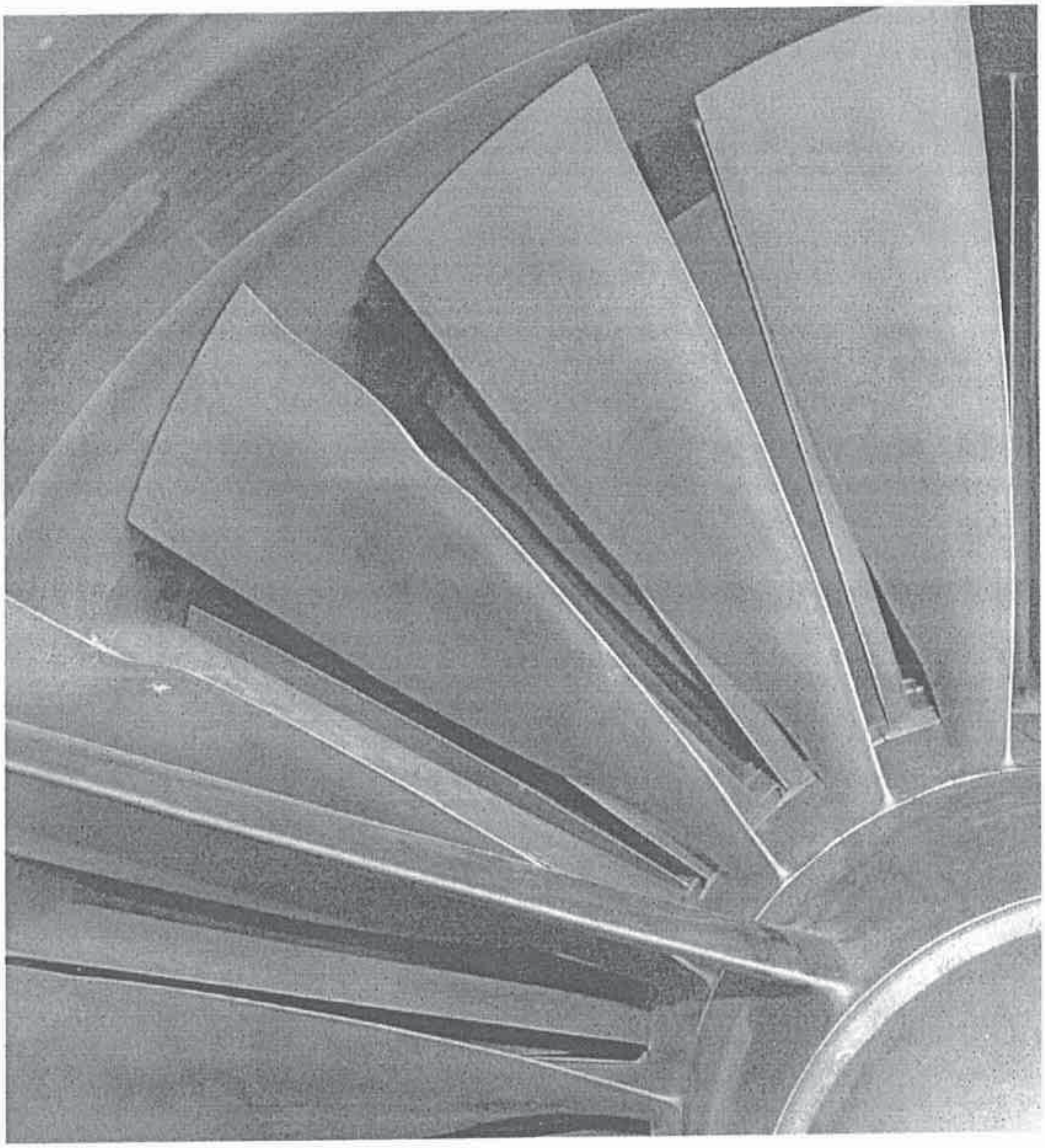
Velocity Diagram



Velocity vectors for radial inward flow hydraulic turbine (Francis type)

EXAMINATION PAPER ATTACHMENTS

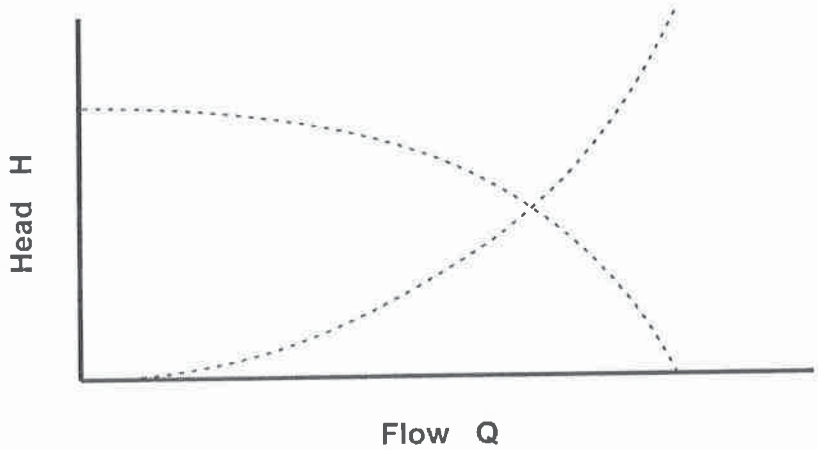
QUESTION 6 COMPRESSOR INLET BLADES



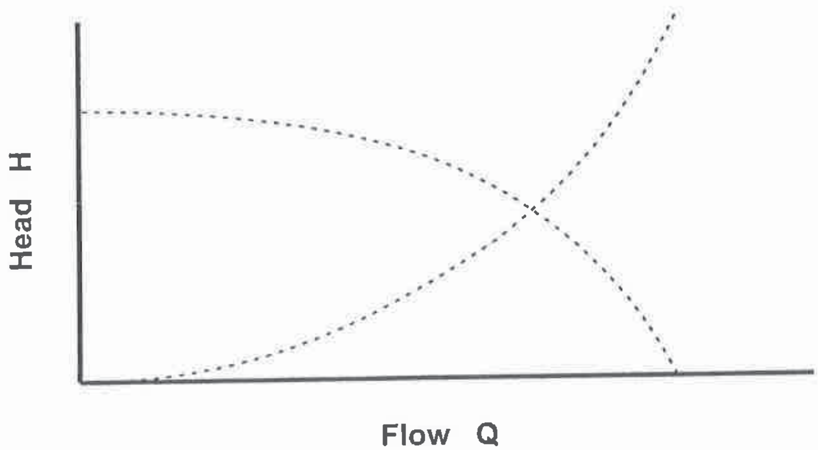
Rolls-Royce Olympus 593-610 first stage low pressure compressor blades

QUESTION 8 FAN CONTROL METHODS NAME ....

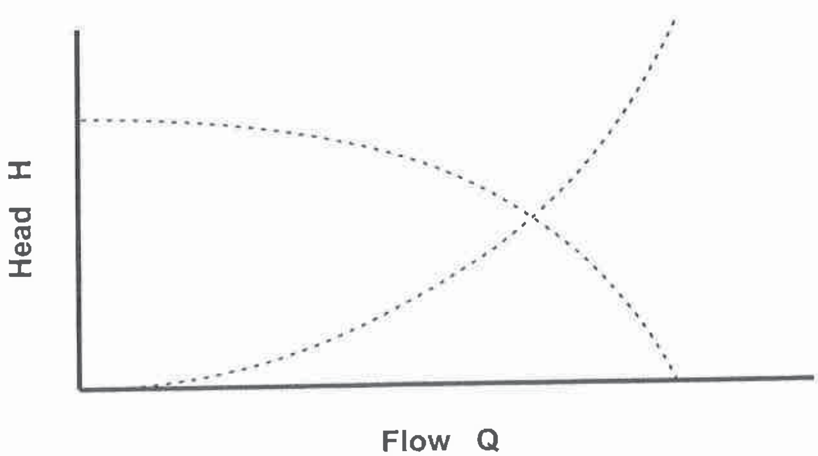
(i) Control by duct dampers



(ii) Control by inlet vanes



(iii) Control by fan speed



EXAMINATION REFERENCE MATERIAL

NOMENCLATURE FOR REFERENCE EQUATIONS (SI UNITS)

a	Sonic velocity	m/s
A	Flow area, Surface area	m^2
c_p	Specific heat at constant pressure	J/kg°C
c_v	Specific heat at constant volume	J/kg°C
b	Width	m
C	Velocity	m/s
D	Diameter	m
E	Energy	J
F	Force	N
g	Gravitational acceleration	m/s^2
h	Specific enthalpy	J/kg
h	System head	m
h_L	Head loss	m
H	Pump or turbine head	m
k	Ratio of specific heats	
L	Length	m
m	Mass	kg
M	Mass flow rate	kg/s
M_A	Mach number	
N	Rotational speed	rev/min
N_S	Specific Speed	
p	Pressure	Pa (N/m^2)
P	Power	W (J/s)
q	Heat transferred	J/kg
Q	Heat	J
Q	Flow rate	m^3/s
r	Radius	m
R	Specific gas constant	J/kg K
s	Entropy	J/kg K
T	Temperature	K
u	Specific internal energy	J/kg
U	Internal Energy	J
U	Velocity	m/s
v	Specific volume	m^3/kg
V	Velocity	m/s
w	Specific work	J/kg
W	Work	J
W	Velocity	m/s
x	Length	m

z	Elevation	m
α	Pump blade angle	°
α	Compressor blade angle	°
β	Pump blade angle	°
β	Compressor blade angle	°
γ	Turbine blade angle	°
φ	Turbine blade angle	°
δ	Turbine blade angle	°
η	Efficiency	
θ	Nozzle angle	°
μ	Dynamic viscosity	Ns/m^2
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
σ_C	Critical cavitation parameter	
τ	Thrust	N
τ	Torque	Nm
φ	Peripheral velocity factor	
ω	Rotational speed	rad/s
Ω	Heat transfer rate	J/s

GENERAL CONSTANTS

Use unless otherwise specified

Acceleration due to gravity:	$g = 9.81\ m/s^2$	
Atmospheric pressure:	$p_{atm} = 100\ kPa$	
Water vapour pressure:	$p_{vapour} = 1.71\ kPa$	(at 15°C)
Water vapour pressure:	$p_{vapour} = 2.34\ kPa$	(at 20°C)
Density of water:	$\rho_{water} = 1000\ kg/m^3$	
Density of air:	$\rho_{air} = 1.21\ kg/m^3$	(at 15°C)
Density of air:	$\rho_{air} = 1.19\ kg/m^3$	(at 20°C)
Specific heat of air:	$c_p = 1.005\ kJ/kg°C$	
Specific heat of air:	$c_v = 0.718\ kJ/kg°C$	
Specific heat of water:	$c_p = 4.19\ kJ/kg°C$	

GENERAL REFERENCE EQUATIONS

Basic Thermodynamics

First Law:	$dE = \delta Q - \delta W$
Enthalpy:	$h = u + pv$
Continuity:	$\rho VA = \text{constant}$
Potential Energy:	$E_{PE} = mgz$
Kinetic Energy:	$E_{KE} = V^2/2$
Internal Energy:	$E_{IN} = U$
Flow Work:	$w = \Delta(pv)$
Energy Equation:	$zg + V^2/2 + u + pv + \Delta w + \Delta q = \text{constant}$

Ideal Gas Relationships

Gas Law:	$pv = RT$
Specific Heat at Constant Pressure:	$c_p = \Delta h/\Delta T$
Specific Heat at Constant Volume:	$c_v = \Delta u/\Delta T$
Specific Gas Constant:	$R = c_p - c_v$
Ratio of Specific Heats	$k = c_p / c_v$
Isentropic Relations:	$p_1/p_2 = (v_2/v_1)^k = (T_1/T_2)^{k/(k-1)}$

FLUID MACHINERY REFERENCE EQUATIONS

Fluid Mechanics

Pressure	$p = \rho gh$
Continuity Equation	$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 = M$
Bernoulli's Equation	$p_1/\rho g + z_1 + V_1^2/2g = p_2/\rho g + z_2 + V_2^2/2g$
Momentum Equation	$F = p_1 A_1 - p_2 A_2 - \rho VA(V_2 - V_1)$ (one dimensional)

Energy Equation

Pump and Turbine	$p_1/\rho g + z_1 + V_1^2/2g + w_{in}/g = p_2/\rho g + z_2 + V_2^2/2g + w_{out}/g$
Pipe Flow	$p_1/\rho g + z_1 + V_1^2/2g = p_2/\rho g + z_2 + V_2^2/2g + h_L$

Compressible Flow

Mach Number	$M_A = V/a$
Sonic Velocity	$a = [kRT]^{1/2}$

Steam Turbines

Nozzle Equation:	$h_1 - h_2 = (V_2^2 - V_1^2) / 2$
Work:	$w = [(V_1^2{}_{absolute} - V_2^2{}_{absolute}) + (V_2^2{}_{relative} - V_1^2{}_{relative})] / 2$
Work:	$w = (V_{S1}\cos\theta - V_{S2}\cos\delta)\, V_{blade}$
Power:	$P = wM$
Force on Blades:	$F = M (V_{S1}\cos\theta - V_{S2}\cos\delta)$
Power to Blades:	$P = M (V_{S1}\cos\theta - V_{S2}\cos\delta)\, V_B$
Power to Blades:	$P = M [(V_{S1}^2 - V_{S2}^2) + (V_{R2}^2 - V_{R1}^2)] / 2$

Gas Turbines

State Equation:	$pv = RT$
Isentropic Equation:	$(T_2/T_1) = (p_2/p_1)^{(k-1)/k}$
Enthalpy Change:	$h_1 - h_2 = c_p (T_1 - T_2)$ (ideal gas)
Nozzle Equation:	$h_1 - h_2 = (V_2^2 - V_1^2) / 2$
Work:	$w = (C_1\sin\alpha_1 + C_2\sin\alpha_2)\, U$
Work:	$w = [(C_1^2 - C_2^2) + (W_2^2 - W_1^2)] / 2$
Power:	$P = wM$

Compressors

Work	$w = U (C_{Y2} - C_{Y1})$
Rotor Enthalpy Change	$h_1 + ½W_1^2 = h_2 + ½W_2^2$
Stator Enthalpy Change	$h_2 + ½C_2^2 = h_3 + ½C_3^2$
Isentropic Equation	$(T_3/T_1) = (p_3/p_1)^{(k-1)/k}$

Hydraulic Machines

Similarity Equations:	$Q_M/Q_P = (\omega_M/\omega_P)(D_M/D_P)^3$
	$H_M/H_P = (\omega_M/\omega_P)^2 (D_M/D_P)^2$
	$P_M/P_P = (\rho_M/\rho_P)(\omega_M/\omega_P)^3 (D_M/D_P)^5$
Pump Specific Speed:	$N_S = \omega Q^{1/2} / (gH)^{3/4}$
Turbine Specific Speed:	$N_S = \omega P^{1/2} / [\rho^{1/2} (gH)^{5/4}]$
Critical Cavitation Parameter:	$\sigma = [\{(p_{atmosphere} - p_{vapour}) / \rho g\} - \Delta z] / H$
Moody Efficiency Relationship:	$\eta_P = 1 - (1 - \eta_M)(D_M/D_P)^{1/4} (H_M/H_P)^{1/10}$
Power:	$P = \rho g Q H$

Pumps

Hydraulic Torque:	$\tau = \rho Q\,(r_2V_{2T} - r_1V_{1T})$
Hydraulic Torque:	$\tau = \rho Q\,(r_2V_2\cos\alpha_2 - r_1V_1\cos\alpha_1)$
Power:	$P = 2\pi N \tau$
Net Positive Suction Head:	$NPSH = [(p_{atmosphere} - p_{vapour}) / \rho g] - \Delta z - h_L$
Peripheral Velocity Factor:	$\varphi = V_{B2} / (2gh)^{1/2}$
Critical Cavitation Parameter:	$\sigma_C = NPSH / H$
Approximate Moody Efficiency:	$(1 - \eta_P) / (1 - \eta_M) \approx (D_M/D_P)^{1/5}$

Hydro Turbines

Power	$P = \tau\omega$
Power	$P = \rho Q\omega\,(r_1V_1\cos\alpha_1 - r_2V_2\cos\alpha_2)$
Power	$P = \rho Q\,(U_1V_1\cos\alpha_1 - U_2V_2\cos\alpha_2)$
Peripheral Runner Velocity	$U_1 = \varphi\,(2gH)^{1/2}$
Absolute Water Velocity	$V_1 = C_1\,(2gH)^{1/2}$
Tangential Velocity	$U = \omega r$
Angular Velocity	$\omega = 2\pi N / 60$

Jet Propulsion

Thrust:	$\tau = M\,(V_{jet} - V_{aircraft})$
Thrust Power:	$\tau V_{aircraft} = M\,(V_{jet} - V_{aircraft})V_{aircraft}$
Jet Power:	$P = M\,(V_{jet}^2 - V_{aircraft}^2) / 2$
Propulsion Efficiency:	$\eta_p = 2\,V_{aircraft} / (V_{jet} + V_{aircraft})$

Wind Turbines

Maximum Ideal Power:	$P_{max} = 8\,\rho A V_1^3 / 27$