UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER II
SESSION 2022/2023

COURSE NAME	:	ELECTROMECHANICAL AND CONTROL
COURSE CODE	:	BDU 20302
PROGRAMME CODE	:	BDC
EXAMINATION DATE	:	JULY/AUGUST 2023
DURATION	:	3 HOURS
INSTRUCTION		1. ANSWER **THREE (3)** QUESTIONS FROM **SECTION A** AND ANSWER **ONE (1)** QUESTION FROM **SECTION B.** 2. THIS FINAL EXAMINATION IS CONDUCTED VIA **CLOSED BOOK.** 3. STUDENTS ARE **PROHIBITED** TO CONSULT THEIR OWN MATERIAL OR ANY EXTERNAL RESOURCES DURING THE EXAMINATION CONDUCTED VIA CLOSED BOOK.

THIS QUESTION PAPER CONSISTS OF **THIRTEEN (13)** PAGES

SECTION A

Q1

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.04225 & -0.11421 & 0 & -32.2 \\ -0.20455 & -0.49774 & 317.48 & 0 \\ 0.00003 & -0.00790 & -0.39499 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0.00381 \\ -24.4568 \\ -4.51576 \\ 0 \end{bmatrix} \eta$$

The longitudinal state equation with input elevator, η deflection above shows full order models of A-7A Corsair II aircraft.

(a) Describe and illustrates the dynamic stability modes contain in longitudinal motion.

(5 marks)

(b) By using the reduced model, analyze the stability corresponding to the short period approximation. Compare and illustrate the pitch rate,q response of the model with high and low damping ratio.

(15 marks)

(c) Determine the steady state of pitch rate response in rad/s when unit step input of 1°.

(5 marks)

Q2 **Figure Q2** shows the lateral control system for aircraft A.

(a) Determine the closed loop transfer function.

(5 marks)

(b) By using second-order system response approximation. Analyze the effect of increasing the gain, K from 1.5 to 5.4 towards the control system (use root that is closer to the origin).

(8 marks)

(c) Compare the stability of the system with the aid of S-plane diagram when the gain K=13 and K=18.

(8 marks)

(d) Determine the gain, K at jw crossing. Give comments.

(4 marks)

Q3 (a) The governing equation of flight motion in a six degrees of freedom aircraft can be written as:

The equation of translational motion:

In x-direction : $m(\dot{U} + QW - RV) = -mg\sin\theta + F_{Ax} + F_{Tx}$

In y-direction : $m(\dot{V} + UR - PW) = mg\cos\theta\sin\Phi + F_{Ay} + F_{Ty}$

In z-direction : $m(\dot{W} + PV - QU) = mg\cos\theta\,\mathrm{Cos}\,\Phi + F_{Az} + F_{Tz}$

The equation of rotational motion:

In x-rotation : $\dot{P}I_{xx} - \dot{R}I_{xz} - PQI_{xz} + RQ(\dot{I_{zz}} - I_{yy}) = I_A + I_T$

In y-rotation : $\dot{Q}I_{yy} + PR(I_{xx} - I_{zz}) + (P^2 - R^2)I_{xz} = M_A + M_T$

In z-rotation : $\dot{R}I_{zz} - \dot{P}I_{xz} + PQ(I_{yy} - I_{xx}) + QR\,I_{xz} = N_A + N_T$

Where

U, V, W : translational velocity in x, y and z direction

$\dot{U}, \dot{V}, \dot{W}$: translational acceleration in x, y and z direction

P, Q, R : translational velocity in x, y and z direction

$\dot{P}, \dot{Q}, \dot{R}$: translational acceleration in x, y and z direction

I_{xx}, I_{yx}, I_{zx} : Inertia and moment of moment inertia in x-direction

I_{xy}, I_{yy}, I_{zy} : Inertia and moment of moment inertia in y-direction

I_{xz}, I_{yz}, I_{zz} : Inertia and moment of moment inertia in y-direction

F_{Ax}, F_{At}, F_{Az} : aerodynamic forces in x, y and z-direction

T_{Ax}, T_{At}, T_{Az} : engine thrust in x, y and z direction

L_A, M_A, N_A : aerodynamic moment of rolling, pitching and yawing

L_T, M_T, N_T : rolling, pitching and yawing moment due to engine thrust.

Based on general equation of motion listed above formulate the following cases:

i. Aircraft flies in steady state

(7 marks)

ii. Aircraft flies in steady state with rectilinear flight condition

(8 marks)

(b) Design the system shown **Figure Q3(b)** so that it exhibits 4.33 % OS by using the root locus method. Note that the breakaway/break-in points are equal to -4.36, -2.77 and -0.62.

(10 marks)

SECTION B

Q4 Assume fuselage aerodynamics effects are neglected. At $\alpha = 2.6°$ the lift coefficient for the wing is measured as 0.48. The lift is found to be zero at a geometric angle of attack $\alpha = -1.1°$. The moment coefficients about center of gravity for $\alpha = 1.3°$ and $\alpha = 4.8°$ are -0.01 and 0.05, respectively. The location of the center of gravity is 0.3.

(a) Calculate $C_{M,ac_{wb}}$ and location of the aerodynamic center of the wing.

(8 marks)

(b) Now assume that a horizontal tail is added to model with the characteristic of tail is shown in **Table Q4(b).** Compute the $C_{M,cg}$ at $\alpha = 4.8°$. Analyze the stability of the aircraft as a whole in term of longitudinal mode.

(10 marks)

(c) If aircraft flying at steady state is pertubated with upward gust of wind. Compare the stability of an aircraft with respect to both moment coefficient curves illustrated in **Figure Q4(c).**

(7 marks)

Q5 **Figure Q5** shows the pitch angle control system that control the dynamics of the aircraft in lateral axis with the gain, K. The transfer functions for each of the components are given by:

$$G_1(s) = \frac{10}{s+10}$$

$$G_2(s) = \frac{3}{s^2+3s+4}$$

(a) Analyze the root locus plot of the open loop transfer function and identify if the imaginary axis crossing exist or not. Find the damped frequency, ω_d and gain, K, if imaginary axis crossing exist.

(10 marks)

(b) By using Ziegler-Nichols method. Determine the suitable controller gain if the gain, K is replaced with the following controller:

i. P Controller
(3 marks)

ii. PD Controller
(2 marks)

iii. PID Controller
(3 marks)

(c) Examine the accuracy of the system with P, PD, and PID controller calculated in **(b).**
(7 marks)

- END OF QUESTIONS -

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023
COURSE NAME: ELECTROMECHANICAL AND CONTROL
PROGRAMME CODE : BDC
COURSE CODE : BDU 20302

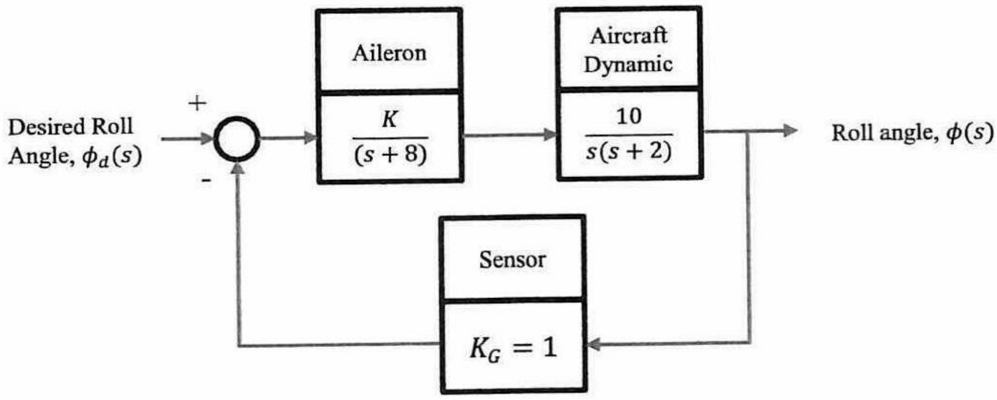

Figure Q2 Aircraft A

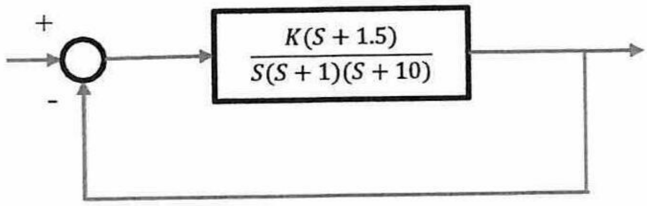

Figure Q3(b) System A

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023 PROGRAMME CODE : BDC
COURSE NAME: ELECTROMECHANICAL AND CONTROL COURSE CODE : BDU 20302

Table Q4(b) Aircraft with tail characteristics

Wing area	0.2 m^2
Wing chord	0.25 m
Distance C.g to A.c of tail	0.19 m
Tail area	0.04 m^2
Tail setting angle	3 degrees
Tail slope	0.2 /degree
Downwash angle	1 degree
$\partial\varepsilon/\partial\alpha$	0.4

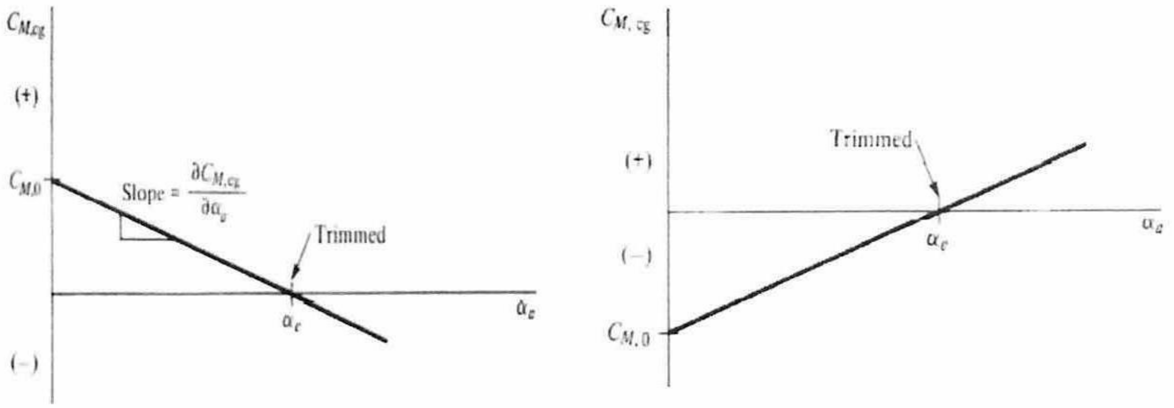

Figure Q4(c) Moment coefficient curves

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023
COURSE NAME: ELECTROMECHANICAL AND CONTROL
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COURSE CODE : BDU 20302

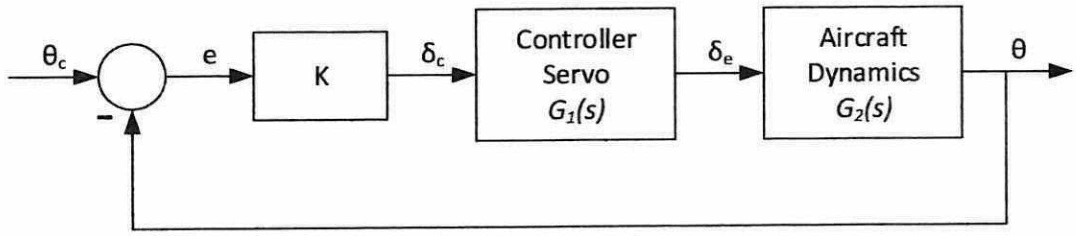

Figure Q5 Pitch control system

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023 PROGRAMME CODE : BDC
COURSE NAME: ELECTROMECHANICAL AND CONTROL COURSE CODE : BDU 20302

Key Equations

The relevant equations used in this examination are given as follows:

1. The determinant of a 3 × 3 matrix:
$$\begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = a\begin{vmatrix} e & f \\ h & i \end{vmatrix} - b\begin{vmatrix} d & f \\ g & i \end{vmatrix} + c\begin{vmatrix} d & e \\ g & h \end{vmatrix} \quad (1)$$

2. Partial fraction for $F(s)$ with real and distinct roots in the denominator:
$$F(s) = \frac{K_1}{(s+p_1)} + \frac{K_2}{(s+p_2)} + \cdots + \frac{K_m}{(s+p_m)} \quad (2)$$

3. Partial fraction for $F(s)$ with complex or imaginary roots in the denominator:
$$F(s) = \frac{K_1}{(s+p_1)} + \frac{K_2 s + K_3}{(s^2+as+b)} + \cdots \quad (3)$$

4. General first order transfer function:
$$G(s) = \frac{s}{s+a} \quad (4)$$

5. General second order transfer function:
$$G(s) = \frac{K}{s^2 + 2\xi\omega_n s + \omega_n} \quad (5)$$

6. The closed loop transfer function:
$$T(s) = \frac{G(s)}{1+G(s)H(s)} \quad (6)$$
where $G(s)$ is the transfer function of the open-loop system, and $H(s)$ is the transfer function in the feedback loop.

7. The final value theorem:
$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} sY(s) \quad (7)$$

8. Time response:
$$T_r = \frac{2.2}{a} \quad (8)$$
$$T_s = \frac{4}{a} \quad (9)$$
$$\%OS = e^{-\left(\frac{\xi\pi}{\sqrt{1-\xi^2}}\right)} \times 100\% \quad (10)$$
$$\xi = \frac{-\ln\left(\%\frac{OS}{100}\right)}{\sqrt{\pi^2 + \left(\ln\left(\%\frac{OS}{100}\right)\right)^2}} \quad (11)$$

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023 PROGRAMME CODE : BDC
COURSE NAME: ELECTROMECHANICAL AND CONTROL COURSE CODE : BDU 20302

$$T_p = \frac{\pi}{\omega_n\sqrt{1-\xi^2}} = \frac{\pi}{\omega} \quad (12)$$

$$T_s = \frac{4}{\xi\omega_n} = \frac{4}{\eta} \quad (13)$$

$$P = \frac{2\pi}{\omega} \quad (14)$$

$$t_{1/2} = \frac{0.693}{|\eta|} \quad (15)$$

$$N_{1/2} = 0.110\frac{|\omega|}{|\eta|} \quad (16)$$

9. Estimation of parameter q (Paynter Numerical Method)

$$q = \max\left|A_{ij}\Delta t\right| \quad (17)$$

10. Estimation of the integer value of p (Paynter Numerical Method)

$$\frac{1}{p!}(nq)^p e^{nq} \leq 0.001 \quad (18)$$

11. Numerical solution of state equation:

$$\mathbf{x}_{k+1} = \boldsymbol{M}\mathbf{x}_k + \boldsymbol{N}\boldsymbol{\eta}_k$$

with matrix $\boldsymbol{M}$ and $\boldsymbol{N}$ are given by the following matrix expansion:

$$\boldsymbol{M} = e^{\boldsymbol{A}\Delta t} = \boldsymbol{I} + \boldsymbol{A}\Delta t + \frac{1}{2!}\boldsymbol{A}^2\Delta t^2 \ldots \quad (19)$$

$$\boldsymbol{N} = \Delta t\left(\boldsymbol{I} + \frac{1}{2!}\boldsymbol{A}\Delta t + \frac{1}{3!}\boldsymbol{A}^2\Delta t^2 + \cdots\right)\boldsymbol{B}$$

12. Characteristic equation of the closed loop system:

$$1 + KG(s)H(s) = 0 \quad (20)$$

13. Asymptotes: angle and real-axis intercept:

$$\sigma = \frac{[\sum Real\ parts\ of\ the\ poles - \sum Real\ parts\ of\ the\ zeros]}{n-m} \quad (21)$$

$$\phi_a = \frac{180°[2q+1]}{n-m} \quad (22)$$

14. The solution to determine real axis break-in and breakaway points:

$$\frac{dK(\sigma)}{d\sigma} = 0 \quad (23)$$

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023 PROGRAMME CODE : BDC
COURSE NAME: ELECTROMECHANICAL AND CONTROL COURSE CODE : BDU 20302

15. An alternative solution to find real axis break-in and breakaway points:

$$\sum \frac{1}{\sigma + z_i} = \sum \frac{1}{\sigma + p_i} \quad (24)$$

16. The angle of departure of the root locus from a pole of $G(s)H(s)$:

$$\theta = 180° + \sum(angles\ to\ zeros) - \sum(angles\ to\ poles) \quad (25)$$

17. The angle of arrival at a zero:

$$\theta = 180° - \sum(angles\ to\ zeros) + \sum(angles\ to\ poles) \quad (26)$$

18. The steady state error:

$$e_{ss} = \lim_{t \to \infty} e(t) = \lim_{s \to 0} sE(s) \quad (27)$$

where the error signal is given as:

$$E(s) = \frac{1}{1 + K(s)G(s)H(s)} \times U(s) \quad (28)$$

19. Linear system (SISO) with state feedback:

$$\dot{\boldsymbol{x}} = (\boldsymbol{A} - \boldsymbol{B}\boldsymbol{K}^{\boldsymbol{T}})\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$$

$$\text{or, } \dot{\boldsymbol{x}} = \boldsymbol{A}_{\boldsymbol{new}}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \quad (29)$$

where $\boldsymbol{A}_{\boldsymbol{new}}$ is the augmented matrix and $u = \boldsymbol{K}^{\boldsymbol{T}}\boldsymbol{x} + \delta_{ref}$

20. The characteristic equation for the standard form of the second-order differential equation:

$$\lambda^2 + 2\xi\omega_n\lambda + \omega_n^2 = 0$$

The roots of the characteristic equation are: (30)

$$\lambda_{1,2} = -\xi\omega_n \pm \omega_n\sqrt{1 - \xi^2} \cdot i$$

$$\lambda_{1,2} = \sigma \pm \omega_d$$

21. The calculation of controller gains using the Ziegler-Nichols method:

Table 1 The Ziegler-Nichols tuning method. (31)

Control Type	K_P	K_I	K_D
P	$0.5K_u$	-	-
PI	$0.45K_u$	$1.2\,K_p/T_u$	-
PD	$0.8K_u$	-	$K_PT_u/8$
Classic PID	$0.6K_u$	$2\,K_p/T_u$	$K_PT_u/8$
Pessen Integral Rule	$0.7K_u$	$2.5\,K_p/T_u$	$3K_PT_u/20$
Some Overshoot	$0.33K_u$	$2\,K_p/T_u$	$K_PT_u/3$
No Overshoot	$0.2K_u$	$2\,K_p/T_u$	$K_PT_u/3$

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023 PROGRAMME CODE : BDC
COURSE NAME: ELECTROMECHANICAL AND CONTROL COURSE CODE : BDU 20302

22. The contribution of the wing-body to M_{cg}:

$$C_{M,cg_{wb}} = C_{M,ac_{wb}} + C_{L_{wb}}\left(h - h_{ac_{wb}}\right)$$

$$C_{M,cg_{wb}} = C_{M,ac_{wb}} + a_{wb}\alpha_{wb}\left(h - h_{ac_{wb}}\right) \quad (32)$$

23. The contribution of the wing-body-tail to M_{cg}:

$$C_{M,cg_{wb}} = C_{M,ac_{wb}} + a\alpha_a\left(h - h_{ac_{wb}} - V_H\frac{a_t}{a}\left[1 - \frac{\partial\varepsilon}{\partial\alpha}\right]\right) + V_H a_t(i_t + \varepsilon_0) \quad (33)$$

24. The equation for longitudinal static stability:

$$C_{M,0} = C_{M,ac_{wb}} + V_H a_t(i_t + \varepsilon_0)$$

$$\frac{\partial C_{M,cg}}{\partial\alpha_a} = a\left[h - h_{ac_{wb}} - V_H\frac{a_t}{a}\left(1 - \frac{\partial\varepsilon}{\partial\alpha}\right)\right] \quad (34)$$

25. The absolute angle of attack, α_a:

$$\alpha_a = \alpha + |\alpha_{L=0}| \quad (35)$$

where α is the geometric angle of attack.

26. Neutral point:

$$h_n = h_{ac_{wb}} + V_H\frac{a_t}{a}\left(1 - \frac{\partial\varepsilon}{\partial\alpha}\right) \quad (36)$$

27. Static margin:

$$SM = h_n - h \quad (37)$$

28. Elevator angle to trim:

$$\delta_{trim} = \frac{C_{M,0} + \left(\partial C_{M,cg}/\partial\alpha_a\right)\alpha_n}{V_H\left(\partial C_{L,t}/\partial\,\delta_e\right)} \quad (38)$$

29. Conversion from the state-space model to transfer function model: (39)

$$G(s) = \boldsymbol{C}\frac{adj(\boldsymbol{sI} - \boldsymbol{A})}{\det(\boldsymbol{sI} - \boldsymbol{A})}\boldsymbol{B}$$

FINAL EXAMINATION

SEMESTER / SESSION : SEM II / 2022/2023
COURSE NAME: ELECTROMECHANICAL AND CONTROL

PROGRAMME CODE : BDC
COURSE CODE : BDU 20302

Table A Laplace transform theorems

Laplace transforms – Table			
$f(t)=L^{-1}\{F(s)\}$	$F(s)$	$f(t)=L^{-1}\{F(s)\}$	$F(s)$
$a \quad t \geq 0$	$\frac{a}{s} \quad s>0$	$\sin \omega t$	$\frac{\omega}{s^2+\omega^2}$
$at \quad t \geq 0$	$\frac{a}{s^2}$	$\cos \omega t$	$\frac{s}{s^2+\omega^2}$
e^{-at}	$\frac{1}{s+a}$	$\sin(\omega t+\theta)$	$\frac{s\sin\theta+\omega\cos\theta}{s^2+\omega^2}$
te^{-at}	$\frac{1}{(s+a)^2}$	$\cos(\omega t+\theta)$	$\frac{s\cos\theta-\omega\sin\theta}{s^2+\omega^2}$
$\frac{1}{2}t^2e^{-at}$	$\frac{1}{(s+a)^3}$	$t\sin\omega t$	$\frac{2\omega s}{(s^2+\omega^2)^2}$
$\frac{1}{(n-1)!}t^{n-1}e^{-at}$	$\frac{1}{(s+a)^n}$	$t\cos\omega t$	$\frac{s^2-\omega^2}{(s^2+\omega^2)^2}$
e^{at}	$\frac{1}{s-a} \quad s>a$	$\sinh \omega t$	$\frac{\omega}{s^2-\omega^2} \quad s>\lvert\omega\rvert$
te^{at}	$\frac{1}{(s-a)^2}$	$\cosh \omega t$	$\frac{s}{s^2-\omega^2} \quad s>\lvert\omega\rvert$
$\frac{1}{b-a}(e^{-at}-e^{-bt})$	$\frac{1}{(s+a)(s+b)}$	$e^{-at}\sin\omega t$	$\frac{\omega}{(s+a)^2+\omega^2}$
$\frac{1}{a^2}[1-e^{-at}(1+at)]$	$\frac{1}{s(s+a)^2}$	$e^{-at}\cos\omega t$	$\frac{s+a}{(s+a)^2+\omega^2}$
t^n	$\frac{n!}{s^{n+1}} \quad n=1,2,3..$	$e^{at}\sin\omega t$	$\frac{\omega}{(s-a)^2+\omega^2}$
t^ne^{at}	$\frac{n!}{(s-a)^{n+1}} \quad s>a$	$e^{at}\cos\omega t$	$\frac{s-a}{(s-a)^2+\omega^2}$
t^ne^{-at}	$\frac{n!}{(s+a)^{n+1}} \quad s>a$	$1-e^{-at}$	$\frac{a}{s(s+a)}$
$\sqrt{t}$	$\frac{\sqrt{\pi}}{2s^{3/2}}$	$\frac{1}{a^2}(at-1+e^{-at})$	$\frac{1}{s^2(s+a)}$
$\frac{1}{\sqrt{t}}$	$\sqrt{\frac{\pi}{s}} \quad s>0$	$f(t-t_1)$	$e^{-t_1s}F(s)$
$g(t)\cdot p(t)$	$G(s)\cdot P(s)$	$f_1(t)\pm f_2(t)$	$F_1(s)\pm F_2(s)$
$\int f(t)dt$	$\frac{F(s)}{s}+\frac{f^{-1}(0)}{s}$	$\delta(t)$ *unit impulse*	1 *all s*
$\frac{df}{dt}$	$sF(s)-f(0)$	$\frac{d^2f}{df^2}$	$s^2F(s)-sf(0)-f'(0)$
$\frac{d^nf}{dt^n}$	$s^nF(s)-s^{n-1}f(0)-s^{n-2}f'(0)-s^{n-3}f''(0)-\cdots-f^{n-1}(0)$		