University of Technology, Sydney

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Synchroniser analysis and shift dynamics of powertrains equipped with dual clutch transmissions

A thesis submitted for the degree of

Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF TERMS AND NOTATION

ABBREVIATIONS USED IN THIS THESIS

DCT	–	Dual clutch transmission
MT	–	Manual transmission
AMT	–	Automated manual transmission
AT	–	Automatic transmission
CVT	–	Continuously variable transmission
TCU	–	Transmission control unit
DOF	–	Degrees of freedom
VFS	–	Variable force solenoid
NVH	–	Noise vibration and harshness
DMFW	–	Dual mass flywheel

CHAPTER 3 NOTATION

General

β	–	Bulk modulus
μ	–	Viscosity
c_r	–	Radial clearance
l	–	Sliding contact length
t	–	Time
A	–	Cross-sectional area
C_d	–	Damping coefficient
C_D	–	Discharge coefficient
D	–	Diameter
F	–	Force
K_s	–	Spring constant
M	–	Mass
P	–	Pressure
Q	–	Flow rate
V	–	Volume
X	–	Displacement
$\dot{X}$	–	Velocity

$\ddot{X}$ – Acceleration

Subscripts

0 – initial condition

syn – synchroniser

C – Cylinder

Cl – Clutch

CV## – Control volume number for fluid system

Exh – Exhaust

IN – Inlet

L – Leak

MMF – Magneto-motive force

O – Orifice

P – Piston or spool

V – Volume

CHAPTER 4 NOTATION

α – Cone angle

β – Chamfer angle

δ – Angular displacement between consecutive chamfers

θ_D – Detent contact angle

θ_H – Chamfer relative alignment

$\dot{\theta}_S$ – Cone relative speed

$\ddot{\theta}_{FW}$ – Freewheeling component acceleration

$\ddot{\theta}_R$ – Ring acceleration

μ – Transmission fluid viscosity

μ_C – Cone dynamic friction

$\mu_{C,S}$ – Cone static friction

μ_{DETENT} – Detent friction coefficient

μ_I – Chamfer friction coefficient

μ_R – Ring/sleeve sliding friction

λ – Chamfer flank contact

Π	–	Dimensionless group
Λ	–	Empirical constant that is dependent on the lubrication case ($1>\Lambda>5$)
a	–	Grooved width
b	–	Semi-width of the contact generatrix in the cone [66]
h	–	Film thickness
m_s	–	Sleeve mass
m_{S+R}	–	Sleeve and ring mass
n	–	Number of grooves
t_B	–	Unblocking time
t_S	–	Synchronisation time
x_S	–	Sleeve displacement
$\ddot{x}_S$	–	Sleeve acceleration
F_A	–	Net sleeve load
F_{DETENT}	–	Detent force
F_{FILM}	–	film squeezing force
F_{LOSS}	–	Seel drag losses
F_R	–	Radial force
I_{FW}	–	Inertia of the freewheeling components
I_R	–	Inertia of the ring
I_V	–	Vehicle inertia
K_{GR}	–	Groove coefficient
N_{CH}	–	Number of chamfers on one ring
R_C	–	Mean cone radius
R_H	–	RMS roughness of the hub
R_I	–	Pitch radius of chamfers
R_m	–	Cone mean radius
R_R	–	RMS roughness of the ring
T_B	–	Blocking torque
T_C	–	Cone torque.
T_D	–	Drag torque
T_I	–	Indexing torque
T_S	–	Synchronisation torque
T_V	–	Vehicle torque

CHAPTER 5 NOTATION

General

α	–	transverse operating pressure angle
β	–	operating helix angle
γ	–	gear ratio
ν	–	kinematic viscosity
μ	–	dynamic viscosity
ρ	–	density
ω	–	rotational velocity
ω_G	–	Gear speed
$\Delta\omega_{CL}$	–	Clutch slip speed
θ	–	Rotational displacement
b	–	Face width
d	–	Diameter
f	–	Friction
h	–	Fluid spacing
r	–	Radius (* denotes radius at critical Reynolds number)
C	–	Drag torque dimensionless coefficient
E	–	Energy
Gr	–	Turbulent flow coefficient
H	–	Sliding ratio at the start of the approach
H	–	Sliding ratio at the end of the recess
I_{FW}	–	Reflected inertia
KE	–	Kinetic energy
M	–	Mesh mechanical advantage
N	–	rotational speed (RPM)
P	–	Mesh power loss (kW)
Re	–	Reynolds number (* denotes critical Reynolds number)
Q	–	Flow rate
T	–	Torque
X	–	Profile coefficient
Z	–	module

Subscripts

o1	–	pinion outside radius
o2	–	gear outside radius
s	–	Start of approach
t	–	End of approach
w1	–	pinion operating pitch radius
w2	–	gear operating pitch radius
A	–	Tooth tip
B	–	Bearing losses
CL	–	Clutch windage
D	–	Drag
F	–	Gear friction
I	–	Inside
M	–	Mesh
O	–	Outside
P	–	Pitch point
SH	–	Inter-shaft shear
V	–	windage
W	–	Gear windage

CHAPTER 6 NOTATION*

***Any previously used terminology can be found in Chapter 4 or 5 notation**

θ_C	–	Control system rotation DOF
θ_P	–	Pinion DOF
I_C	–	Control system inertia ($_0$ for initial, Δ for change in inertia)
I_P	–	Pinion inertia
K_C	–	Control shaft stiffness
T_{CONT}	–	Control torque
T_{SYN}	–	Synchroniser torques
x_C	–	Chamfer contact displacement
Δx_S	–	Net sleeve displacement over one chamfer

CHAPTER 7 NOTATION*

***Any previously used terminology can be found in Chapter 4, 5 or 6 notation**

R	–	Cone radius

r – Chamfer pitch radius

CHAPTER 8 NOTATION

General

θ – Angular displacement

$\dot{\theta}$ – Angular velocity

$\ddot{\theta}$ – Angular acceleration

γ – Gear ratio

ω – Frequency

ϕ – Phase angle

ζ – Damping ratio

x – Displacement

$\dot{x}$ – Velocity

$\ddot{x}$ – Acceleration

T – Time

C – Damping coefficient

I – Inertia

K – Spring coefficient

M – Mass

T – Torque

X – Amplitude coefficient

Subscripts

1 – Refers to components associated with odd gears

2 – Refers to components associated to even gears

e – Engine

hys – Hysteresis

AX – Axle

C – Clutch

DIFF – Differential

F – Flywheel or Dual mass flywheel primary

DM – Clutch drum or Dual mass flywheel secondary integrated with clutch

FD – Final drive

G	–	Gear
P	–	Pinion
S	–	Synchroniser
SL	–	Synchroniser sleave
T	–	Tyre
W	–	Wheel hub

Engine models

θ	–	Crank angle
ω_e	–	Engine speed
m_T	–	Mass of gas
A_P	–	Piston area
M_P	–	Piston mass
P	–	Instantaneous piston pressure
R	–	Ideal gas constant
$\dot{S}$	–	Piston speed
T	–	Piston temperature
T_P	–	Piston torque
T_t	–	Inertia change torque
V	–	Piston volume

Clutch model

μ_D	–	Dynamic friction coefficient
μ_S	–	Static friction coefficient
$\Delta\dot{\theta}_{SL}$	–	Clutch slip speed
n	–	Number of friction surfaces
r_I	–	Inside radius
r_O	–	Outside radius
F_A	–	Axial force
T_C	–	Clutch torque
T_{avg}	–	Average torque
X	–	Piston displacement
X_0	–	Contact displacement for friction plates

Synchroniser model

Refer to Chapter 4 notation

Vehicle torque model

$\theta_{incline}$ – Angle of inclination

ρ_{air} – Air density

g – Gravity

C_D – Coefficient of drag

C_{tire} – Dimensionless tire retarding force

F_{aero} – Aerodynamic drag load

$F_{incline}$ – Incline load

F_{roll} – Aerodynamic drag load

F_R – Net resistance force

H_v – Vehicle height

M_v – Vehicle mass

R_{wheel} – Wheel radius

T_R – Net resistance torque

V_W – Linear velocity of driving wheels

W_v – Vehicle width

CHAPTER 9 NOTATION

***Any previously used terminology can be found in Chapter 8 notation**

General

Θ – Amplitude coefficient

Subscripts

C – Clutch

D – clutch drum

E – Engine

T – Transmission

V – Vehicle

1,2 – clutch or gear number

CHAPTER 11 NOTATION

*Any previously used terminology can be found in Chapter 8 notation

General

θ –rotational degree of freedom

θ_C – Contact displacement rotation

C – Damping

I – Inertia

K – stiffness

M – Mass

r – radius

t –time

TA – throttle angle

x – gear linear degree of freedom

X_C – contact displacement length

y – pinion linear degree of freedom

Subscripts

B – Bearing

Refer to Chapter 8 subscripts

ABSTRACT

Transient dynamic investigations of dual clutch transmission equipped powertrains are conducted in this thesis through the development and application of torsional multi-body models incorporating multiple nonlinearities. Shift control studies are performed using detailed hydraulic model integrated with a 4DOF powertrain model. Results illustrate that accuracy of torque estimation, time delay in engine and clutches, and torque balance in the powertrain all influence the shift quality. Powertrain transient studies have been carried out to investigate the impact of multiple nonlinearities on powertrain dynamics and shift quality. This makes use of the clutch friction stick-slip algorithm to model nonlinearity in clutch engagements, with other nonlinearities including mean and harmonic engine torque models and dual mass flywheel with hysteresis. Comparisons between 4 and 15 DOF powertrain models are made, and the impact of using engine harmonics for the DCT powertrain identified. Results of these studies are also discussed with respect to stick-slip response clutches and the effect on post shift transient response. Finally, a backlash model is introduced for gears and synchronisers to study response under a variety of operating conditions, including synchroniser engagement, shift transients and engine tip-in/tip-out.

Investigations of synchroniser mechanism dynamics and control are undertaken with a rigid body mechanism model, and as part of the DCT powertrain using a 15 DOF multi-body model. Broad ranging parameter studies are undertaken for design and environmental variables that impact on synchroniser performance, and dimensionless torques are introduce for the study of synchroniser design parameters. Slip regeneration is identified as a significant issue in mechanism actuation, in terms of engagement repeatability and damage to chamfer friction surfaces. Alignment control methods are studied to attempt to reduce the impact of chamfer alignment and regenerated slip on engagement performance. Finally two design modifications are suggested for the mechanism to eliminate the slip issue, and provide higher synchroniser torques for a similar design envelope. Powertrain simulation results suggest that under nominal actuation, using the mean engine torque model, vibrations of the sleeve increase during indexing alignment of chamfers, indicating increased wear of friction surfaces. With the inclusion of the harmonic engine torque model, vibrations in the transmission increases significantly throughout the engagement process; however these results do not indicate that there is an increased likelihood of clash during speed synchronisation.