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Automotive Transmissions

Fundamentals, Selection, Design and Application

Springer

Gisbert Lechner · Harald Naunheimer

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In Collaboration with Joachim Ryborz

With 370 Figures

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Preface to the English Edition

"Automotive Transmissions" was first published in German in May 1994. It was so well received that we decided to publish the book in English, especially in view of the trend to market globalisation.

This book gives a full account of the development process for automotive transmissions. It seeks to impart lines of reasoning, demonstrate approaches, and provide comprehensive data for the practical task of developing automotive transmissions. Much of the content is concerned with aspects of technology and production in the field of automotive transmissions that are of general validity, and hence of enduring relevance. The dynamics of the automotive transmission market since 1994 is reflected in numerous new types of transmission. Principal factors include the increasing use of electronics, light-weight construction, and the automation of manual gearboxes. Chapter 12 considers numerous production designs to illustrate the theoretical principles expounded in the earlier chapters, considering the main types of transmission and examining important detail solutions incorporated in specific mechanisms. Today's current design engineering is no longer state of the art tomorrow, with the next change of model. The designs presented here therefore claim to represent the different types of transmission design considered, rather than the latest production technology.

Certain aspects of the book relate to the situation in Germany, particularly as regards transport systems and the economic significance of motor vehicles.

This English language edition could not have come to fruition without the assistance of many contributors. We are particularly indebted to Dipl-Ing Joachim Ryborz as the manager and co-ordinator of the project, and to his assistants at the Institute of Machine Components (IMA), University of Stuttgart.

We would also like to thank Stephen Day of Übersetzungsbüro Herrera for his professional translation of this book, and Dr Ian Cole for proof-reading the final text.

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Stuttgart and Augsburg
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Gisbert Lechner

Harald Naunheimer

Preface to the German Edition

It was in 1953 that H. Reichenbächer wrote the first book on motor vehicle transmission engineering. At that time the German motor industry produced 490 581 vehicles including cars, vans, trucks, busses and tractor-trailer units. In 1992 production had reached 5.2 million. The technology at that time only required coverage of certain aspects, and Mr Reichenbächer's book accordingly restricted itself to basic types of gearbox, gear step selection, gear-sets with fixed axles, epicyclic systems, Föttinger couplings and hydrodynamic transmissions.

Automotive engineering and the technology of mechanism design have always been subject to evolution. The current state of the art is characterised by the following interrelations:

Environment ⇔ Traffic ⇔ Vehicle ⇔ Transmission.

Questions such as economy, environment and ease of use are paramount. The utility of a transmission is characterised by its impact on the traction available, on fuel consumption and reliability, service life, noise levels and the user-friendliness of the vehicle.

There are new techniques which now have to be taken into account, relating to development methodology, materials technology and notably strength calculation. Examples include serviceability calculations, the introduction of specific flank corrections, taking account of housing deformation, and the need for light-weight construction.

Transmission design engineering bas been enriched by numerous variants. The manual two-stage countershaft transmission, preferred for longitudinal engines, and the single-stage countershaft transmission preferred for transverse engines now have many subvariants, e.g. automatic transmissions, continuously variable transmissions, torque converter clutch transmissions, twin clutch transmissions, and transmissions for all-wheel drive.

The engine and transmission must increasingly be considered as one functional unit. The terms used are "power train matching" and "engine/transmission management". This can only be achieved by an integrated electronic management system covering the mechanical components in both engine and transmission.

The technique of Systematic Engineering developed in the 1960's, and the increasing use of computers for design, simulation and engineering (CAD), are resulting in ever-reducing development cycles. This trend is reinforced by competitive pressures. Systematic product planning is another significant factor in this regard.

It was therefore necessary to create an entirely new structure for the present book "Automotive Transmissions". Modern developments have to be taken into account. The great diversity and range of issues in developing transmissions made it difficult to select the material for this completely new version of "Automotive Transmissions", especially within the prevailing constraints. Not every topic could be covered in detail. In those places where there is an established literature, the authors have chosen to rely on it in the interests of brevity.

The purpose of this book is to describe the development of motor vehicle transmissions as an ongoing part of the vehicle development system. Only by actively taking this interaction into account is it possible to arrive at a fully viable transmission design. The aim is to highlight the basic interrelations between the drive unit, the vehicle and the transmission on the one hand, and their functional features such as appropriate gear selection, correct gear step, traction profile, fuel consumption, service life and reliability on the other. Of course another major concern was to represent the various engineering designs of modern vehicle transmissions in suitable design drawings.

The book is addressed to all engineers and students of automotive engineering, but especially to practitioners and senior engineers working in the field of transmission development. It is intended as a reference work for all information of importance to transmission development, and is also intended as a guide to further literature in the field.

Without the assistance of numerous people this book would not have been written. We would like to thank Dr Heidrun Schröpel, Mr Wolfgang Elser, Dr Ekkehard Krieg, Dr Winfried Richter, Mr Thomas Spörl, Mr Thilo Wagner, Dr Georg Weidner and Prof Lothar Winkler for researching and revising chapters. We also wish to acknowledge the contribution of numerous assistants and postgraduates for important work on specific aspects.

We wish to thank Christine Häbich for her professional editing. We would like to thank many employees and scientific assistants of the IMA (Institut für Maschinenelemente) for reviewing and checking various parts of the text.

Such a book cannot be published without current practical illustrations. The publishers wish to acknowledge their gratitude to numerous companies for making illustrations available: Audi AG, BMW AG, Eaton GmbH, Fichtel & Sachs AG, Ford Werke AG, GETRAG, Mercedes-Benz AG, Adam Opel AG, Dr.-Ing. h.c. Porsche AG, and Volkswagen AG. We are particularly indebted to ZF Friedrichshafen AG who have always been most forthcoming in responding to our numerous requests for graphic material.

We are also indebted to Springer-Verlag for publishing this book. We would particularly like to thank Mr M Hofmann, whose faith in our project never wavered, and whose gentle but firm persistence ensured that the book did indeed reach completion. Dr Merkle then prepared the work for printing. We must also thank the publisher of the "Design Engineering Books" series, Prof Gerhard Pahl for his patience and advice. Our thanks especially to our families for their understanding and support.

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Gisbert Lechner

Harald Naunheimer

Terms and Symbols

A formula you cannot derive is a corpse in the brain /C. WEBER/

Physical variables are related by mathematical formulae. These can be expressed in two different ways:

- quantity equations,
- unit equations.

Quantity Equations

Quantity equations are independent of the unit used, and are of fundamental application. Every symbol represents a physical quantity, which can have different values:

Value of the quantity = numerical value x unit .

Example: Power P is generally defined by the formula

$$P = T\,\omega \ , \tag{1}$$

where T stands for torque and ω stands for angular velocity.

Unit Equations

If an equation recurs frequently or if it contains constants and material values, it is convenient to combine the units, in which case they are no longer freely selectable.

In unit equations the symbols incorporate only the numerical value of a variable. The units in unit equations must therefore be precisely prescribed.

Example: In order to calculate the effective power P in kW at a given rotational speed n in 1/min, the above equation (1) becomes the unit equation

$$P = \frac{T\,n}{9550} \ . \tag{2}$$

The unit equation (2) applies where the prescript P is expressed in kW, T in Nm and n in 1/min.

Terms and Symbols

(Only those which occur frequently; otherwise see text)

A	Surface area, transverse couple surface area = projection of vehicle front area
A_R	Synchroniser friction contact
B_{10}	System service life for a failure probability of 10%
B_x	System service life for a failure probability of x%
C	Pitch point, dynamic contact figure, constant
CC	Torque converter lock-up clutch
CG	Constant gear
CG_H	Front-mounted splitter constant high
CG_L	Front-mounted splitter constant low
CG_{main}	Main gear unit constant
CG_R	Range constant
D	Diameter
E	Modulus of elasticity
F	Force
F_a	Acceleration resistance, axial force
F_B	Braking force
F_H	Slope negative lift force
F_L	Air resistance, bearing force
F_n	Normal force
F_Q	Transversal force
F_R	Wheel resistance
F_r	Radial force
F_S	Lateral force
F_{St}	Gradient resistance
F_t	Tangential force
F_U	Circumferential force
F_Z	Traction
$F(t)$	Distribution function, failure probability
G_R	Wheel load
J	Mass moment of inertia
K_G	Gear characteristic value
L	Service life
M_b	Bending moment
M_t	Torsional moment
M_v	Reference moment
N	Fracture cycles
P	Power
P_A	Friction power related to area (synchroniser)
P_e	Effective power at engine output
P_m	Average friction work during synchroniser slipping times
$P_{Z,B}$	Demand power at wheel
Q	Lateral force, volume flow
R	Reaction force
R_a	Average peak-to-valley height

R_e	Yield point
R_m	Tensile strength
$R(t)$	Survivability, reliability
S	Safety factor, locking safety with synchronisers, slip, interlock value
S_B	Brake slip
S_H	Rear-mounted splitter unit high
S_L	Rear-mounted splitter unit low
S_T	Drive slip
T	Torque, characteristic service life
T_B	Acceleration torque (synchroniser), locking torque (differential)
T_L	Load torque
T_R	Friction torque (clutch, synchroniser), reactor torque (torque converter)
TC	Torque converter
TCC	Torque converter clutch
U	Revolutions
V_H	Total displacement
W	Moment of resistance, work, usable work, friction work
W_A	(Specific) friction work per unit area
W_b	Moment of resistance against deflection
W_t	Moment of resistance against torsion
a	Acceleration, axle base
b	Form parameter, failure gradient, overall length, width, fuel consumption
b_0	Size factor
b_e	Specific fuel consumption
b_S	Surface factor
b_s	Fuel consumption per unit of distance
c	Constant, rigidity, absolute speed
c_s	Tooth spring rigidity
c_u	Circumferential component of absolute speed
c_W	Drag coefficient
c_γ	Average value of tooth spring rigidity over time
d	Diameter
e	Eccentricity
f	Deflection
f_R	Coefficient of rolling resistance
$f(t)$	Density function
g	Acceleration due to gravity
h_i	Load cycle
i	Ratio
i_A	Power-train ratio (from engine to wheels)
i_E	Final ratio
i_G	Gear ratio
$i_{G,\,tot}$	Overall gear ratio, ratio spread
i_{CG}	Constant gear ratio
i_M	Centre gear ratio
i_N	Hub gear ratio
i_S	Moving-off element ratio
i_V	Variator ratio
j	Number of friction contacts
k	Wöhler curve equation exponent
$k(\nu)$	Characteristic value of a torque converter

m	Gear modulus, mass, linear scale (converter)
m_F	Vehicle mass
n	Rotational speed, quantity, stress reversals, number of bearings
n_M	Engine speed
p	Contact pressure, pressure, number of gear pairs
q	Gradient, surface load
q'	Gradient in %
r	Radius, degree of redundancy
r_{dyn}	Dynamic tyre radius
s	Travel, gearshift sleeve travel, fin pitch
s_{Fn}	Root thickness chord
t	Statistical variable, time
t_0	Time without failure
t_m	Mean of Weibull distribution
t_R	Slipping time, friction time
t_S	Shifting time
u	Gear ratio, circumferential speed
v	Speed, flow rate
v_F	Vehicle speed
v_{th}	Theoretical speed where $\lambda = 0$
v_W	Wind speed
w	Work input, relative wind speed
x, y, z	Co-ordinates
z	Number of speeds, number of teeth, number of load cycles
z_i	Number of teeth gear i
α	Meshing angle, taper angle of a taper synchroniser, viscosity pressure coefficient
α_{DK}	Throttle valve angle
α_K	Force meshing angle relative to tip edge
α_k	Statistical form factor
α_n	Normal meshing angle
α_{St}	Gradient angle
α_0	Strain ratio
β	Helix angle at pitch circle, aperture angle of claws
β_K	Dynamic beam stress rate
Δ	Interval, difference
ΔS	Wear path
ΔV	Wear
ε	Total contact
ε_α	Transverse contact ratio
ε_β	Overlap ratio
η	Efficiency, dynamic viscosity
ϑ	Temperature
λ	Performance coefficient (converter, retarder), drive slip, rotational inertia coefficient
$\lambda(t)$	Failure rate
μ	Torque conversion, coefficient of friction
μ_0	Stall torque ratio
μ_G	Coefficient of sliding friction
μ_H	Coefficient of bonding friction

ν	Speed ratio, kinematic viscosity
ρ	Density, angle of friction of the claws
σ	Direct stress
σ_b	Bending stress
σ_D	Fatigue strength
σ_H	Hertzian stresses
σ_v	Reference stress
τ	Torsional stress, torque increase with combustion engine
φ	Gear step, bending angle
φ_1	Basic step with progressive stepping
φ_2	Progression factor with progressive stepping
φ_{th}	Gear step with geometrical stepping
ω	Angular velocity

Subscripts

0	Nominal or initial state
1	Pinion (= small gear), input
2	Wheel (= large gear), output
1, 2, 3, ...	At point 1, 2, 3, ...
A	Offer, related to area, drive shaft, power train, moving off
B	Demand, brake
C	Clutch
CG	Constant gear
CS	Countershaft
D	Duration, fatigue-resistant, deficit, opening, direct drive
E	End
Ex	Excess
F	Vehicle, root, free-wheel
G	Gearbox
H	Adhesion, main, main gearbox, main shaft wheel, ring gear, high (= fast)
IS	Input shaft
L	Air, load, low (= slow)
L, L1, L2	At bearing point, at bearing point 1, 2
M	Engine, motor, model
MS	Main shaft
N	Rear-mounted range-change unit
OS	Output shaft
P	Pump, pump wheel, planetary step
PV	Pump test
Q	Transverse
R	Reverse gear, roll, slip, friction, wheel, range-change unit, reactor
Roll	Roll
S	Status, system, splitter unit
Sch	Pulsating (strength)
St	Gradient
T	Turbine wheel, drive
TC	Torque converter
U	Circumference
V	Front-mounted splitter unit, variator, loss, trial

W	Reversing (strength)
Z	Traction, tensile load, intermediate gear, tooth, opening

a	Acceleration, axial, values at tip circle, tip of gear, outlet, external
abs	Absolute
b	Bending
dyn	Dynamic
e	Effective, inlet
fric	Friction
front	Front
fuel	Fuel
rear	Rear
i	Internal, control variable $i = 1, 2, 3, \ldots n$
id	Ideal
in	Input
i, j	At point i, j
j	Control variable
k	Control variable
kt	Beam stress
m	Mean, number of stress classes
main	Main
max	Maximum
min	Minimum
n	n-th speed, nominal, nominal operating point
oil	Oil
out	Output
perm	Permissible
r	Radial
red	Reduced
ref	Reference
rel	Relative
res	Resultant
spec	Specific
stat	Static
t	Torsion, time
th	Theoretical
tot	Total
twist	Twist
w	Reversing, pitch circle
x, y, z	In *x, y, z* direction, around *x, y, z* axis
z	Highest speed, number of speeds

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