

Vehicle Propulsion Systems

Lecture 7

Non Electric Hybrid Propulsion Systems

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Outline

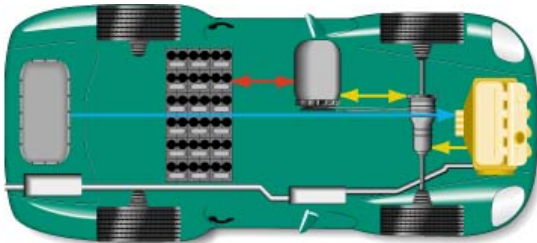
- Repetition
- Short Term Storage
- Hybrid-Inertial Propulsion Systems
 - Basic principles
 - Design principles
 - Modeling
 - Continuously Variable Transmission
- Hybrid-Hydraulic Propulsion Systems
 - Basics
 - Modeling
- Hydraulic Pumps and Motors
- Pneumatic Hybrid Engine Systems
- Case studies

2/48

3/48

Hybrid Electrical Vehicles – Parallel

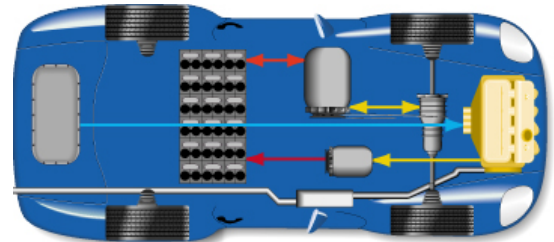
- ▶ Two parallel energy paths
- ▶ One state in QSS framework, state of charge



4/48

Hybrid Electrical Vehicles – Serial

- ▶ Two paths working in parallel
- ▶ Decoupled through the battery
- ▶ Two states in QSS framework, state of charge & Engine speed

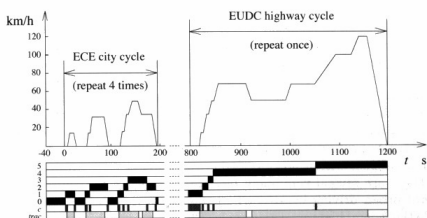


5/48

Optimization, Optimal Control, Dynamic Programming

What gear ratios give the lowest fuel consumption for a given driving cycle?

– Problem presented in appendix 8.1



Problem characteristics

- ▶ Countable number of free variables, $i_{g,j}, j \in [1, 5]$
- ▶ A “computable” cost, $m_f(\dots)$
- ▶ A “computable” set of constraints, model and cycle
- ▶ The formulated problem

$$\begin{aligned} \min_{i_{g,j}, j \in [1,5]} & m_f(i_{g,1}, i_{g,2}, i_{g,3}, i_{g,4}, i_{g,5}) \\ \text{s.t.} & \text{model and cycle is fulfilled} \end{aligned}$$

6/48

7/48

Optimal Control – Problem Motivation

Car with gas pedal $u(t)$ as control input:

How to drive from A to B on a given time with minimum fuel consumption?

- ▶ Infinite dimensional decision variable $u(t)$.
- ▶ Cost function $\int_0^t \dot{m}_f(t) dt$
- ▶ Constraints:
 - ▶ Model of the car (the vehicle motion equation)

$$\begin{aligned} m_v \frac{d}{dt} v(t) &= F_r(v(t), u(t)) - (F_a(v(t)) + F_r(v(t)) + F_g(x(t))) \\ \frac{d}{dt} x(t) &= v(t) \\ \dot{m}_f &= f(v(t), u(t)) \end{aligned}$$

- ▶ Starting point $x(0) = A$
- ▶ End point $x(t_f) = B$
- ▶ Speed limits $v(t) \leq g(x(t))$
- ▶ Limited control action $0 \leq u(t) \leq 1$

General problem formulation

- ▶ Performance index

$$J(u) = \phi(x(t_b), t_b) + \int_{t_a}^{t_b} L(x(t), u(t), t) dt$$

- ▶ System model (constraints)

$$\frac{d}{dt} x = f(x(t), u(t), t), x(t_a) = x_a$$

- ▶ State and control constraints

$$u(t) \in U(t)$$

$$x(t) \in X(t)$$

8/48

Dynamic programming – Problem Formulation

- ▶ Optimal control problem

$$\min J(u) = \phi(x(t_b), t_b) + \int_{t_a}^{t_b} L(x(t), u(t), t) dt$$

$$\text{s.t. } \frac{d}{dt} x = f(x(t), u(t), t)$$

$$x(t_a) = x_a$$

$$u(t) \in U(t)$$

$$x(t) \in X(t)$$

- ▶ $x(t), u(t)$ functions on $t \in [t_a, t_b]$
- ▶ Search an approximation to the solution by discretizing
 - ▶ the state space $x(t)$
 - ▶ and maybe the control signal $u(t)$
 in both amplitude and time.
- ▶ The result is a combinatorial (network) problem

9/48

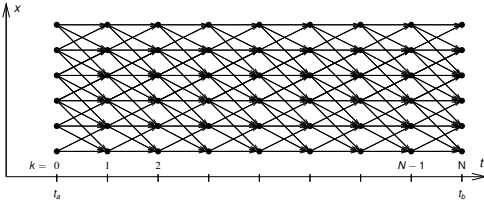
Deterministic Dynamic Programming – Basic algorithm

$$J(x_0) = g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k)$$

$$x_{k+1} = f_k(x_k, u_k)$$

Algorithm idea:

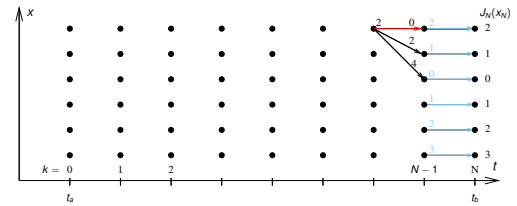
Start at the end and proceed backwards in time to evaluate the optimal cost-to-go and the corresponding control signal.



10/48

Deterministic Dynamic Programming – Basic Algorithm

Graphical illustration of the solution procedure



11/48

Arc Cost Calculations

There are two ways for calculating the arc costs

- ▶ Calculate the exact control signal and cost for each arc.
 - Quasi-static approach
- ▶ Make a grid over the control signal and interpolate the cost for each arc.
 - Forward calculation approach

Matlab implementation – it is important to utilize matrix calculations

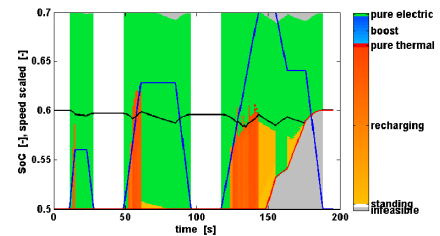
- ▶ Calculate the whole bundle of arcs in one step
- ▶ Add boundary and constraint checks

2D and 3D grid examples on whiteboard

12/48

Parallel Hybrid Example

- ▶ Fuel-optimal torque split factor $u(SOC, t) = \frac{T_{e-motor}}{T_{gearbox}}$
- ▶ ECE cycle
- ▶ Constraints $SOC(t = t_f) \geq 0.6$, $SOC \in [0.5, 0.7]$



13/48

Outline

Repetition

Short Term Storage

Hybrid-Inertial Propulsion Systems

- Basic principles
- Design principles
- Modeling
- Continuously Variable Transmission

Hybrid-Hydraulic Propulsion Systems

- Basics
- Modeling

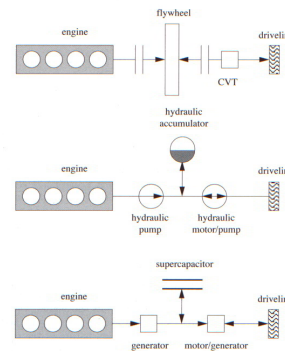
Hydraulic Pumps and Motors

Pneumatic Hybrid Engine Systems

Case studies

14/48

Examples of Short Term Storage Systems



15/48

Short Term Storage – F1

2009 FIA allowed the usage of 60 kW, KERS (Kinetic Energy Recovery System) in F1.

Technologies:

- ▶ Flywheel
- ▶ Super-Caps, Ultra-Caps
- ▶ Batteries

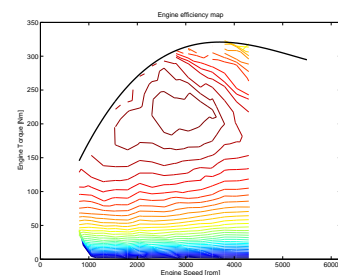
2014, will allow KERS units with 120 kilowatts (160 bhp).

–To balance the sport's move from 2.4 l V8 engines to 1.6 l V6 engines.

16/48

Basic Principles for Hybrid Systems

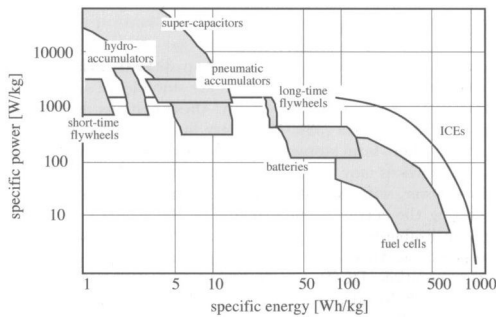
- ▶ Kinetic energy recovery
- ▶ Use “best” points – Duty cycle.
 - ▶ Run engine (fuel converter) at its optimal point.
 - ▶ Shut-off the engine.



17/48

Power and Energy Densities

Asymptotic power and energy density – The Principle



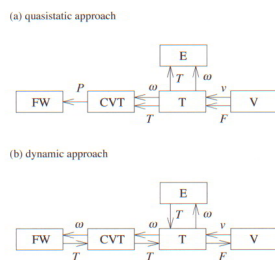
18/48

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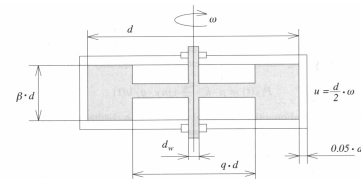
19/48

Causality for a hybrid-inertial propulsion system



20/48

Flywheel accumulator



► Energy stored ($\Theta_f = J_f$):

$$E_f = \frac{1}{2} \Theta_f \omega_f^2$$

► Wheel inertia

$$\Theta_f = \rho b \int_{Area} r^2 2\pi r dr = \dots = \frac{\pi}{2} \rho b \frac{d^4}{16} (1 - q^4)$$

21/48

Flywheel accumulator – Design principle

► Energy stored (SOC):

$$E_f = \frac{1}{2} \Theta_f \omega_f^2$$

► Wheel inertia

$$\Theta_f = \rho b \int_{Area} r^2 2\pi r dr = \dots = \frac{\pi}{2} \rho b \frac{d^4}{16} (1 - q^4)$$

► Wheel Mass

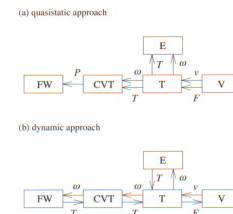
$$m_f = \pi \rho b d^2 (1 - q^2)$$

► Energy to mass ratio

$$\frac{E_f}{m_f} = \frac{d^2}{16} (1 + q^2) \omega_f^2 = \frac{v^2}{4} (1 + q^2)$$

22/48

Quasistatic Modeling of FW Accumulators



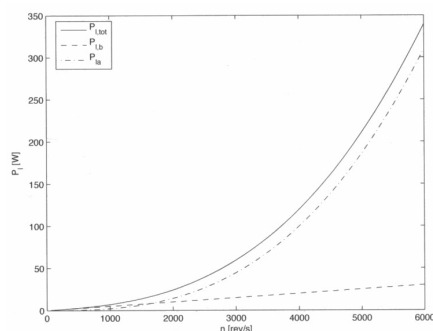
Flywheel speed (SOC) $P_2(t)$ – power out, $P_1(t)$ – power loss

$$\Theta_f \omega_2(t) \frac{d}{dt} \omega_2(t) = -P_2(t) - P_1(t)$$

23/48

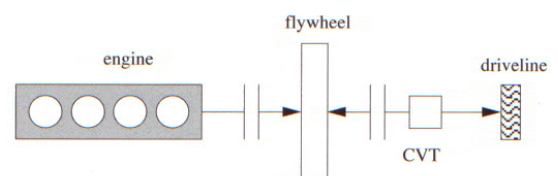
Power losses as a function of speed

Air resistance and bearing losses



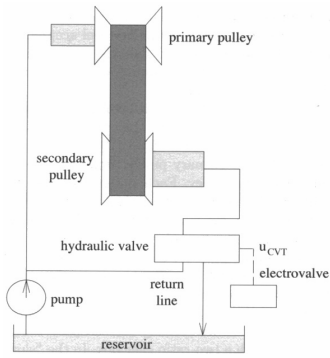
24/48

Continuously Variable Transmission (CVT)



25/48

CVT Principle



26/48

CVT Modeling

- Transmission (gear) ratio ν , speeds and transmitted torques

$$\omega_1(t) = \nu(t) \omega_2(t)$$

$$T_{H1}(t) = \nu (T_{H2}(t) - T_I(t))$$

- Newtons second law for the two pulleys

$$\Theta_1 \frac{d}{dt} \omega_1(t) = T_1(t) - T_{H1}(t)$$

$$\Theta_2 \frac{d}{dt} \omega_2(t) = T_2(t) - T_{H2}(t)$$

- System of equations give

$$T_1(t) = T_I(t) + \frac{T_2(t)}{\nu(t)} + \frac{\Theta_{CVT}(t)}{\nu(t)} \frac{d}{dt} \omega_2(t) + \Theta_1 \frac{d}{dt} \nu(t) \omega_2(t)$$

27/48

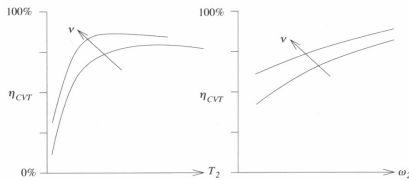
CVT Modeling

- Transmission (gear) ratio ν , speeds and transmitted torques

$$\omega_1(t) = \nu(t) \omega_2(t)$$

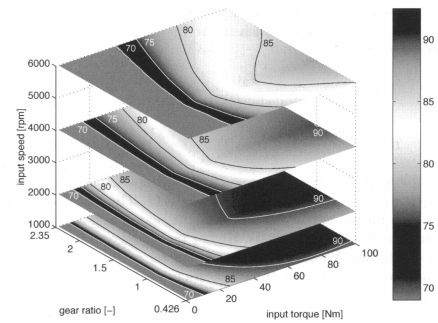
$$T_{H1}(t) = \nu (T_{H2}(t) - T_I(t))$$

- An alternative to model the losses, is to use an efficiency definition.



28/48

Efficiencies for a Push-Belt CVT



29/48

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Modeling

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Hybrid-Hydraulic Propulsion Systems

Basics

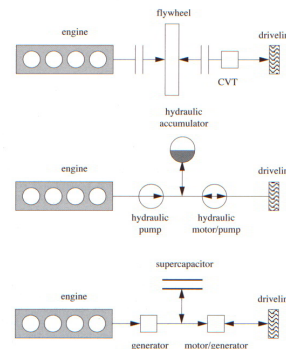
Modeling

Hydraulic Pumps and Motors

Pneumatic Hybrid Engine Systems

Case studies

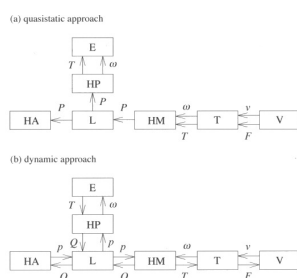
Examples of Short Term Storage Systems



30/48

31/48

Causality for a hybrid-hydraulic propulsion system



32/48

Modeling of a Hydraulic Accumulator

Modeling principle

-Energy balance

$$m_g c_v \frac{d}{dt} \theta_g(t) = -p \frac{d}{dt} V_g(t) - h A_w (\theta_g(t) - t)$$

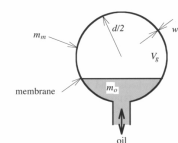
-Mass balance

(=volume for incompressible fluid)

$$\frac{d}{dt} V_g(t) = Q_2(t)$$

-Ideal gas law

$$p_g(t) = \frac{m_g R_g \theta_g(t)}{V_g(t)}$$



Power generation

$$P_2(t) = p_2(t) Q_2(t)$$

33/48

Model Simplification

Simplifications made in thermodynamic equations to get a simple state equation.

- ▶ Assuming steady state conditions.
 - Eliminating θ_g and the volume change gives

$$p_2(t) = \frac{h A_w \theta_w m_g R_g}{V_g(t) h A_w + m_g R_g Q_2(t)}$$

- ▶ Combining this with the power output gives

$$Q_2(t) = \frac{V_g(t)}{m_g} \frac{h A_w P_2(t)}{R_g \theta_w h A_w - R_g P_2(t)}$$

- ▶ Integrating $Q_2(t)$ gives V_g as the state in the model.
- ▶ Modeling of the hydraulic systems efficiency, see the book.
- ▶ **A detail for the assignment**
 - This simplification can give problems in the simulation if parameter values are off. (Division by zero.)

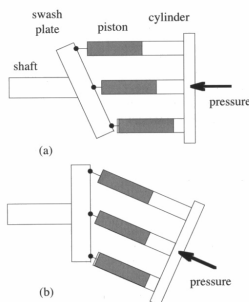
34/48

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35/48

Hydraulic Pumps



36/48

Modeling of Hydraulic Motors

- ▶ Efficiency modeling

$$P_1(t) = \frac{P_2(t)}{\eta_{hm}(\omega_2(t), T_2(t))}, \quad P_2(t) > 0$$

$$P_1(t) = P_2(t) \eta_{hm}(\omega_2(t), -|T_2|(t)), \quad P_2(t) < 0$$

- ▶ Willans line modeling, describing the loss

$$P_1(t) = \frac{P_2(t) + P_0}{e}$$

- ▶ Physical modeling
 - Wilson's approach provided in the book.

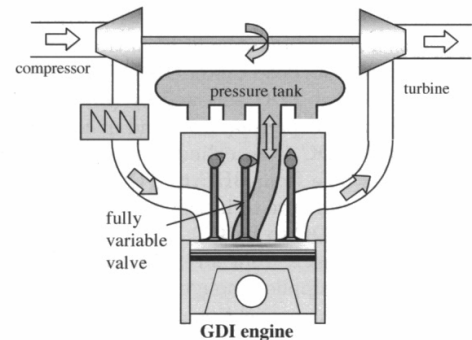
37/48

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38/48

Pneumatic Hybrid Engine System



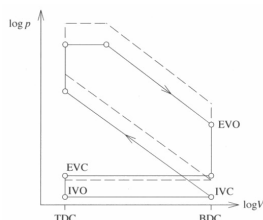
39/48

Conventional SI Engine

Compression and expansion model

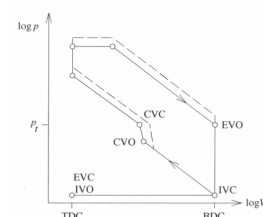
$$p(t) = c v(t)^{-\gamma} \Rightarrow \log(p(t)) = \log(c) - \gamma \log(v(t))$$

gives lines in the log-log diagram version of the pV-diagram



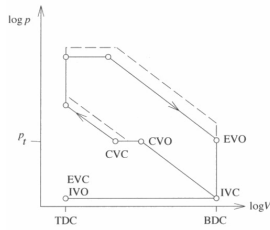
40/48

Super Charged Mode



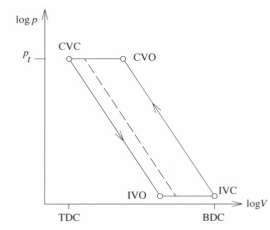
41/48

Under Charged Mode



42/48

Pneumatic Brake System



43/48

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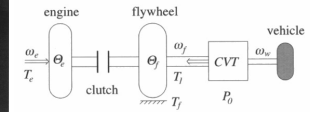
Hydraulic Pumps and Motors

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Case studies

Case Study 3: ICE and Flywheel Powertrain

- ▶ Control of a ICE and Flywheel Powertrain
- ▶ Switching on and off engine



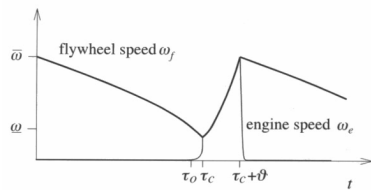
44/48

45/48

Problem description

For each constant vehicle speed find the optimal limits for starting and stopping the engine

–Minimize fuel consumption

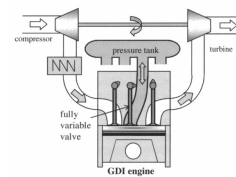


–Solved through parameter optimization \Rightarrow Map used for control

46/48

Case Study 8: Hybrid Pneumatic Engine

- ▶ Local optimization of the engine thermodynamic cycle
- ▶ Different modes to select between
- ▶ Dynamic programming of the mode selection



47/48