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# Parallel HEV Model Specifications

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# 1. Proposed Parallel HEV Model

## 1.1 Proposed Requirements of the Parallel HEV Model

The parallel HEV model consists of the engine model, electric motor model, rechargeable energy storage system (RESS) model, and a driving model. The engine model calculates the engine torque from engine control signals such as the engine torque command, the motor model calculates the electric motor torque from electric motor control signals such as the electric motor torque command, and the RESS model calculates the RESS voltage from the electric motor current generated by the motor. The driving model determines rotational frequencies of shafts such as vehicle speed using the calculated engine and motor torques, and clutch stroke and gear shift position signals from ECU.

The parallel HEV model consists of three sub-systems: the engine model that calculates the engine torque, the electric motor model calculating the electric motor torque and current, the RESS model calculating the RESS voltage, and the driving model calculating the rotational frequencies of shafts such as vehicle speed. Section 2 describes the engine model, Section 3 the electric motor model, Section 4 the RESS model, and Section 5 the driving model.

# 2. Proposed Engine Model

## 2.1 Requirements of the Engine Model

The engine model calculates the output torque of the engine from the engine torque command values, throttle valve opening or injection amount command values, and the torque map in relation to the engine rotational frequency. Then, it adds up the output torque of the engine, the starter toque, and the external torque loaded on the engine. Upon receiving the rotational frequency control or limit demand from the actual ECU, the PID control function inside the engine model controls the engine rotational frequency. The engine is stopped by the input of the Ignition OFF or Fuel Cut ON signal.

A conceptual diagram of the engine model is shown in Figure 2.1.

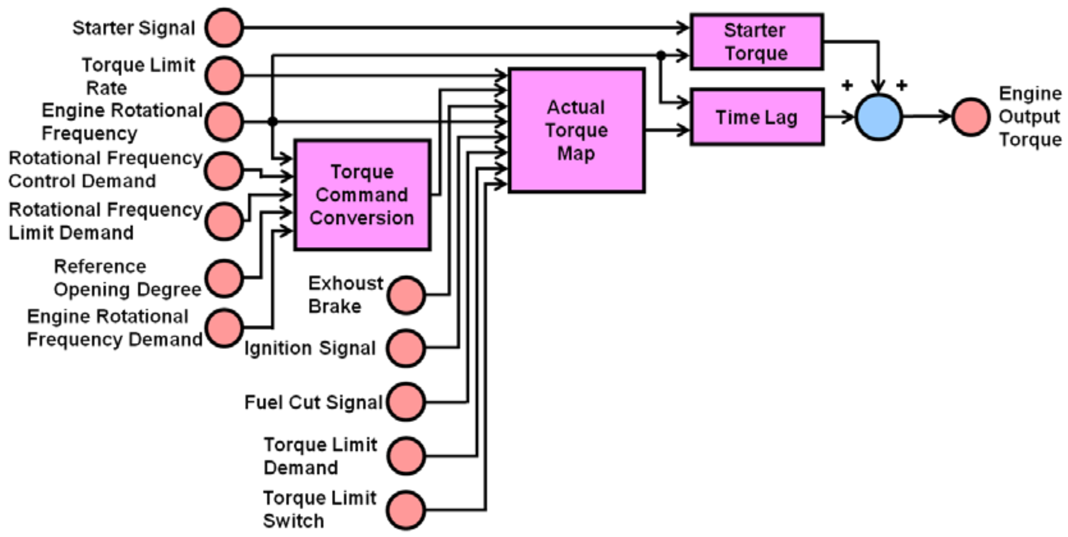


Fig. 2.1 Conceptual Diagram of the Engine Model

## 3. Proposed Electric Motor Model

### 3.1 Requirements of the Electric Motor Model

The electric motor model calculates the actual torque from the actual torque map developed from the toque command values from the ECU, the motor rotational frequency, and the measured RESS voltage values. Upon receiving the rotational frequency control demand from the ECU, it controls the motor rotational frequency using the control input calculated by the PI control as torque command. When the motor clutch is engaged, the motor rotational frequency is synchronized accordingly.

A conceptual diagram of the electric motor model is shown in Figure 3.1.

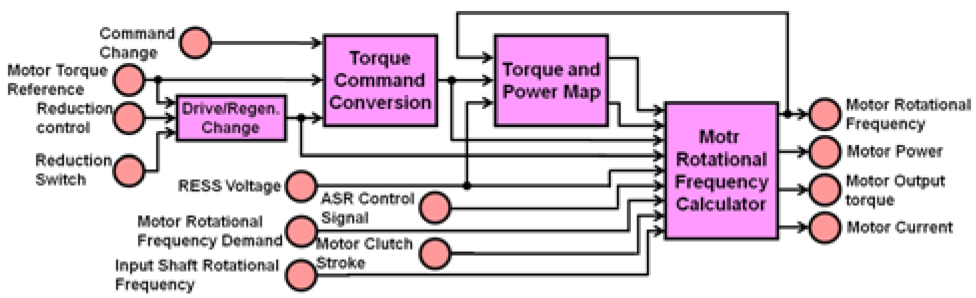


Fig. 3.1 Conceptual Diagram of the Electric Motor Model

## 4. Rechargeable Energy Storage System Model

## 4.1 Requirements of the Rechargeable Energy Storage System Model

The rechargeable energy storage system (RESS) model calculates the RESS current by summing the input motor current and the auxiliary current calculated from the input of the RESS voltage to the map, and then determines the capacitor voltage and SOC, and the battery voltage and SOC using the RESS current. Depending on the vehicle model, either the output of the capacitor or that of the battery is used as the output of the RESS.

The model consists of two sub-systems: the capacitor model that calculates the capacitor voltage and SOC, and the battery model that calculates the battery voltage and SOC. Section 4.2 describes these two models.

A conceptual diagram of the rechargeable energy storage system model is shown in Figure 4.1.

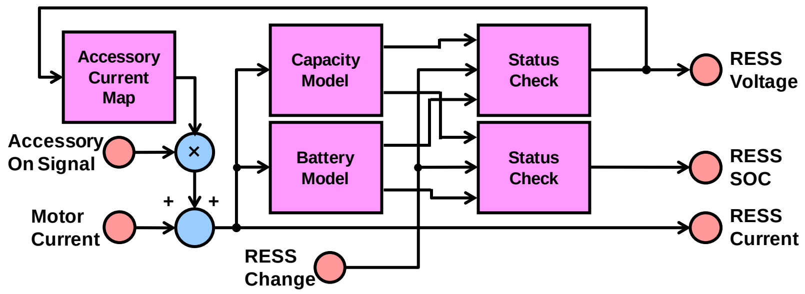


Fig. 4.1 Conceptual Diagram of the Rechargeable Energy Storage System Model

## 4.2 Sub-systems in the Rechargeable Energy Storage System Model

### 4.2.1 Requirements of the Capacitor Model

The terminal voltage and the state of charge (SOC) of the capacitor are calculated with the following equations: First, the charge of the capacitor is calculated by subtracting the electric current integrated value from the initial charge with equation (1). Then the resulting charge is divided by the nominal capacity to calculate the open voltage with equation (2). Finally with equations (3), (4) and (5), the terminal voltage and SOC are calculated using the open voltage.

A conceptual diagram of the capacitor model is shown in Figure 4.2.

$$Q = \frac{C_{nominal}V_{\max}}{10}\sqrt{SOC_{initial}} - \frac{1}{s}I \quad \cdots\cdots \quad (1)$$

$$V_O = \frac{Q}{C_{nominal}} = \frac{V_{\max}}{10}\sqrt{SOC_{initial}} - \frac{1}{C_{nominal}}\frac{1}{s}I \quad \cdots\cdots \quad (2)$$

$$V_S = V_O - R_i I = \frac{V_{\max}}{10}\sqrt{SOC_{initial}} - \frac{1}{C_{nominal}}\frac{1}{s}I - R_i I \quad \cdots\cdots \quad (3)$$

$$P = V_S I \quad \cdots\cdots \quad (4)$$

$$SOC = \frac{P}{P_{\max}}100 = \frac{C_{nominal}V^2/2}{C_{nominal}V_{\max}^2/2}100 = \frac{V^2}{V_{\max}^2}100 = 100\left(\frac{V_{\max}}{10}\sqrt{SOC_{initial}} - \frac{1}{C_{nominal}}\frac{1}{s}I\right)^2 \Big/ V_{\max}^2 \quad \cdots \quad (5)$$

$I$ : Motor current [A]
$V_S$ : Capacitor terminal voltage [V]
$V_O$ : Capacitor open voltage [V]
$V_{max}$ : Capacitor normal maximum voltage [V]
$P$ : Capacitor power [W]
$P_{max}$ : Maximum charging/discharging power [W]
$SOC$ : Capacitor SOC [%]
$SOC_{initial}$ : Capacitor initial SOC [%]
$C_{nominal}$ : Capacitor nominal capacity [F]
$Q$ : Charge [C]
$R_i$ : Capacitor internal resistance [Ω]

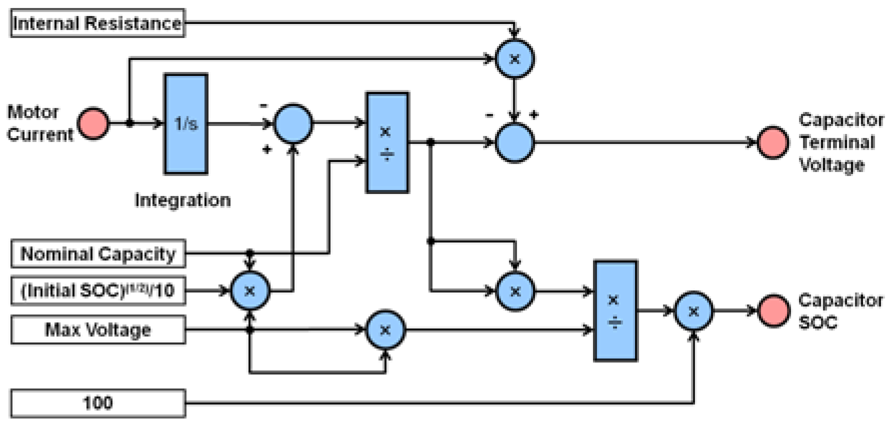


Fig. 4.2 Conceptual Diagram of the Capacitor Model

4.2.2 Requirements of the Battery Model

SOC and the charging/discharging power of the nickel hydride or lithium ion battery are calculated with the following equations (6) and (7); where SOC is calculated by current integration on the assumption that the Coulomb efficiency is 100%. Since the open voltage and internal resistance of the battery change with SOC, they should be calculated from their respective maps in relation to SOC.

A conceptual diagram of the battery model is shown in Figure 4.3.

$$SOC = SOC_{initial} - \int_0^t \frac{I}{C_{nominal} \times 3600} \times 100 \quad \cdots \quad (6)$$

$$P = V_S I = (V_o - R_i I) I \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (7)$$

$I$ : Motor current [A]
$V_o$ : Battery open voltage [V]
$V_S$ : Battery terminal voltage [V]
$P$ : Battery power [W]
$R_i$ : Internal resistance [Ω]
$SOC$ : Battery SOC [%]
$SOC_{\text{initial}}$ : Initial SOC [%]
$C_{nominal}$ : Rated capacity [Ah]
$t$ : Elapsed time [sec]

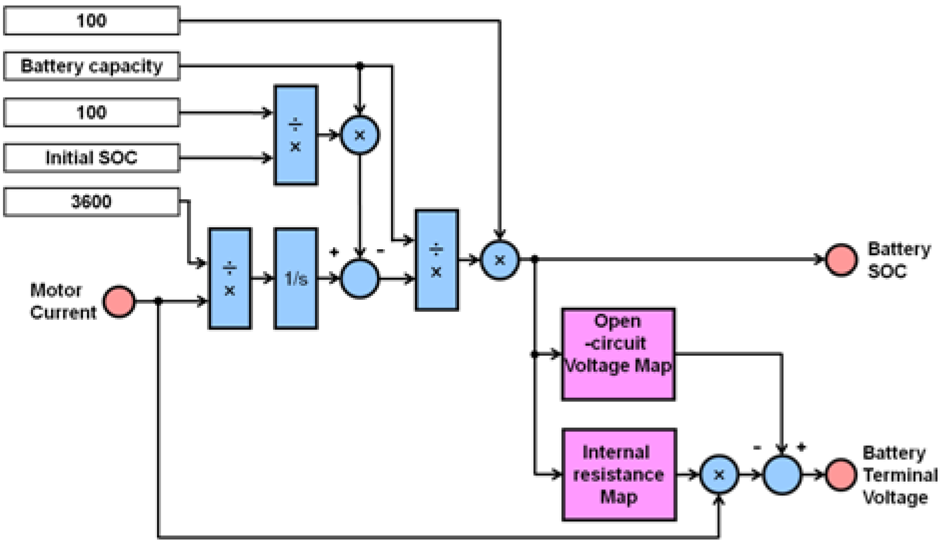

Fig. 4.3 Conceptual Diagram of the Battery Model

## 5. Proposed Driving Model

### 5.1 Requirements of the Driving Model

The driving model calculates the hill climbing resistance from the grade and the surface resistance from the vehicle speed. It also calculates the velocity reset signal for each rotating part from the ignition signal and vehicle speed. The load torque on each rotating part is calculated from the resultant surface and hill climbing resistances, velocity reset signal, gear shift position, clutch stroke, fluid coupling signal, and lock-up clutch signal. And the rotational frequency of each rotating part is calculated from the determined load torque, engine output torque and motor output torque.

The model consists of three sub-systems: the hill climbing resistance model that calculates the hill climbing resistance, the surface resistance model calculating the surface resistance, and the driving system calculating the rotational frequencies. Section 5.2 describes these models and the system.

A conceptual diagram of the driving model is shown in Figure 5.1.

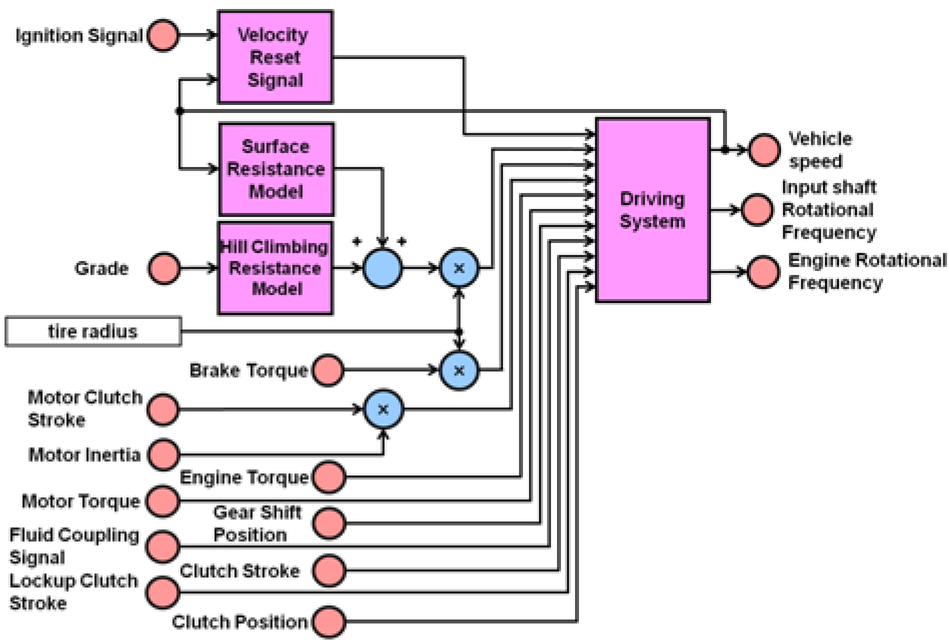


Fig. 5.1 Conceptual Diagram of the Driving Model

## 5.2 Sub-systems in the Driving Model

### 5.2.1 Requirements of the Hill Climbing Resistance Model

The hill climbing resistance model calculates the climbing resistance [N] from the input grade [%] using the following equation (8).

A conceptual diagram of the hill climbing resistance model is shown in Figure 5.2.

$$f = mg\sin\left(\operatorname{atan}\left(\frac{\theta}{100}\right)\right) \cdots (8)$$

$m$ : Vehicle mass [kg]

$g$ : Acceleration of gravity [m/s$^2$]

$\theta$ : Grade [%]

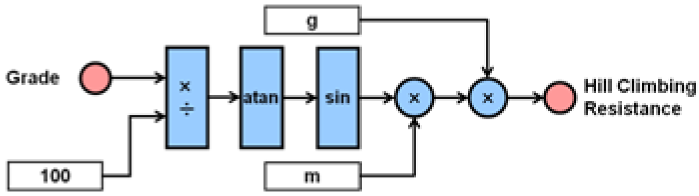

Fig. 5.2 Conceptual Diagram of the Hill Climbing Resistance Model

5.2.2 Requirements of the Surface Resistance Model

The surface resistance model calculates Road_Load [N] from the input vehicle speed [km/h] using the following equation.

A conceptual diagram of the surface resistance model is shown in Figure 5.3.

$$f = g\left(la + lbV + lcV^2\right) \cdots (9)$$

*la* : Coefficient for zero term in the load equation
*lb* : Coefficient for the first term in the equation
*lc* : Coefficient for the second term in the equation
*V* : Vehicel speed [km/h]

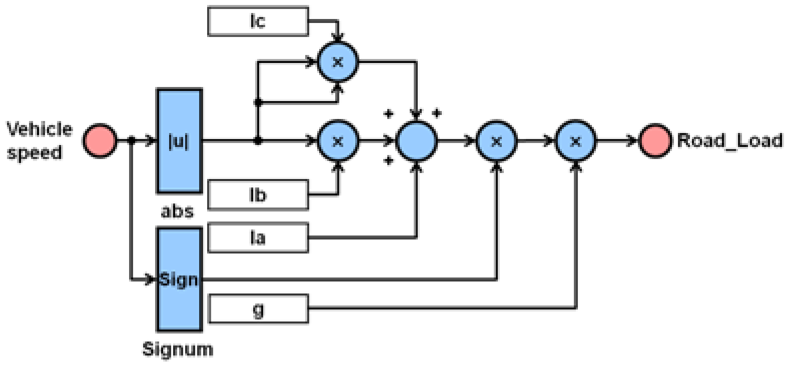

Fig. 5.3 Conceptual Diagram of the Surface Resistance Model

5.2.3 Model Requirements of the Driving System

The driving system calculates the load torque for each rotating part from the input vehicle and tire load torques, gear shift position, clutch position, clutch stroke, fluid coupling signal and lock-up clutch stroke, and then calculates the rotational frequency of each rotating part from its load torque, engine output torque and electric motor torque. According to the shift gears, it changes the gear ratio in the transmission, transmission efficiency and the rotary inertia. It also changes where the motor torque is added according to the clutch position, and determines the transmission torque from the engine, motor and load torques according to the clutch stroke.

The driving system consists of two sub-systems: the transmission model for the transmission, and the clutch system for the clutch and the calculation area of the transmission torque and engine rotational frequency for the fluid coupling and lock-up clutch. Section 5.2.5 describes the transmission model and clutch system.

A conceptual model diagram of the driving system is shown in Figure 5.4.

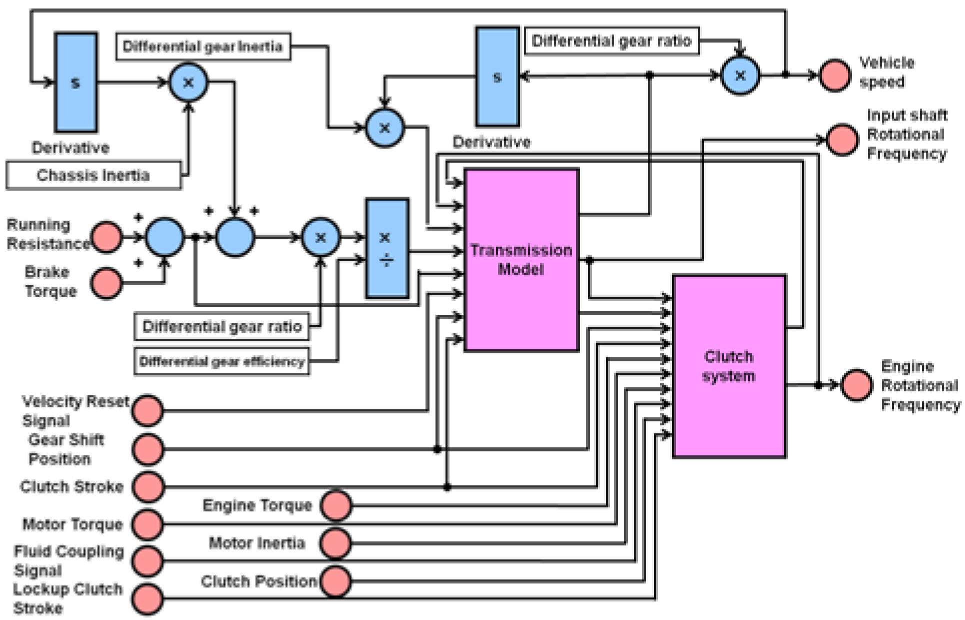

Fig. 5.4 Conceptual Model Diagram of the Driving System

### 5.2.4 Sub-systems in the Driving System

#### 5.2.4.1 Requirements of the Transmission Model

The transmission model calculates the input shaft load torque from the input differential load torque, differential acceleration resistance, input shaft rotational acceleration, and transmission gear ratio according to the gear shift position, transmission efficiency and rotary inertia. It also calculates the output rotational frequency by integrating the output shaft rotational acceleration determined by the multiplication of the input shaft rotational acceleration and the gear ratio, and the input shaft rotational frequency by integrating the input shaft rotational acceleration.

A conceptual diagram of the transmission model is shown in Figure 5.5.

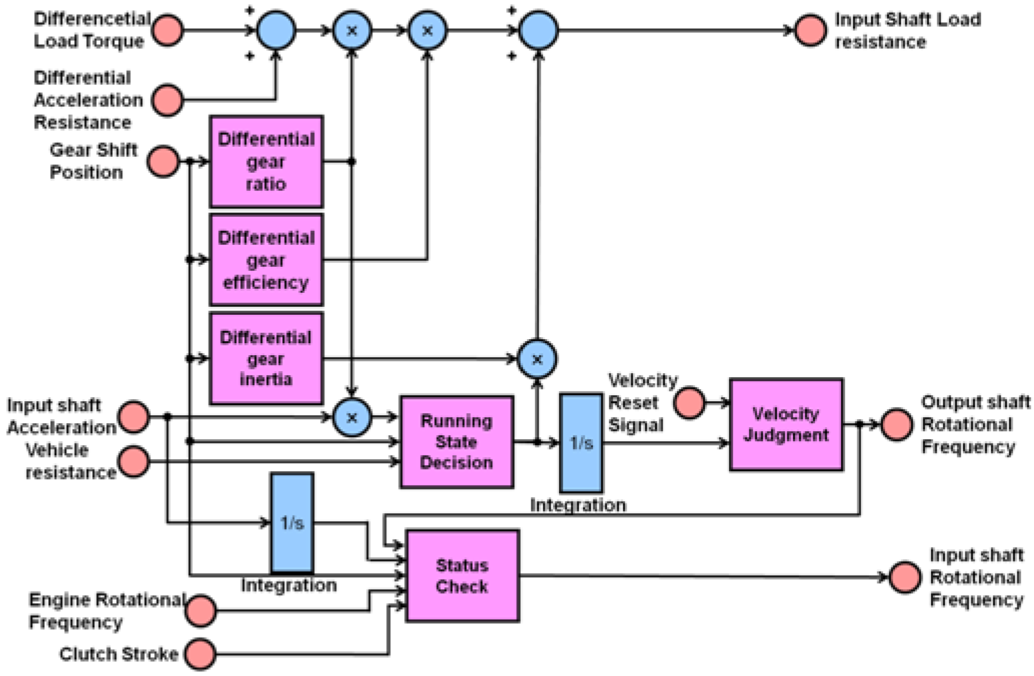


Fig. 5.5 Conceptual Diagram of the Transmission Model

5.2.4.2 Model Requirements of the Clutch System

The clutch system changes where the electric motor torque is added according to the clutch position, and determines the output/input torque of the fluid coupling and lock-up clutch, turbine rotational frequency, engine rotational frequency and input shaft rotational acceleration from the engine rotational frequency, input shaft rotational frequency, fluid coupling signal, clutch stroke, lock-up clutch stroke, electric motor inertia moment, gear shift position, input shaft load torque and engine torque. When calculating the acceleration for each rotating part, depending on the fluid coupling signal, it uses either the engine torque, fluid coupling and lock-up clutch input/output torque, electric motor torque, or input shaft load torque, changes torque transmissibility depending on the engagement ratio of the clutch stroke and lock-up clutch stroke, and then determines whether the rotational acceleration should be calculated based on the output or torque.

The clutch system consists of two sub-systems: the fluid transmission model for the fluid coupling area, and the lock-up clutch model for the lock-up clutch area. Section 5.2.5.3 describes these two models.

A conceptual model diagram of the clutch system is shown in Figure 5.6.

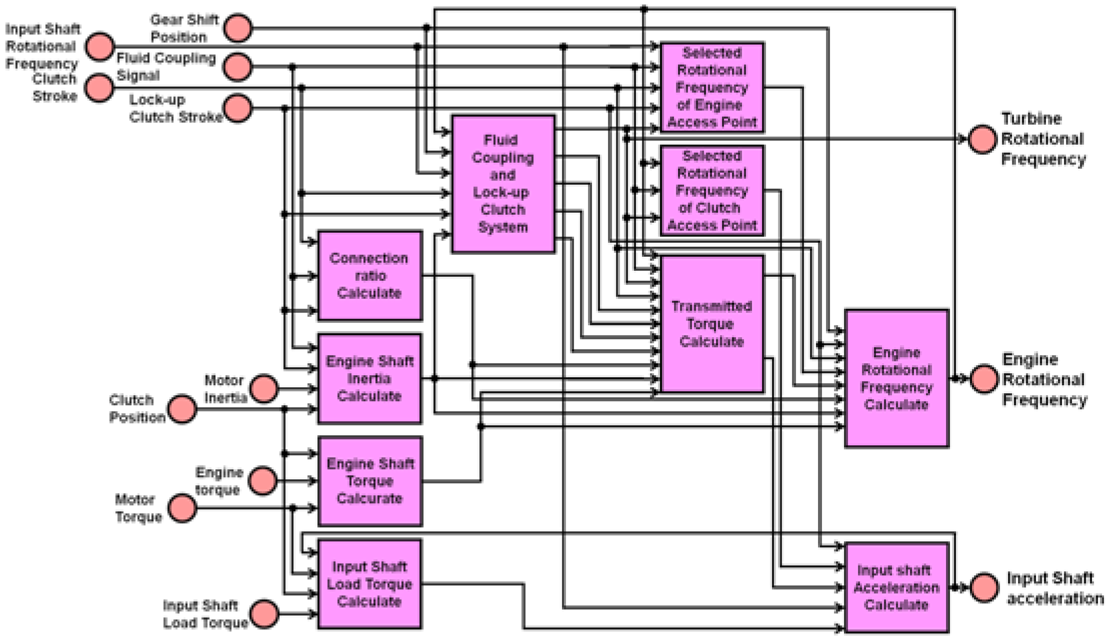


Fig. 5.6 Conceptual Model Diagram of the Clutch System

5.2.4.3 Sub-systems in the Clutch System

5.2.4.3.1 Requirements of the Fluid Transmission Model

The fluid transmission model calculates the frequency ratio of the input engine and turbine rotational frequencies, and determines the torque ratio and capacity for the calculated frequency ratio based on the characteristics maps. It sets forward driving when the engine rotational frequency is higher than that of the turbine, and reverse driving when the engine rotational frequency is lower. For forward driving, the calculated torque capacity is the fluid transmission input torque and the torque capacity multiplied by the torque ratio is the output torque. For reverse driving, the torque capacity multiplied by the torque ratio is the fluid transmission input torque, and the torque capacity is the output torque.

A conceptual diagram of the fluid transmission model is shown in Figure 5.7.

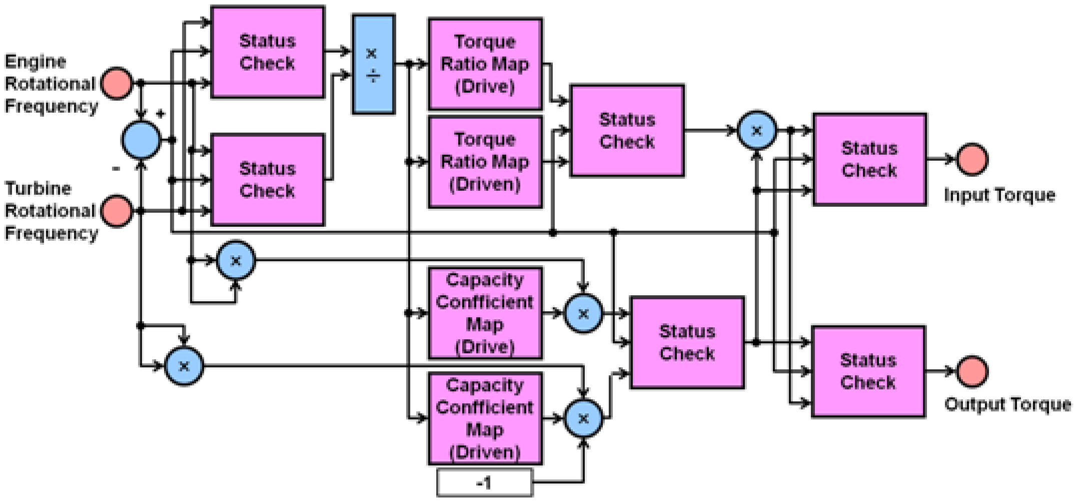


Fig. 5.7 Conceptual Diagram of the Fluid Transmission Model

5.2.5.4.2 Requirements of the Lock-up Clutch Model

The lock-up clutch model compares the input engine shaft torque and the maximum transmission torque, and determines the input torque of the lock-up clutch by multiplying the engine shaft torque by the lock-up clutch stroke as long as the engine shaft torque is equal to or below the maximum transmission torque. If the former exceeds the latter, the input torque is determined by the maximum transmission torque by the clutch stroke. For the lock-up clutch output torque, considering the situation where the lock-up clutch is not completely engaged, the lock-up clutch input torque is once converted to energy, and then again converted to torque at the output side, which is finally output as the lock-up clutch output torque.

A conceptual diagram of the lock-up clutch model is shown in Figure 5.8.

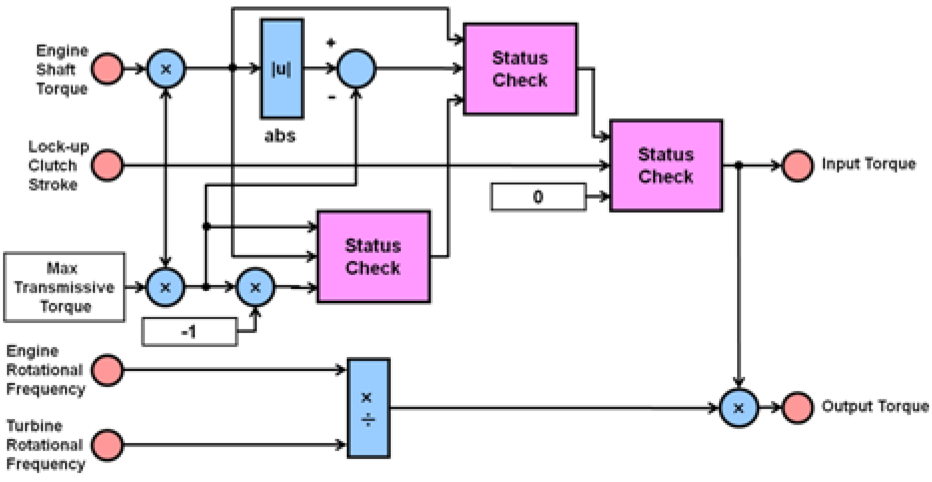


Fig. 5.8 Conceptual Diagram of the Lock-up Clutch Model