Adaptive cruise control

System description

Like the basic cruise-control system that has been available as a standard feature for many years, ACC (Adaptive Cruise Control) can be categorized as a driver-assistance system. Cruise control regulates driving speed to maintain the desired speed selected by the driver using the cruise-control unit. In addition to the basic cruise-control function, ACC measures the distance to the vehicle in front and its relative speed, and uses this information together with other collected data (position of other vehicles in the same or different lane; in future, even stationary objects) to regulate the time gap between the vehicles. ACC is thus able to adapt the vehicle's speed to match the speed of the vehicle traveling in front and maintain a safe distance from it. The driver is able to override or switch off the ACC function at any time (e.g. by depressing the gas or brake pedal).

Distance sensor

In the main, ACC systems currently have a radar sensor (Fig. 1, Item 1) that operates in a frequency range of between 76 and 77 GHz and emits four radar lobes. Once activated, ACC detects a range of up to approximately 200 m in front of the vehicle.

The radar beams reflected by vehicles in front are analyzed for timing, Doppler shift and amplitude ratio. These factors are used to calculate distance, relative speed and angle position relative to vehicles in front.

Network architecture

The ACC function cannot be represented independently as a stand-alone system; various subsystems (engine-management system, electronic stability program, transmission control, instrument cluster) must be networked with each other. The evaluation and control electronics (control unit) of the ACC are integrated in the sensor housing. They receive and send data on a CAN data bus from and to other electronic control units.

Course setting

To ensure reliable ACC operation no matter what the situation – e.g. also on bends – it is essential that the preceding vehicles can be allocated to the correct lane(s).
For this purpose, the information from the ESP sensor system (yaw rate, steering angle, wheel speeds and lateral acceleration) is evaluated with regard to the ACC-equipped vehicle's own curve status.

1 Adaptive cruise control (ACC)

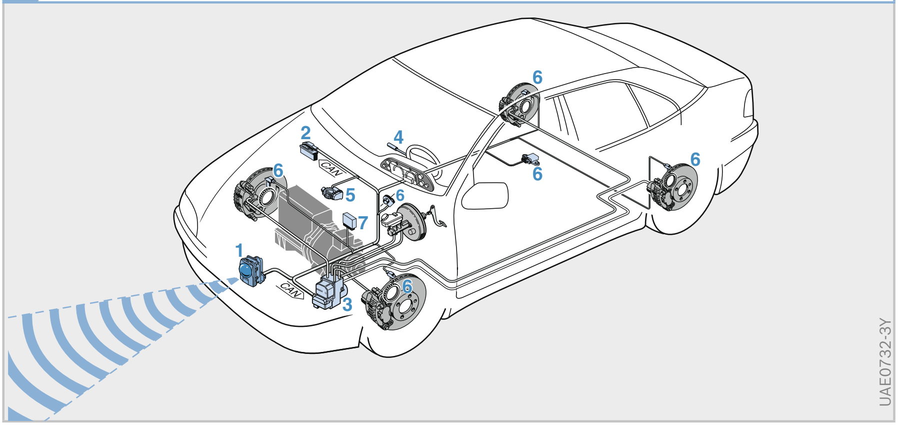

Fig. 1
1 ACC sensor and control unit
2 Engine-management system ECU (ME or DI Motronic) for gasoline engines or electronic diesel control (EDC) for diesel engines
3 Active brake intervention via ESP
4 Control and display unit
5 Engine-control intervention by means of electrically adjustable throttle valve (ME or DI Motronic)
6 Sensors
7 Transmission-shift control by means of electronic transmission control (optional)

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Setting options

The driver inputs the desired speed and the desired time gap; the time gap available to the driver usually ranges from 1 to 2 s. The time gap to the vehicle in front is calculated from the radar signals and compared with the desired time gap specified by the driver. If this value is shorter than the desired value, the ACC system responds in a manner appropriate to the traffic situation by initially reducing engine torque, and only if necessary by automatically braking the vehicle. If the desired time gap is exceeded, the vehicle accelerates until either the speed of the vehicle in front or the desired speed set by the driver is reached.

Engine-control intervention

Speed control requires an electronic engine-performance control system. The ME or DI Motronic engine-management system and the electronic diesel control (EDC) are integrated with this function. This system allows the vehicle to be accelerated to the desired speed or, if an obstacle appears, to be decelerated by means of automatic throttle closing.

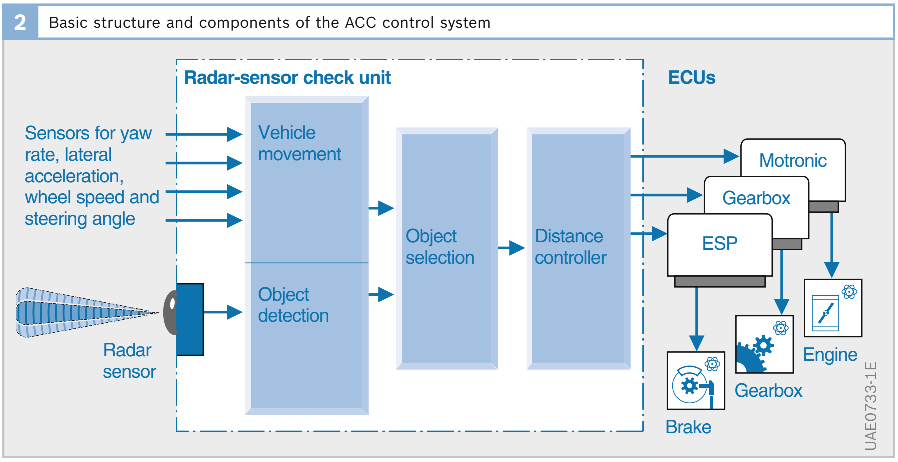
Brake intervention

If the rate of deceleration achieved by easing off the gas is not sufficient, the vehicle will have to be braked. The electronic stability program (ESP) is required here as it is able to initiate the brake intervention.

Due to the design of ACC as a comfort system, the braking deceleration calculated by the ACC controller is limited to approximately 2 to 3 m/s² with current ACC systems. If this is not sufficient for the current traffic situation (e.g. if the vehicle in front brakes sharply), the vehicle audibly requests the driver to take over responsibility for braking. The necessary braking deceleration is then to be achieved using the service brake. Safety functions, such as panic braking, are not part of the ACC system.

The other stabilizing systems of ABS, TCS or ESP may be active as normal during an active ACC control intervention as necessary. Depending on the parameter settings of ACC, stabilization interventions may result in ACC being deactivated.

2 Basic structure and components of the ACC control system



Control and display

Controls include switches, push-buttons or thumbwheels for

- Activating the function and
- Setting the desired speed and
- Desired time gap

The following information may be displayed to the driver in the instrument cluster:

- Desired speed
- Information on the activation status
- The time gap selected by the driver
- Indication of the follow-up mode, which informs the driver as to whether the system is controlling the distance to a detected target object or not

System limits

ACC does not yet permit control operations in city environments. This system can only be activated at speeds in excess of 30 km/h.

Control algorithms

The control system basically consists of three control modules:

- *Control module 1: cruise control*
  If the radar sensor has not detected any vehicles in front, the system maintains the desired speed set by the driver.
- *Control module 2: follow-up control*
  The radar sensor has detected vehicles in front. Control essentially maintains the time gap to the nearest vehicle at a constant setting.
- *Control module 3: control when cornering*
  When negotiating tight bends, the radar sensor can “lose sight” of the vehicle in front because of the limited width of its “field of vision”. Until the vehicle comes in sight of the radar again, or until the system is switched to normal cruise control, special measures come into effect. Depending on the manufacturer, the speed would then be maintained, the current rate of lateral acceleration adapted or the ACC function deactivated, for example.

Object detection and lane allocation

The central task of the radar sensor and its integrated electronics is to detect objects and allocate them either to the same lane as the one on which the vehicle is traveling, or to a different lane. Firstly, lane allocation demands the precise detection of vehicles in front (high angle resolution and accuracy), and secondly, a precise knowledge of the motion of the system’s own vehicle. Vehicle motion is calculated from the signals sent by sensors also used for the electronic stability program (ESP) (course prediction). These include the wheel-speed sensors and driving-dynamics sensors for the yaw rate and lateral acceleration. Optionally, information supplied by a steering-angle sensor may also be processed. The decision as to which of the detected objects is used as the reference for adaptive cruise control is essentially based on a comparison between the positions and motion of the detected objects and the motion of the system’s own vehicle.

Adjustment

The radar sensor is fitted at the front end of the vehicle. Its radar lobes are aligned relative to the vehicle longitudinal axis. This is done using adjusting screws at the fastening part of the sensor. If it is moved out of alignment by physical force, e.g. deformation of the mounting due to accident damage or any other effect, realignment must be carried out. Small degrees of misalignment are automatically corrected by the permanently active alignment routines implemented in the software. If manual realignment is required, this is indicated to the driver.

Ranging radar

The radar (RAdiation Detecting And Ranging) transceiver unit transmits packets of electromagnetic waves using an antenna. These reflect off an object made of electrically conductive materials (e.g. vehicle body) and are then received. The signals received in this manner are “compared” with the transmitted signals with respect to their propagation time and/or frequency.

Measuring principles

Propagation time measurement

For all radar methods, the distance measurement is based on the direct or indirect propagation time measurement for the time between when the radar signal is transmitted and when the signal echo is received. The direct propagation time measurement is used to measure period τ. With direct reflection, this is equal to twice the distance d to the reflector divided by the speed of light c:

$$\tau = 2d/c$$

For a distance of $d = 150$ m and $c \approx 300{,}000$ km/s, the propagation time is

$$\tau \approx 1\ \mu\text{s}.$$

Frequency modulation

Direct propagation time measurement requires much effort; an indirect propagation time measurement is simpler. The method is known as FMCW (Frequency Modulated Continuous Wave). Rather than comparing the times between the transmitted signal and received echo, the FMCW radar compares the frequencies of the transmitted signal and received echo. The prerequisite for a meaningful measurement is a modulated transmit frequency.

With the FMCW method, radar waves linearly modulated in their frequency are transmitted for a duration of typically a few milliseconds and in a cycle of a few hundred MHz (f_s, continuous curve in Fig. 3). The signal reflected off a vehicle in front is delayed in accordance with the signal propagation time (f_e, dashed line in Fig. 3). In the rising ramp, the frequency is lower; in the falling ramp, the frequency is higher by the same amount. The difference in frequency Δf is a direct measure for the distance.

If there is additionally a relative speed between the vehicles, the receive frequency f_e is increased (f_e', dotted line in Fig. 3) by a specific amount Δf_d in both the rising and falling ramp due to the Doppler effect. This produces two different frequency differences Δf_1 and Δf_2. Their addition produces the distance between the vehicles, and their subtraction the relative speed of the vehicles.

The signal processing in the frequency range therefore delivers a frequency for each object that as a linear combination produces a term for distance and relative speed. From the measured frequencies of two ramps with a different gradient, it is possible to determine the distance to and the relative speed of an object. For situations involving several targets, several ramps with a different gradient are required.

3 FMCW method

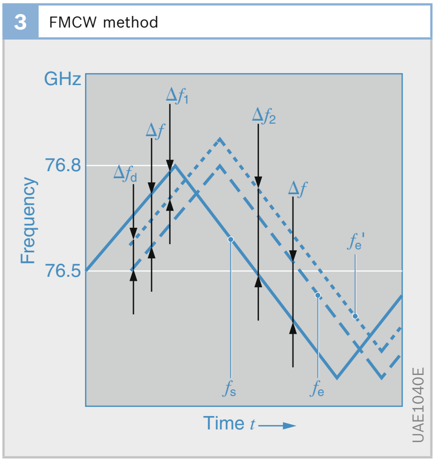


Fig. 3

f_s	Transmission signal
f_e	Return signal at same road speed
f_e'	Return signal with relative road speed

Doppler effect
Although the relative speed of the other vehicle can be measured using a number of subsequent distance measurements, it is calculated more quickly, more reliably and more accurately when the Doppler effect is utilized in the measurement.

For an object moving relative to the radar sensor with a relative speed (relative speed v_{rel}), the signal echo undergoes a frequency shift f_{D} compared to the emitted signal. At the relevant differential speeds, this is represented as:

$$f_{\mathrm{D}} = -2 f_{\mathrm{C}} \cdot v_{\mathrm{rel}}/c$$

f_{C} is the carrier frequency of the signal. At the radar frequencies commonly used for ACC, $f_{\mathrm{C}} = 76.5$ GHz, there is a frequency shift of $f_{\mathrm{D}} \approx -510 \cdot v_{\mathrm{rel}}/\mathrm{m}$, and thus 510 Hz at a relative speed of −1 m/s (approaching).

Angle measurement
The third basic dimension which is needed is the side offset (angle) of the preceding vehicle. The only way this can be measured is by radiating the radar beam in a number of different directions. The (reflected) signals are then applied to determine from which direction the strongest reflection came. This method needs either high-speed back-and-forth movement of the beam (scanning), or the installation of a multi-beam antenna array.

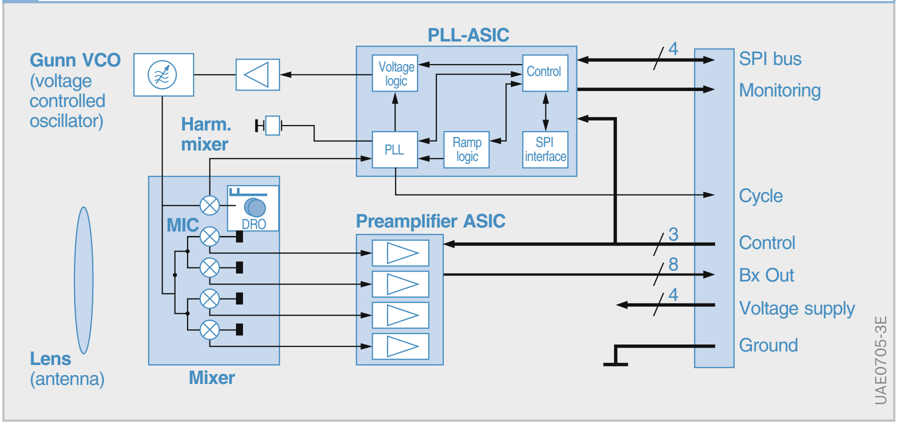
High-frequency part of the ACC sensor

The high-frequency part can be broken down into four functional groups.

HF generation
The HF generation and control section makes the high frequency available for transmission (Fig. 4). The HF output of between 76 and 77 GHz is generated using a voltage-controlled oscillator (VCO) comprising a Gunn diode in a mechanical resonator. A small part of the output generated is downmixed into an intermediate frequency band using a dielectrical resonance oscillator (DRO) with harmonic mixer and supplied to the control electronics (PLL-ASIC, PLL = Phase Locked Loop). The latter controls the VCO by means of an output driver and provides frequency stabilization and modulation.

Transmission and reception circuit
In the transmission and reception circuit, the HF output is divided between four transmission/reception channels by three Wilkinson splitters. Using bandpass mixers, this output is supplied to the antenna while the return signal is downmixed to the basic band.

4 Block diagram of a 4-channel FMCW radar



Amplification

Signals in the basic band are amplified in an ASIC. It has four channels, switching amplification, and a special characteristic curve. To some extent, this compensates for the large signal dynamics in that high frequencies (correspondingly high distances) are more strongly amplified. In addition, the characteristic is integrated with a low-pass anti-aliasing filter for subsequent scanning.

Antenna system

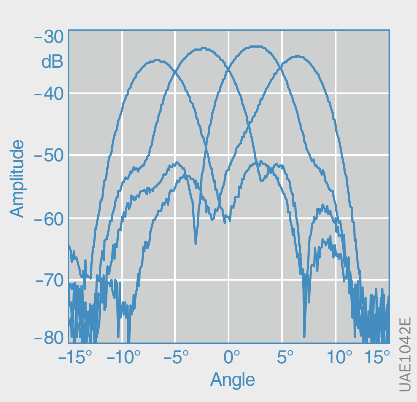
The antenna system is a monostatic system. It comprises four combined transmitter and receiver patches on the HF substrate, four polyrods (plastic cones) for prefocusing and a plastic lens for beam concentration. As part of the housing, the lens also acts as a radar-optical window and shield. The radar waves are emitted simultaneously and coherently by the four antenna patches to produce a single transmission wave. The beams are only actually split into four separate beams on the receiver side. Four separate receiver channels are used here.

The transmit frequency is modulated by the voltage-controlled oscillator (VCO) in a linearly ramped fashion (Fig. 3) with a gradient of $m = \mathrm{d}f/\mathrm{d}t$. While the received signal returns after the propagation time $\tau = 2d/c$ the transmit frequency has changed in the meantime by the differential frequency $f_\mathrm{D} = \tau \cdot m$. Therefore, the propagation time, and thus the distance, can be measured indirectly by ascertaining the differential frequency between the transmitted and received signals. The differential frequency, in turn, can be ascertained using a mixer, followed by low-pass filtering. To determine the frequency, the signal is digitized and converted into a frequency spectrum using an FFT (Fast Fourier Transformation).

However, the information about the difference frequency does not only contain information for the propagation time but also for the Doppler shift. This situation means that there is at first a certain ambiguity in the evaluation. It can be resolved by applying multiple FMCW modulation cycles with different gradients.

To determine the angle at which the radar locates an object, multiple radar lobes are transmitted and evaluated. At least two overlapping radar beams are required to measure the angle. No conclusions on the angle of sight can be drawn from the relationships between the amplitudes that are measured for an object in adjacent beams. If, for example, four radar beams are used, the horizontal angular dependence of which is shown in Figure 5 in the form of a two-way antenna diagram as an example, it is possible to determine the horizontal angle of sight by comparing amplitude and phase of the measured radar signals using the antenna diagram.

5 Two-way antenna diagram



Radar signal processing

The low-frequency part of the FMCW radar comprises several components (Fig. 6).

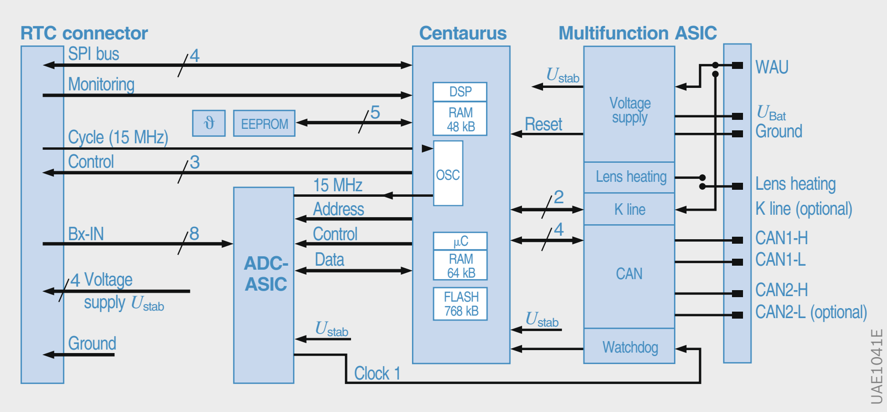
A dual-core processor is used for digital data processing. The digital signal processor (DSP) contained in this module is used for data acquisition, calculating the fast fourier transform (FFT) and for other basic signal processing. The processor also contains a microcontroller in which additional signal processing, the application software and control unit functions are executed. Furthermore, various peripherals are integrated in the dual processor: serial interfaces, two CAN controllers (Controller Area Network), an analog/digital converter and various digital ports.

The processor is surrounded by various peripheral modules. The analog radar signals from the HF PCB are converted into digital sample values in an analog/digital converter (ADC). This takes place simultaneously for four channels. A digital low-pass filter is also integrated in this module to ensure limitation to the Nyquist bandwidth. An EEPROM is used as an external, non-volatile memory. Application parameters and, if applicable, fault codes are stored here. A multifunction ASIC is used to generate the supply voltages (different DC voltages) and as an output driver (K line, CAN, lens heating to prevent icing). In addition, a watchdog is also integrated. Using a temperature sensor, it is possible to measure the internal temperature of the system.

The unit is connected to the vehicle by an eight-pin connector. The connector supplies battery voltage (approximately 12 V), ground (GND), two CAN buses, or alternatively a wakeup or K line, or a radome heater, or a time gap signal.

The low-frequency circuit can be designed using standard printed-circuit board technology. Figure 7 provides a look inside the unit.

6 Low-frequency block diagram



7 Exploded view of an FMCW radar with integrated signal processing

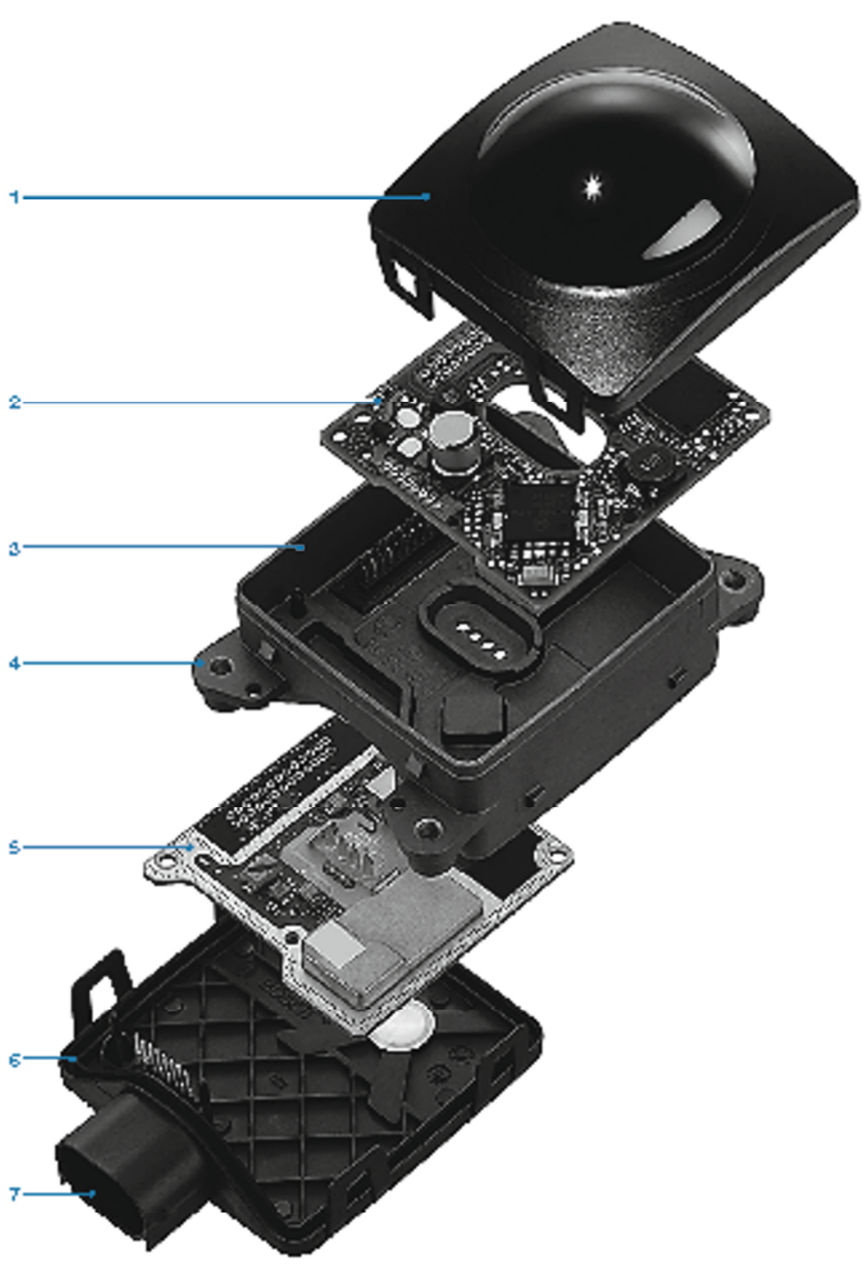


Fig. 7

1 Upper housing section with lens
2 HF PCB
3 Bearing points for alignment
4 Intermediate carrier
5 LF PCB
6 Housing base
7 Plug