Measurement of TDC in Engine by Microwave Technique

TERUO YAMANAKA, MICHIRU ESAKI, AND MASAO KINOSHITA

Abstract —**A microwave technique for determining the top dead center (TDC) of an engine has been developed. Factors affecting systematic errors were investigated experimentally using high-resolution pulses (0.015°) and a uniquely designed probe. Consideration is made for cycle change of the cylinder wall temperature. The main factors are attributable to the thermal expansion of the cylinder and the cylinder pressure change. Under well-defined engine conditions, accuracy of ±0.1° CA (crank angle) is probable for TDC measurement. A static method was also employed for an accuracy cross-check.**

I. Introduction

CYLINDER PRESSURE measurement is very important for evaluation of engine performance. For statistical data acquisition of the dynamic phenomenon, sensors and a computer have been used. Improvements in transducers, amplifiers, and recording equipment have allowed error reduction in determining the pressure amplitude. However, there still remains the problem of determining the correct phasing of the pressure data with respect to crank positions. Typical methods for determining the TDC of an engine are classified into two general techniques: static and dynamic.

In the static methods, it is possible to measure piston positions directly while an engine is stationary. A typical static method [1] can yield high accuracy (within 0.1° CA). However, this technique unavoidably ignores dynamic effects caused by changing bearing clearances and parts deformation due to mechanical and thermal loadings.

Dynamic methods are usually used under motoring conditions although they attempt to measure the TDC for a rotating engine. An inductice or capacitive proximity probe must be positioned extremely close to the piston at the TDC position because the piston position changes very slowly with crank angle near TDC, at less than 9μm per 1° CA. In addition, the probe installation is restricted owing to engine vibration and severe loading.

There is another method for TDC determination without detecting the piston position directly. In the method, the pressure data of the cylinder is measured and the TDC is calculated by a thermodynamic model. However, this technique has a similar shortcoming as the dynamic method mentioned above. Furthermore, there is a question if the thermodynamic model can be adopted.

It is required to determine the TDC within an accuracy of ±0.1° CA under dynamic conditions with minimum disturbance to the engine operation.

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The authors are with Toyota Central Research and Development Laboratories, Inc., 41-1, Aichig-gun, Aichi-ken, 480-11, Japan.

As a precise method, microwave techniques for determining the TDC was proposed [2] and the timing apparatus using this technique has been developed [3], [4]. This method has many advantages such as a high degree of precision, dynamic measurement capability, and simple apparatus configuration. We also developed an apparatus [5] for ignition timing measurement which can easily acquire and handle experimental data, and we confirmed such advantages as described above. However, some doubts have been raised on the accuracy of the TDC measured by microwave techniques. Therefore, we made experimental investigations of the factors affecting systematic errors by use of high-resolution pulses and estimated the accuracy of this method.

II. Principle of the TDC Measurement

The combustion chamber of a diesel engine can be regarded as a variable-length microwave resonator. It is possible to determine the TDC from examining a series of resonance location data taken as a function of crank angle. The probe, prechamber, and cylinder comprise a microwave cavity which is tuned by the piston position as shown in Fig. 1. Reflected signals from the cavity vary in amplitude as the piston ascends in the compression stroke and descends in the power stroke as shown at the lower part of Fig. 1. The detected microwave signal exhibits a peak at every resonance dip because a detector with a negative output signal was used as indicated in Fig. 1. Although these signals are complicated and difficult to be analyzed, they should be symmetrical with respect to TDC in principle. TDC can be measured by determining the center of symmetry.

III. Experimental Setup

Fig. 2 shows a schematic diagram of the setup used to measure TDC positions with a resolution of 0.015° CA (24 000 pulses per revolution). Fig. 3 shows a photograph of the setup. A microwave signal is led to the combustion chamber (cylinder) through a connecting passage in the prechamber. The signal is coupled to the cylinder by the dipole of a probe, which is mounted on the hole for the glow plug in the prechamber.

A. Probe

Fig. 4 shows a cross-sectional view of the probe with an enlarged view of the microwave antenna. For convenience in installing and removing, the probe is comprised of an

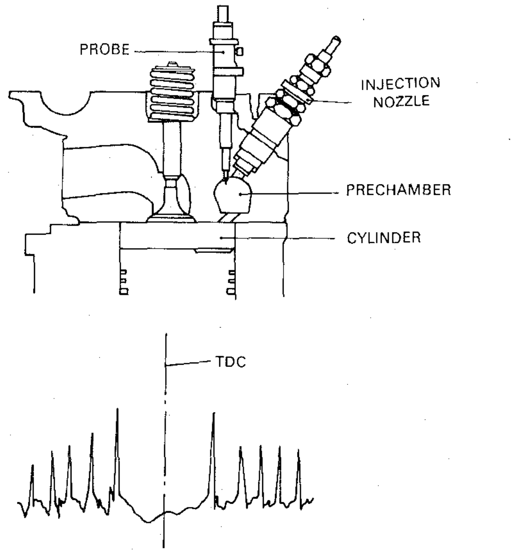

Fig. 1. Cutaway view of a probe installed in a diesel engine (upper) and a typical microwave signal near TDC (lower).

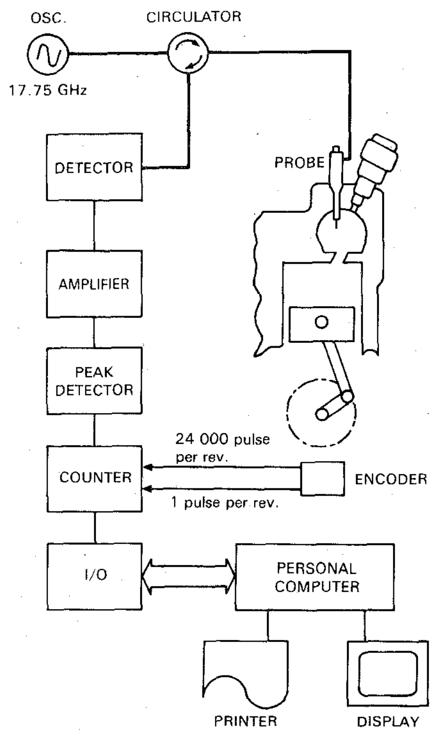

Fig. 2. Schematic diagram of a experimental setup.

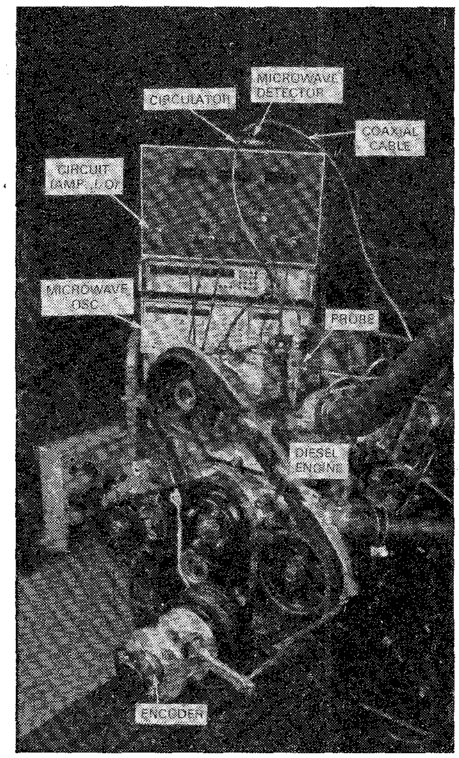

Fig. 3. A photograph of the setup.

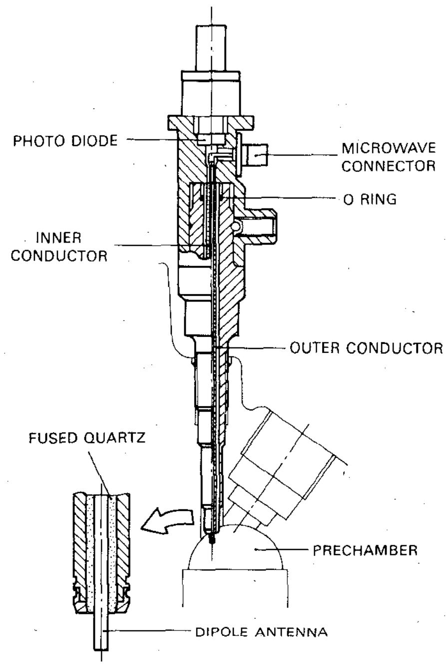

Fig. 4. Cross-sectional view of the probe.

upper part and a lower part. The two parts can be connected by simple insertion; locking is done automatically by ball plungers. The lower part is installed to the engine by screwing. As the lower part of the probe is exposed to high-temperature gas (more than 2000 K), its design is unique; the dielectrical material of the coaxial part is transparent fused quartz, and the inner and outer conductors are made from tungsten and stainless steel, respectively. For conductivity improvement, both inner and outer conductors are plated with gold. The diameters of the inner and outer conductors are 1.1 mm and 2.3 mm, respectively. Fig. 5 shows photographs of the probe, assembled and disassembled.

The gas seal is made with an O ring and epoxy adhesive. The upper and lower coaxial parts are connected in the same manner as in SMA connectors.

The upper part has a microwave connector and a photo diode which can detect combustion light in the prechamber for measurement of ignition timing.

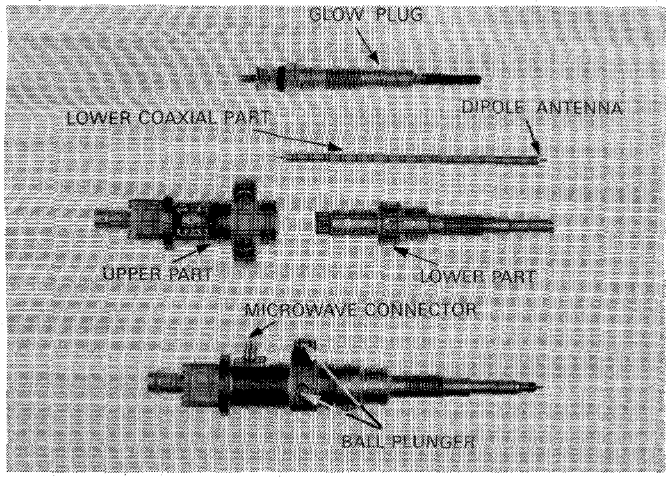

Fig. 5. Photographs of the probe and glow plug.

B. Microwave Circuit

As a microwave source, a sweep generator was used. Its frequency can be changed from 12 to 18 GHz. In this experiment, a frequency of 17.75 GHz and an output power of 1 mW were mainly used. To separate transmitting waves from reflecting waves of the probe, a circulator was used. Flexible coaxial cables were used as transmission lines. The sensitivity of a microwave detector was 0.5 mV per μW.

C. Processing Unit

Microwave signals from the microwave detector were processed in synchronization with the timing pulses generated from an encoder mounted on the engine crank shaft. Peaks in microwave signals (Fig. 1) were detected by an analog circuit and transformed to pulses. Crank angle locations of these peaks and the TDC timing pulse (1 pulse per revolution) are determined by counting encoder pulses.

Only locational data for a TDC timing pulse and two adjacent peak pulses to it were stored in counters, then sent to a personal computer. The computer was used both for calculation of TDC locations and statistical data processing.

IV. Results

A. Probe Characteristics

For installing convenience, the probe was mounted in the hole for the glow plug. In order to be fixed in the screw hole for the plug, the probe was designed to have a maximum outer diameter of 6 mm, and a rotational symmetry with regard to its axis.

In terms of the microwave techniques, the engine cylinder itself is considered as a single aperture resonator, and the probe is connected to the cylinder through a connecting passage acting as a waveguide and prechamber acting as a filter. The theoretical design of the microwave characteristics of the probe is difficult because of the complicated cavity configuration. Therefore, we measured the coupling characteristics by changing the microwave frequency and insert length of the probe. Fig. 6 shows a typical result of

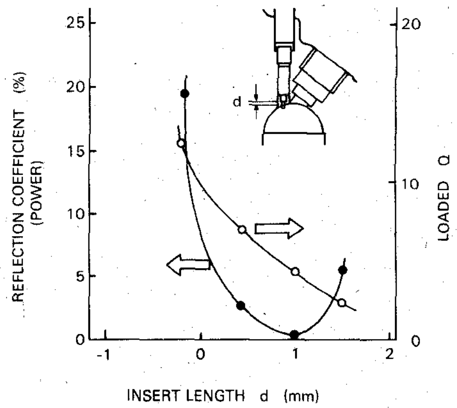

Fig. 6. Coupling characteristic at 17.7 GHz.

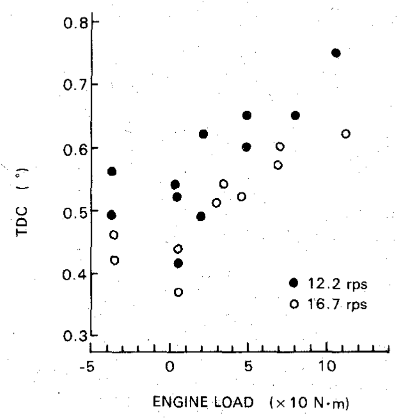

Fig. 7. TDC versus engine load in compression stroke. Solid lines are to guide the reader's eye.

the measured reflection coefficient of power and the Q value against insert length. We determined the optimum value of the insert length and the operating frequency from these experimental results.

Microwave characteristics of the probe were little affected by deposition of carbon particles onto the fused quartz, and the probe was not damaged even at a full engine load of 50 rps.

B. Effect of Engine Operating Conditions

Several sets of experiments were run to examine the effect of engine operating conditions on the precision of this method and on the accuracy of the TDC calculation. Figs. 7 and 8 show the results in an engine speed range of 12.2 and 16.7 rps, and over a load range between motoring (no firing) and full load. The TDC values are expressed by the difference between a calculated TDC and a TDC timing pulse, set to the TDC mark on the crank pulley. The standard deviation of TDC values was between 0.03° CA and 0.06° CA for a sample number of 32. The change of TDC values in compression stroke by the engine operating conditions is almost the same as the data reported by other authors. There is a clear difference between the change of TDC values in the compression stroke and in the suction stroke. Fig 9 and 10 show resonance locations in BTDC (before TDC) and ATDC (after TDC) over those engine

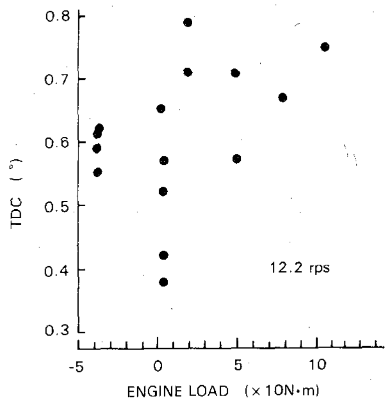

Fig. 8. TDC versus engine load in suction stroke.

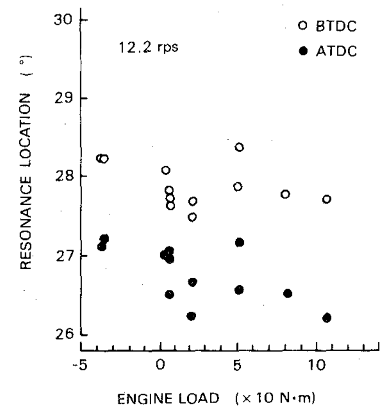

Fig. 9. Resonance location versus engine load in compression and power stroke.

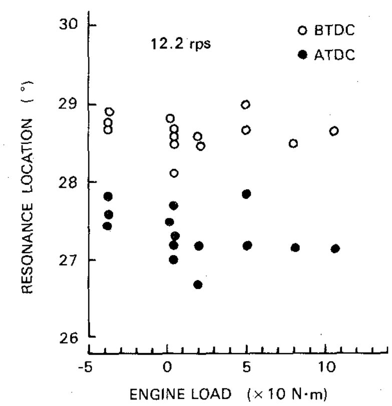

Fig. 10. Resonance location versus engine load in exhaust and suction stroke.

operating conditions. From these results, we can know the dynamic piston positions in detail.

The resonance locations in the compression stroke (BTDC) are scattered within the resolution of the encoder (0.015° CA). Therefore, the dispersion of the calculated TDC resulted mainly from that of resonances in the power stroke. These results also indicate that the resonance sharpness is adequate enough even at its very low Q value (20–30).

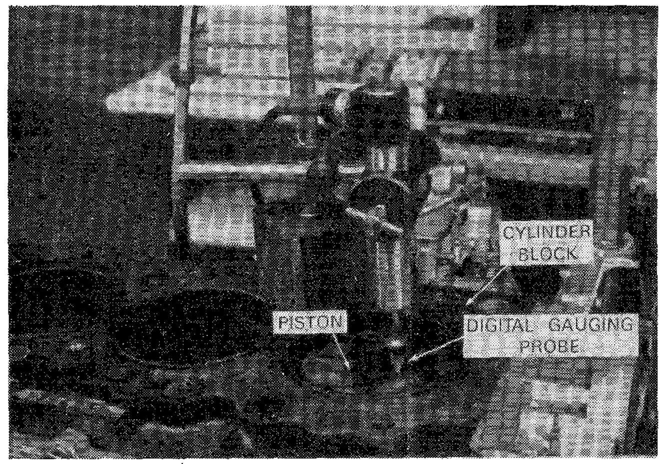

Fig. 11. A photograph of the apparatus in the static method.

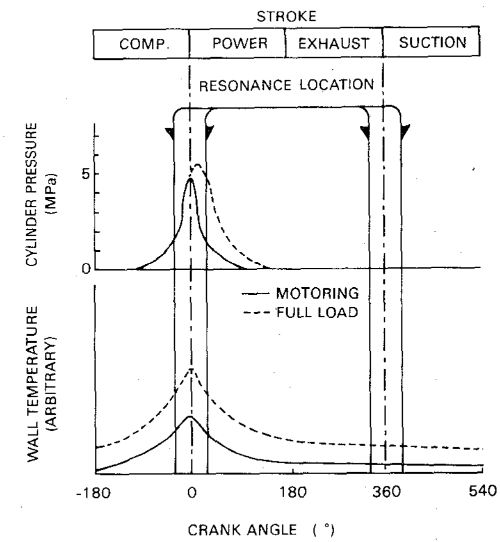

Fig. 12. Schematic diagram of the wall-temperature change and cylinder pressure change in one cycle.

C. Static Measurement Results

As a cross-check, we chose the static method [1] which can yield high accuracy. Fig. 11 shows a photograph of the apparatus in this method. The measured TDC value was 0.60° CA.

V. Discussion

A. Factors Affecting the Systematic Error

It is clear that engine operating conditions affect measurement of the TDC (Figs. 7 and 9). Other authors [4] explained that this effect results from asymmetry of the piston motion around TDC, caused by the difference in the dielectric properties between combustion products and air. However, this effect cannot be explained quantitatively, because it is about ten times as large as the effect estimated by them. We examined carefully changes of TDC values when engine operating conditions were changed from motoring to firing and vice versa. We found a hysteretic change. Therefore, we assumed a thermal expansion of the

TABLE I
QUANTITATIVE EFFECT ON PISTON POSITION AT ENGINE SPEED OF 12.2 rps.

Factor	Resonance location (28° CA)	
	at BTDC	at ATDC
Cylinder Pressure	0.10°/1.5MPa	0.17°/1.5MPa
Wall Temperature	0.38°/Tb*	0.41°/Ta*

* Cylinder wall temperature under motoring at BTDC and ATDC, respectively.

cylinder due to compression and combustion, and gas pressure change therein as factors causing the asymmetry.

B. Quantitative Effect of the Factors

In order to examine the pressure effect, we removed injection nozzles and measured resonance locations and TDC values immediately after 30-min operation of the engine. Engine speed was 11.6 rps in both engine operation and measurement. After an 11-min operation of the nozzleless engine, we measured resonance locations and TDC values again in order to examine the effect of thermal expansion of the cylinder.

From analysis of these data, previous data by resonance locations (Figs. 9 and 10) and experimental pressure data by using a transducer, the cylinder pressure, and the wall temperature are considered to change as shown schematically in Fig. 12. Table I shows numerical values of the pressure and the wall temperature effect, deduced from the consideration described above.

C. Estimation of the Systematic Error

We can estimate the systematic error of the TDC value from the pressure and the wall temperature of an engine according to the quantitative results in Section V-B.

In motoring condition (12.2 rps), the pressure difference in BTDC and that in ATDC is negligible, and the wall temperature difference in BTDC and that in ATDC is considered to be within $\pm 1/4$ Ta ($\pm 0.05°$ CA) [6], [7]. Here, Ta is wall temperature of the cylinder in motoring. Therefore, the range of the TDC value in motoring is $0.52 \pm 0.05°$ CA.

In full load condition (12.2 rps), the pressure difference in BTDC and that in ATDC is considered to be 3.3 MPa from experimental data. After compensation of the pressure difference, the TDC value becomes 0.57° CA. The wall-temperature difference in BTDC and that in ATDC is considered to be within $\pm 1/2$ Ta ($\pm 0.1°$ CA). Therefore, the range of the TDC value in full load is $0.57 \pm 0.1°$ CA.

Thus, the present method provides the probability of attaining an accuracy of $\pm 0.1°$ CA for TDC, the target value, required for the analysis of engine indicator diagrams, if the engine operating conditions are well defined and an appropriate statistical analysis is made for data.

D. Cross-Check by the Static Method

It has been considered that the dynamic method and the static method give different TDC values owing to dynamic effect. However, the static method can give a basic TDC because the piston position is determined geometrically by crank mechanism. As described so far, the microwave technique can yield the TDC value (0.52° CA in motoring) almost coincident with that (0.6° CA) obtained by the static method. Therefore, we conclude that the present method provides accurate measurement of TDC under dynamic conditions.

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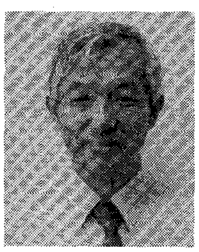
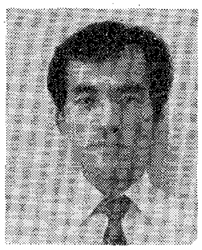


Teruo Yamanaka received the B.E. and M.E. degrees in electronics engineering from Nagoya University, Nagoya, Japan, in 1964 and 1966, respectively.

In 1966, he joined Toyota Central Research and Development Laboratories, Inc., Aichi, Japan. He was engaged in research on automotive microwave radar systems and his current research interests include application of microwave techniques to engine systems.

Mr. Yamanaka is a member of the Institute of Electronics and Communication Engineers of Japan.



Michiru Esaki was born in Nagoya, Japan, on January 9, 1952. He graduated from the electric course of Aichi Technical High School, Japan, in 1970.

He joined Toyota Central Research and Development Laboratories, Inc., Aichi, Japan, in 1970. He is an Associated Research Scientist in the Electronics and Instrumentation Section. He has been engaged in the development of microcomputer systems for laboratory automations. His current research interests include electric instruments for developmental research of metal materials.

Masao Kinoshita was born in Nagoya, Japan, on June 7, 1956. He received the B.E. and M.E. degrees in mechanical engineering from Gifu University, Gifu, Japan, in 1979 and 1981, respectively.

He joined Toyota Central Research and Development Laboratories, Inc., Aichi, Japan, in 1981. He is an Associated Research Scientist in the Engine Control Section. His current research interests include fuel-injection systems for automotive engines.

Mr. Kinoshita is a member of the Japan Society of Mechanical Engineers.