Measurement of Ultrasound Speed in Several Car Engine Oils as a Function of Temperature

Volker Wilkens and Hans-Peter Reimann
Ultrasonics Section
Physikalisch-Technische Bundesanstalt, PTB
38116 Braunschweig, Germany
Ultrasonics@ptb.de

***Abstract*—Measurements of the ultrasound propagation speed in engine oils as a function of temperature in the range from 8 °C to 153 °C were performed. The data obtained are important for the validation and for the uncertainty estimation of the ultrasound-based oil-filling level measurement systems recently developed for car engines.**

Keywords-filling-level meter, ultrasound speed

I. INTRODUCTION

Recently, sensors for the automatic monitoring of the oil-filling-level in car engines have been developed which are based on ultrasound measurements. To determine the accuracy of this technique, basic investigations were necessary to examine the ultrasound propagation speed in car engine oils as a function of the oil temperature. In addition, the variation of the propagation speed depending on the oil specification, the brand and the usage time in engines is important for the applicability of the sensor technique.

II. METHOD

The ultrasound propagation speed was determined directly by measurements of the propagation path and of the corresponding time-of-flight in a pulse-echo arrangement. To minimize the impact of material expansion due to the large temperature variation, a differential measurement procedure was applied at each measurement temperature step.

The measurement set-up used is depicted in Fig. 1. The engine oil sample under test was located in a cylindrical container. The amount of each engine oil sample used was approximately 220 ml. The measurement container was positioned inside a larger outer tank filled with 2.5 l of silicone oil which served as caloric reservoir to achieve a homogeneous thermal dispersion. Heating was performed from the bottom with the aid of a heating plate. Cooling down to measurement temperatures below room temperature was achieved by a heat exchanging pipe in the silicone oil connected to an external chiller. The outer tank was lined with a thermal insulating rockwool layer. Inside the measurement container, a magnetic stir bar was used, and in the outer tank, circulation was induced by a mechanical stirrer. The temperature of the engine oil was measured at medium height in the measurement container by a PT100 probe connected to a multimeter. Each engine oil sample was initially heated up to at least 156 °C, and the sound speed measurements were then performed during slowly decreasing temperature due to less heating or cooling at temperature steps of 2 °C. The minimum temperature of the oil to be achieved with the set-up was approx. 8 °C. The measurement time for the complete temperature range was about 23 hours for one oil sample.

To transmit and receive the ultrasound waves, a 6 mm diameter piezo-ceramic transducer was used. This transducer was similar to those used with the filling-level sensor system and it was provided by the customer who had commissioned this investigation. The electronics, which are normally integrated inside the transducer housing, were not provided in this element. Apart from quick availability, the advantages of using this component were: the small piezo-element size, which ensures a small nearfield distance; the resonance frequency at the desired ultrasound frequency; and, most importantly, the proven heat resistance. A slight disadvantage regarding the intended pulse-echo measurements was the miss-

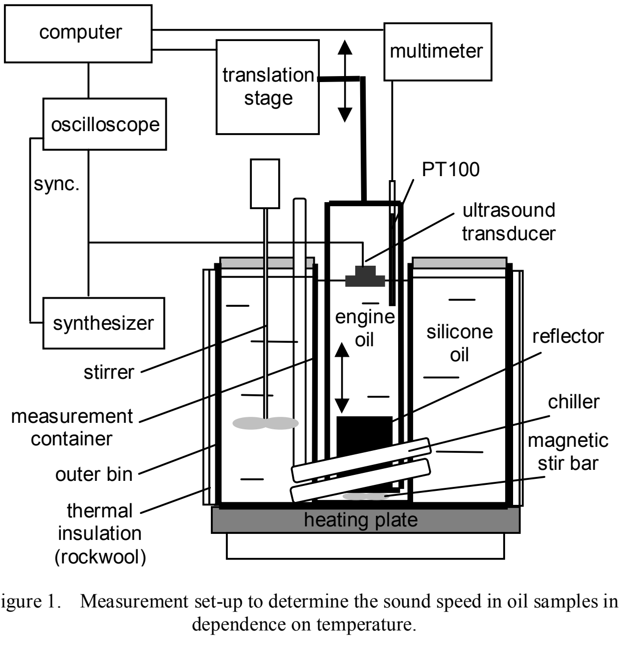

Figure 1. Measurement set-up to determine the sound speed in oil samples in dependence on temperature.

The investigations were commissioned and funded by Hella Fahrzeugkomponenten GmbH, Bremen, Germany.

ing damping on the rear side, but this was compensated by the signal processing described below. The transducer element was directly driven by a signal synthesizer. The ultrasound frequency used was 2.04 MHz and the voltage amplitude applied was in the range from 1.8 V to 2.2 V. The transmitted waveforms comprised 8 periods at a repetition frequency of 200 Hz. The transducer was slightly immersed in the engine oil at the top of the measurement container and the ultrasound was emitted vertically downwards. The ultrasound echo coming from a stainless steel reflector beneath the transducer was received by the same transducer. To measure the received echo, a digital oscilloscope was connected to the transducer in parallel using 1 MΩ input resistance. Horizontal alignment of the reflector surface was achieved using a circular level. The transducer was adjusted by means of a three-point mount by maximizing the received reflector echo amplitude.

For each sound speed measurement, first the echo signal coming from the reflector at a distance z_2 from the transducer (53 mm, 58 mm or 63 mm, chosen in dependence on the signal strength) was recorded, then the reflector was vertically moved by a certain distance using a stepper-motor-driven translation stage, and afterwards a second echo signal from the reflector at a shorter distance z_1 (13 mm or 18 mm) was recorded. Thus, the varied portion of the ultrasound propagation path was outside the nearfield of the transducer. During both aquisitions, triggering of the oscilloscope was performed identically using the synchronization output of the synthesizer. Also, the delay setting of the oscilloscope was not altered between both aquisitions. The recorded signal length chosen was 15000 data points for a time range of 150 µs, i. e. the sampling rate was 100 MS/s and the time increment was 0.01 µs. To reduce the noise level, at least 100 aquisitions were averaged in the oscilloscope. By cross-correlation of the recorded time waveforms, the time-of-flight difference between the two echoes was determined.

The measurement was automatically controlled by a specifically programmed computer software. The program collects the temperature data from the multimeter and each time the temperature falls below a specified level it starts the ultrasound speed measurement, i. e. recording of the first echo, translation of the reflector including compensation for play, recording of the second echo, backtranslation of the reflector to the initial position, and storage of the temperature and waveform data. Further evaluation of the data and determination of the sound speed as quotient of the double translation distance and the time-of-flight difference was done offline afterwards using commercial mathematical software. A typical cross-correlation function of the echoes from the reflector at two distances is depicted in Fig. 2. The modulation of this function is caused by the finite signal length transmitted comprising 8 periods. Due to the missing acoustic damping of the transducer, further shortening of the received waveforms was not possible. Nevertheless, the time-of-flight could be determined precisely by a maximum search of the correlation function. In cases where two very similar correlation peak heights led to ambiguity, clarification was achieved by consideration of the sound speed results obtained for neighbouring temperature points and viewing the overall trend since the results obtained using the two correlation peaks would typically differ by about 10 m/s.

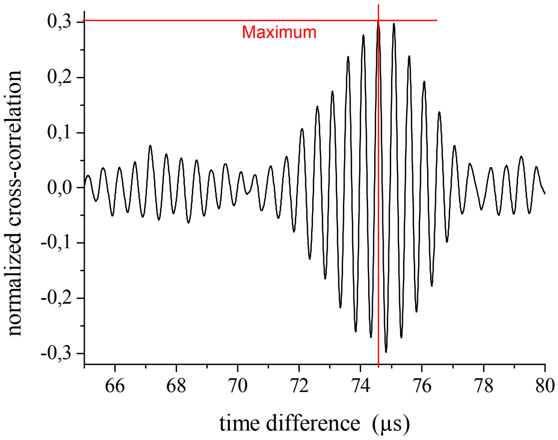

Figure 2. Example of a cross-correlation function of the echoes from the reflector at two different distances and determination of the time-of-flight difference (oil measurement).

For the estimation of the uncertainty of the temperature at each individual measurement point, contributions from the calibration uncertainty of the temperature probe and from the variation range of the temperature during the time needed for the ultrasound speed measurement were considered. The latter contribution was derived from the difference between the two temperature measurements performed just before and immediately after the translation of the reflector. For the estimation of the uncertainty of the ultrasound speed, the calibration uncertainty of the stepper-motor-driven translation stage in relation to the translation distance chosen was considered. Further contributions taken into account resulted from the discrete temporal resolution (time increment) of the oscilloscope measurement in relation to the time-of-flight difference measured and from the adjustment uncertainty regarding the parallelism of the translation direction (vertical axis) and the sound propagation axis. Due to the differential measurement technique, it was not necessary to take the temperature-induced material expansion into account.

III. RESULTS

A. Reference Measurement for Pure Water

To test the complete measurement set-up including the numerical evaluation procedure, measurements of the temperature-dependent ultrasound speed in pure water were performed in the temperature range from 5 °C to 96 °C. In this way, a comparison of the measurement results obtained with the current set-up with independent data precisely known from literature [1] was possible and could be used for verfication. The measurement results are depicted in Fig. 3, together with the individual expanded uncertainties for temperature and sound speed (95 % confidence level). In addition, the polynomial curve taken from literature is given for comparison. The agreement of the data is very good, e. g. the standard deviation of the measured data from the polynomial is 0.019 %, and the literature data lie within the expanded uncertainty ranges determined for the measurement (95 % confidence level) in all cases.

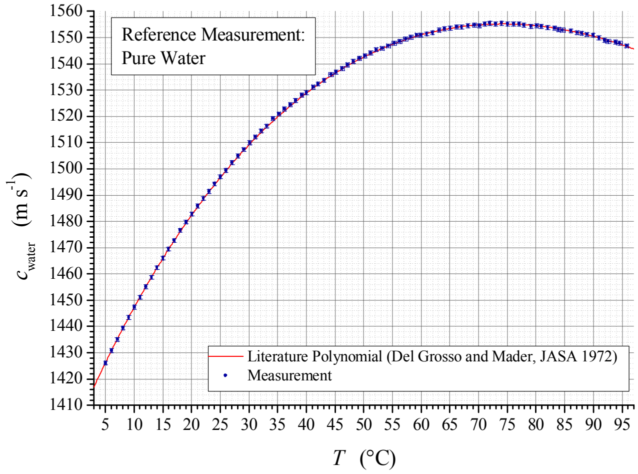

Figure 3. Sound speed measurement results for pure water c_{water} versus temperature T in comparison with data from literature [1].

B. Measurements for Engine Oil Samples

The ultrasound speed as determined for 10 different engine oil samples in dependence on the oil temperature is depicted in Fig. 4. The uppercase characters in the legend denote different oil brands, followed by the oil specification (in case F, the specification was simply: for use in benzine or diesel engines), followed by a usage time description (unused, usage time in hours, or expressed in thousand km). The results qualitatively show a similar behaviour for all oil samples tested. The sound speed decreases monotonously from about 1485 m/s at 8 °C to about 1025 m/s at 150 °C. Only slight differences in the absolute height of the curves were observed. The random variation of the results for each individual oil sample was slightly larger than in the case of the reference measurements in water. The reason for this may be streaming processes taking place relatively slow due to the viscosity of the oil. Since a systematic analysis of this effect was not possible, this random scatter was accounted for in an enlarged overall uncertainty range for the sound speed measurement data as depicted in Fig. 4. The average expanded uncertainty was approx. 0.16 % (95 % confidence level).

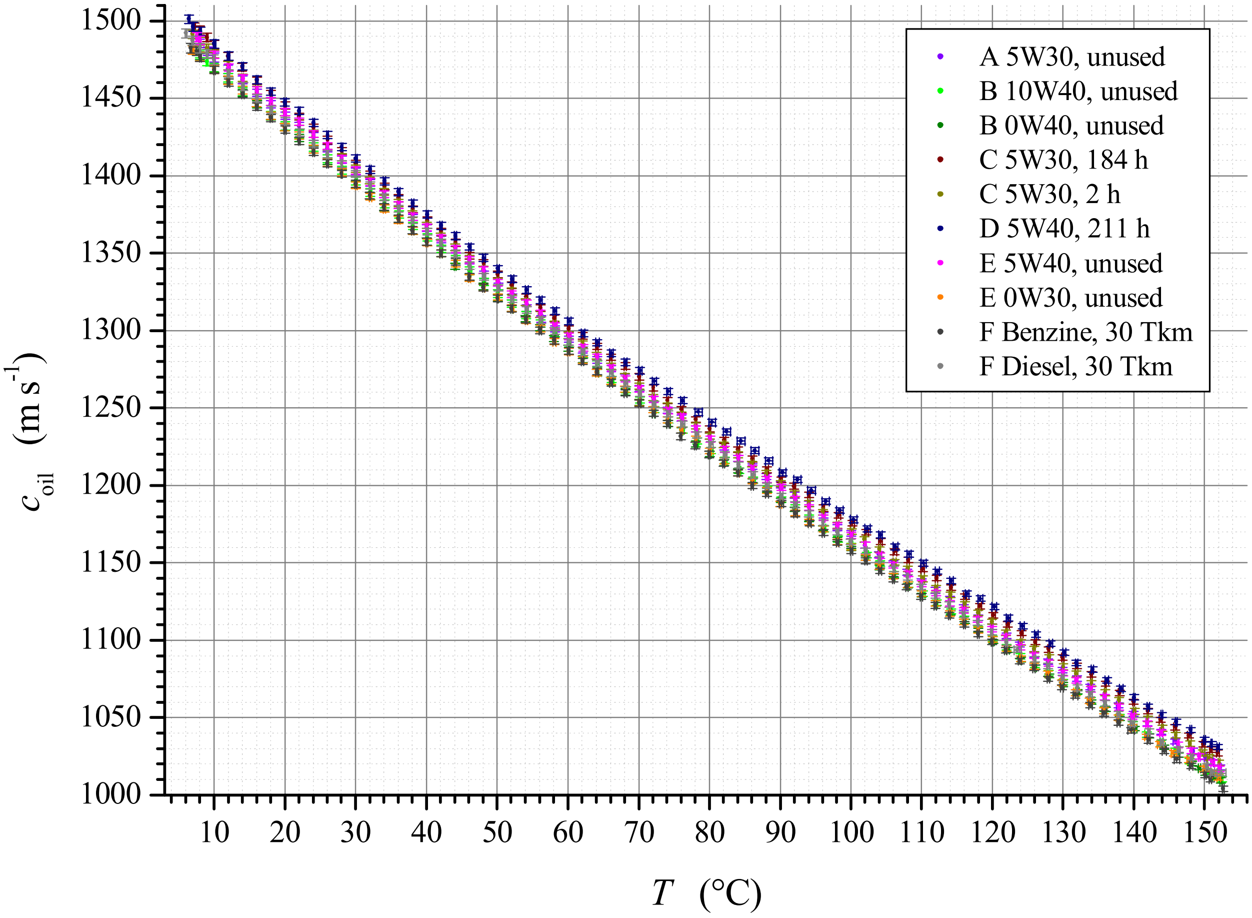

Figure 4. Sound speed measurement results c_{oil} for 10 different engine oil samples versus temperature T including uncertainties (95% confidence level).

In addition, 4th order polynomial fits were calculated for each engine oil sample data set using a least squares fitting routine to quantitatively describe the temperature dependence. The interpolation curves are depicted in Fig. 5, together with the mean value curve of all oil samples investigated. The maximum deviations from the mean value were, for instance, -0.52 % and +0.66 % at 8 °C, and -0.94 % and +1.33 % at 150 °C.

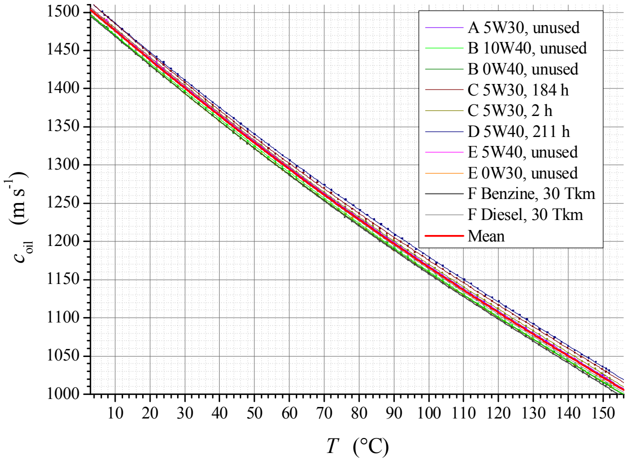

Figure 5. Sound speed measurement results, polynomial fits, and mean curve of the oil samples investigated.

IV. CONCLUSIONS

The ultrasound propagation speed of 10 different engine oil samples was investigated as a function of temperature in the range from 8 °C to 153 °C. The measurement set-up was specifically designed to cope with both the wide temperature range and the small oil volumes available for some of the specifically treated samples. A differential measurement technique was chosen to minimize the impact of temperature-induced material expansions. To keep the expenses of the project at a reasonable level, a stepper-motor-driven translation stage normally used for hydrophone scanning applications was used to realize the distance variation. This translation stage was immediately available and its accuracy is regularly checked. The necessary time measurements were performed using a calibrated digital oscilloscope. The time-consuming sound speed measurements were run automatically and were controlled by a computer, while the further data processing was performed afterwards semi-automatically to enable consistency checks by the operator. The measurement technique and the evaluation procedure were tested by measurement of the speed of sound in pure water, and very good agreement with the data available from literature was observed.

The results for the engine oils qualitatively show a similar behaviour for all samples tested. The sound speed decreases monotonously from about 1485 m/s at 8 °C to about 1025 m/s at 150 °C. The maximum deviations from the mean value were -0.52 % and +0.66 % at 8 °C, and -0.94 % and +1.33 % at 150 °C. The data obtained can be used to better compensate for the temperature dependence of the filling-level meter sensor and to improve the uncertainty estimation for the ultrasound-based oil level measurements in car engines.

ACKNOWLEDGMENT

The authors wish to thank Serkan Canaran for the mechanical preparation of the measurement set-up, Peter Pätzold for the calibration measurement of the temperature sensor, Walter Molkenstruck for assembling the ultrasound transducer head, and Torsten Eggers from Hella Fahrzeugkomponenten GmbH for considering PTB.

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