DOPPLER MEASUREMENT OF LATERAL AND LONGITUDINAL VELOCITY FOR AUTOMOBILES AT MILLIMETERWAVES

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ABSTRACT

In this paper a Doppler radar system is presented which is able to measure the lateral and the longitudinal speed of an automobile. The knowledge of the lateral speed gives a better understanding of the vehicle's dynamic behaviour especially in critical situations. The theoretical measurement accuracy is evaluated and compared to experimental data. The accuracy depends on the antenna configuration as well as on its beamforming properties. Data which were recorded during testruns in real environment are in good agreement with the theoretical expected values.

INTRODUCTION

Today, there is a growing interest in microwave systems for automotive applications. Doppler radar systems in vehicles can provide velocity information which are independent of wheel slip and variable rolling radius. An additional important information for the car driver is the knowledge of the lateral speed which gives information about the dynamic behavior of a vehicle in curves. With this paper we report on a prototype system which is able to measure both, the longitudinal speed, which may be used for anti-blocking- and anti-slipping-systems, and the lateral speed of a car. The evaluated Doppler system was developed from different realized designs which were compared to each other in relation to its measurement accuracy as well as its practicality.

BASIC CONCEPTS

Conventional Doppler sensors measuring true ground speed observe the ground located in the near zone of the antenna. Invidual scatterers, due to the inhomogeneities of the ground, produce the Doppler signal while moving through the antenna beam. In order to compensate for the variation of the vehicle's pitch angle usually a Janus configuration with two beams is chosen. This principle has been realized by using only one waveguide leaky wave antenna terminated by a short. To measure longitudinal and lateral velocity separately two sensors of the same kind looking in the corresponding orthogonal directions may be used. Such a system gives unacceptable large errors regarding lateral velocity, which is due to the simultaneous presence of a dominant longitudinal velocity component in common vehicle applications. So different configurations of two Janus sensors were evaluated resulting in an optimum configuration which is shown in Fig. 1, where α_0 (41 deg.) designates the radiation angle with respect to its longitudinal axis, and γ_0 (30 deg.) the tilt angle of the antenna with relation to its vertical plane. With respect to the axis of the main direction of motion the leaky wave antennas are rotated, giving four illuminated ground areas. So four linear combinations of longitudinal and lateral speed can be measured from which the components of interest can be calculated.

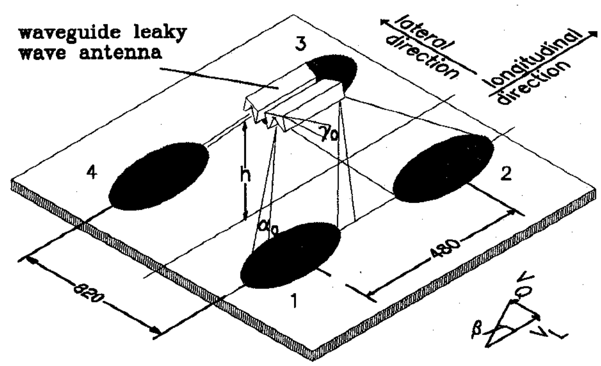

Fig. 1. Optimal antenna configuration.

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SYSTEM DESCRIPTION

Fig. 2 shows the block diagram of the microwave setup. A Gunn-oscillator with an output power of 20 dBm and a transmitting frequency of 61 GHz is used as a microwave source. The complex mixer allows to separate positive and negative Doppler frequency components related to the Janus configuration beams. With these information the pitch and roll angle of the vehicle can be compensated. A waveguide leaky wave antenna works as a transmitting and as a receiving antenna. The far-field beamwidth in longitudinal direction of the antenna is 2.1 deg., in lateral direction 19.6 deg. As the distance to the ground is appoximately 0.25 meter, near field conditions have to be considered to characterize the antennas properly [2],[3].

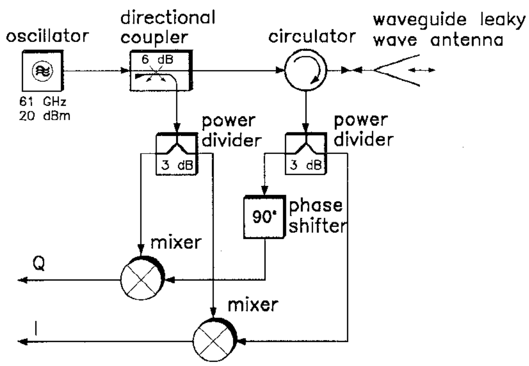

Fig. 2. Block diagram of the microwave setup.

MEASUREMENT ERRORS

The individual measurement errors occuring in each antenna beam can be properly described by the relative spectral width of the obtained Doppler spectra ($\Delta f_{d_i}/f_{d_i}$). The spectral width is influenced by:

- limited observation length for a point scatterer*
- non-ideal antenna pattern*
- distance to the ground as a function of the observation angle
- absolute longitudinal and lateral speed*
- influence of the lateral position of point scatterers
- misadjustment of the antennas
- specular reflection
- vehicle's vibrations
- road surface characteristics
- acceleration during the aperture time

Only the dominant errors (*) will be considered in this paper.

AM-Error (scanning noise):

The critical velocity v_c is defined as the velocity where the maximal possible observation time T_B of a point scatterer is identical with the measurement time T_M

$$v_c = L_B/T_B\Big|_{T_B=T_M} \tag{1}$$

The observation length L_B can be calculated for waveguide leaky wave antennas approximately to:

$$L_B \approx A_L, \tag{2}$$

where A_L (0.26 m) is the aperture length. The observation length is in the first approximation independent of the drift angle β. The measurement time T_M determines the spectral width if the vehicle's total velocity v_0 is less than the critical velocity v_c

$$\Delta f_{d,i} = \frac{1}{2}\Delta f_{3\mathrm{dB}} \approx \frac{1}{2T_M}. \tag{3}$$

We obtain for the relative uncertainty

$$\frac{\Delta f_{d,i}}{f_{d,i}}\Big|_{\mathrm{AM}} = \frac{1}{2T_M}\frac{\lambda_0}{2v_0\cos\delta}\Big|_{T_B\geq T_M}. \tag{4}$$

If v_0 is greater than the critical velocity v_c, integration takes place over independent observations of duration T_B resulting in a relative error of

$$\frac{\Delta f_{d,i}}{f_{d,i}}\Big|_{\mathrm{AM}} = \frac{\lambda_0}{2T_M 2v_o\cos\delta}\sqrt{\frac{T_M}{T_B}}\Big|_{T_B\leq T_M}. \tag{5}$$

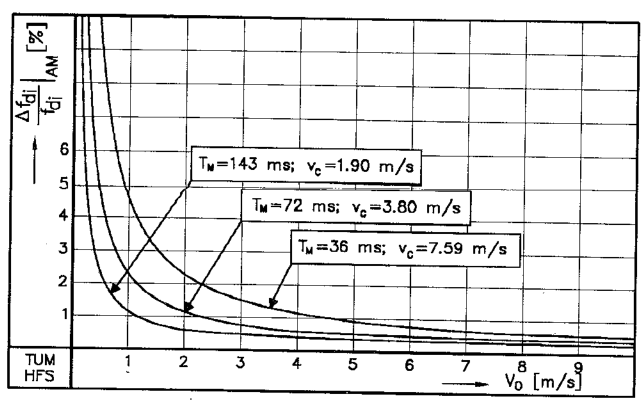

Fig. 3. AM-Error in dependence of the measurement time T_M.

FM-Error (fluctuation noise):

The non-ideal antenna pattern expresses that the aspect angle is changing for a point scatterer while moving through the illuminated area resulting in a additional frequency variation. The aspect angle δ_i is the angle under which a point scatterer can be observed.

$$\cos\delta_i = a\cos\alpha_0\cos\beta + b\sin\alpha_0\sin\beta\sin\gamma_0 \qquad (6)$$

where i is the beam number, β the drift angle of the vehicle, and a and b the coefficients which are determined by the number of the antenna beam (Fig.1).

$$a = \begin{cases} -1; & i = 1,4 \\ +1; & i = 2,3 \end{cases}; \quad b = \begin{cases} -1; & i = 1,2 \\ +1; & i = 3,4 \end{cases}$$

With the effective beamwidths in longitudinal (γ_l) and lateral direction (γ_q) taking into account the actual near-field characteristics we obtain the greatest variation of $\cos\delta$ for a single antenna beam

$$\Delta\cos\delta_{l,i} = \sin\frac{\gamma_l}{2}(a\sin\alpha_0\cos\beta + b\cos\alpha_0\sin\beta\sin\gamma_0), \qquad (7)$$

$$\Delta\cos\delta_{q,i} = \sin\frac{\gamma_q}{2}\sin\alpha_0\sin\beta\cos\gamma_0. \qquad (8)$$

The resulting FM deviation can be written in the following form:

$$\Delta f_{d,i}\Big|_{\mathrm{FM}} = \frac{2v_0}{\lambda_0}(|\Delta\cos\delta_{l,i}| + |\Delta\cos\delta_{q,i}|). \qquad (9)$$

The spectral width for an individual antenna beam which can be attributed to the influence of observation time and FM deviation of the Doppler signal is approximately given by

$$\Delta f_d\Big|_{\mathrm{FM+AM}} = \Delta f_{d,i}|_{\mathrm{FM}} + \Delta f_{d,i}|_{\mathrm{AM}}, \qquad (10)$$

resulting for a four beam configuration in an effective total spectral width of

$$\Delta f_d\Big|_{\mathrm{FM+AM}} = \frac{1}{4}\cdot \sqrt{\sum_{i=1}^{4}(\Delta f_{d,i}|_{\mathrm{FM}} + \Delta f_{d,i}|_{\mathrm{AM}})^2} \qquad (11)$$

Using four beams in a configuration according to Fig. 1 the longitudinal and lateral velocity can be calculated from the observed Doppler frequencies:

$$v_l = \frac{\lambda_0}{2\cos\alpha_0}\frac{|f_{d1}| + |f_{d2}| + |f_{d3}| + |f_{d4}|}{4} \qquad (12)$$

$$v_q = \frac{\lambda_0}{2\sin\alpha_0\sin\gamma_0}\frac{|f_{d1}| + |f_{d2}| - |f_{d3}| - |f_{d4}|}{4} \qquad (13)$$

Assuming all velocity vectors in the four beams to be equal, the overall relative error for the longitudinal velocity is related to the total spectral width by

$$\frac{\Delta v_l}{v_l}\Big|_{\mathrm{FM+AM}} = k\frac{\lambda_0}{2v_0\cos\alpha_0\cos\beta}\Delta f_d\Big|_{\mathrm{FM+AM}}, \qquad (14)$$

where k is a factor which mainly depends on SNR and the statistical nature of the scatterers on the surface. Comparing measured and theoretical accuracies of longitudinal velocity according to Fig. 6, the factor k turns out to be 0.27 using an estimated effective beamwidth of 1.5 deg. The total error for the lateral velocity becomes

$$\Delta v_q\Big|_{\mathrm{FM+AM}} = k\frac{\lambda_0}{2\sin\alpha_0\sin\gamma_0}\Delta f_d\Big|_{\mathrm{FM+AM}}. \qquad (15)$$

RESULTS

The experimental data obtained during test runs under real traffic and under various environmental conditions have confirmed that the observed measurement errors can be reliably predicted. Fig. 3 displays the total relative error for the longitudinal velocity, which increases with increasing drift angle. The AM-part was calculated assuming identical measurement and observation time ($T_M = T_B$). Fig. 4 shows the calculated absolute error for the lateral speed. The error increases with growing longitudinal velocity v_l as well as with the drift angle β. Fig. 5 and Fig. 6 depicts the relative measurement error of the longitudinal and lateral speed. The comparison between calculated and measured data (σ/v_q), which were collected during a testrun in real environment shows a good agreement. Fig. 7 shows again the lateral velocity of the vehicle. The travelled distance was about 3 km. Marker A describes a 90 deg. curve in positive direction, marker B a 90 deg. curve in negative direction, marker C a traffic roundabout.

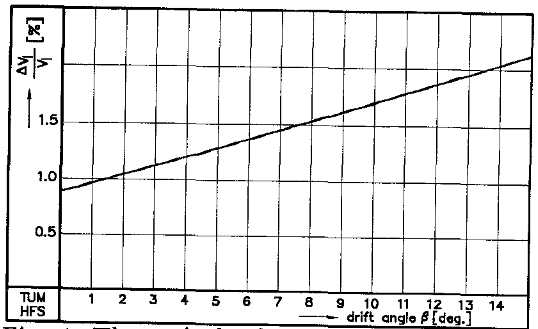

Fig. 4. Theoretical relative measurement uncertainty of the longitudinal velocity.

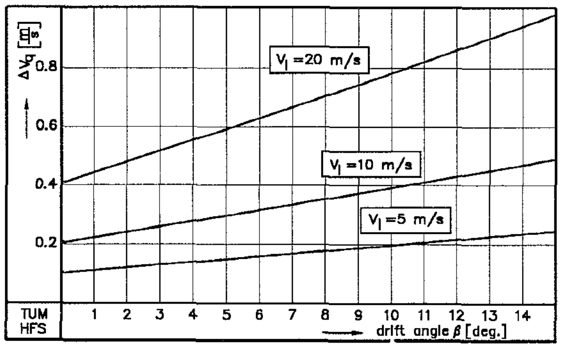

Fig. 5. Theoretical absolute measurement uncertainty of the lateral velocity.

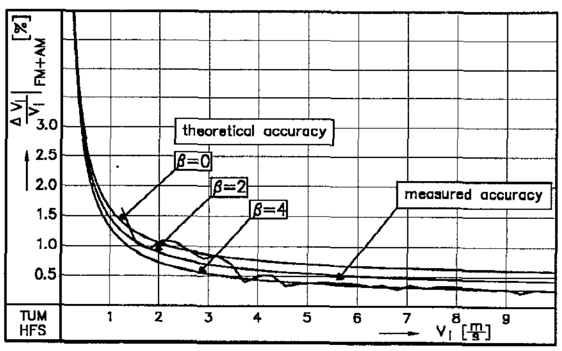

Fig. 6. Comparision between calculated and measured longitudinal velocity uncertainty.

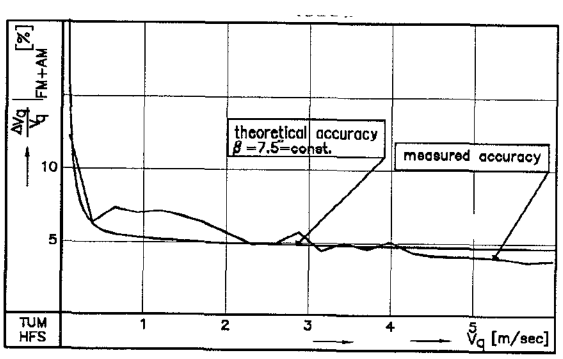

Fig. 7. Comparision between calculated and measured lateral velocity uncertainty.

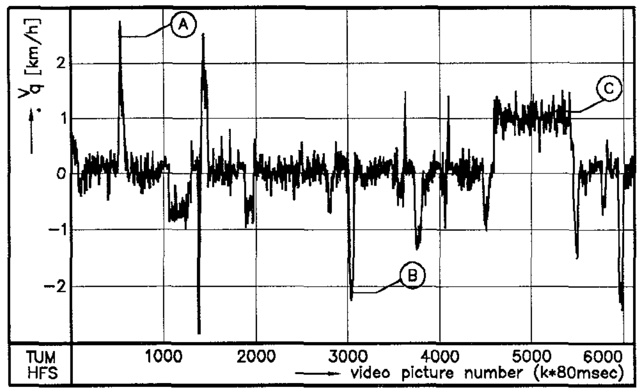

Fig. 8. Lateral speed of a vehicle, measured data.

CONCLUSION

Optimum system configurations for the measurement of lateral and longitudinal true ground speeds have been found and realized in an experimental system. A new model incorporating all important parameters including the near field antenna characteristics has been set up and verified using experimental data. The calculated error has shown that the accuracy depends very strongly on the beamforming properties of the antenna. The measurement accuracies which can be obtained from an optimized system make it a promising approach to measure and monitor the vehicle's dynamic behavior in the near future.

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