WIND SHEAR DETECTION FROM PCM-RECORDED MLS-FLIGHT DATA *)

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Abstract

During the test phase of the SETAC microwave landing system, flight tests were performed for wind determination along the flight path. Approach profiles were curved in elevation and azimuth. All flight parameters were recorded on board in digital form by a PCM-flight data acquisition system. The evaluation of the recorded flight data on a digital computer showed that some signals contained disturbances resulting from sensor dynamics or digital noise due to numerical differentation. Non-recursive digital filters were applied to eliminate undesired signal properties. The longitudinal wind component and its power spectrum were computed. Wind shear was detected by the off-line use of non-recursive digital filters as well.

I. Introduction

The existence of dangerous wind shears in the atmospheric boundary layer has been identified as the cause of several aircraft accidents during the last years. This demonstrated drastically that todays knowledge of the actual wind conditions on the aircraft's flight path is insufficient. Particularly the reported airport surface winds do not always correspond to the wind situation the pilot finds on his approach in the terminal manoeuvering area. Consequently this leads to the demand for a highly reliable and precise determination of wind vector components as well as wind gradients. It serves to expand the general notion of wind behavior in the atmospheric boundary layer, and in addition wind shear detection is needed for the design of autopilots and for a better information of pilots flying a manual approach.

If the true airspeed vector and the inertial velocity of the aircraft are both known in direction and magnitude, the wind velocity can be computed from the difference between inertial velocity and true airspeed.

One prerequisite for determining wind components and -gradients is the knowledge of all parameters, which identify the flight condition of the aircraft. This includes angle of attack, side slip angle, pitch and bank angle, as well as the magnitude of true airspeed and inertial velocity of the aircraft.

In order to obtain a precise representation of the aircraft's flight path, there is the need to equip the aircraft with an Inertial Navigation System (INS) or to applicate a Microwave Landing System (MLS). Different methods are used to compute the components of the aircraft's inertial velocity. The INS-platform integrates accelerations, while the measured aircraft position has to be differentiated utilizing MLS.

Flight tests for evaluating a Guidance and Control Unit (GCU) of the Bodenseewerk Gerätetechnik GmbH for the SETAC microwave landing system were performed in August and September 1978 in Manching, Germany.(1) Primary aim of the flight tests was to demonstrate that the curved approach paths generated by the GCU could be manually flown with the flight director. The Technische Universität Braunschweig was responsible for data acquisition on board the Do 28 Skyservant aircraft (See Fig.1).

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Fig. 1: Do 28 SKYSERVANT

All major parameters for determining wind were registered on board the Do 28 SKYSERVANT aircraft at a sample rate of 92 Hz on a recorder using Pulse Code Modulation (PCM). More than 90 curved approaches in azimuth and elevation were flown and recorded at varying weather conditions.

II. Wind Determination from MLS-Data

As already mentioned, the wind vector $\underline{V}_W$ may be computed by taking the difference between the inertial velocity $\underline{V}_k$ and the true airspeed $\underline{V}$ (See Figure 2). Both, true airspeed and inertial velocity, are in the same order of magnitude. Therefore an accurate determination of inertial velocity as well as true airspeed must be insured when satisfactory precision shall be obtained for the resulting wind speed, especially for calm winds.

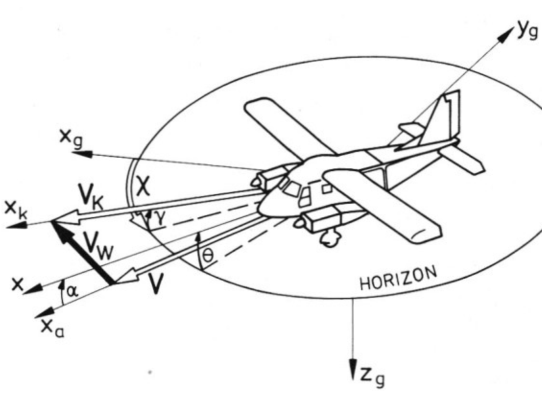


Fig. 2: Determination of the Wind Vector

With the MLS-System the position of the aircraft is fixed in planar coordinates by knowing elevation $_L$, azimuth $_L$ from the MLS ground transmitters, and slant range to the azimuth antenna by DME-measurement (See Fig. 3). Transforming this data into Cartesian coordinates, height of the aircraft as well as lateral distance from runway centerline and runway centerline distance are given. Then the components of the inertial velocity in the earth-fixed axes system (x_g, y_g, z_g) can be determined by differentiation of height, lateral distance, and centerline distance with respect to time.

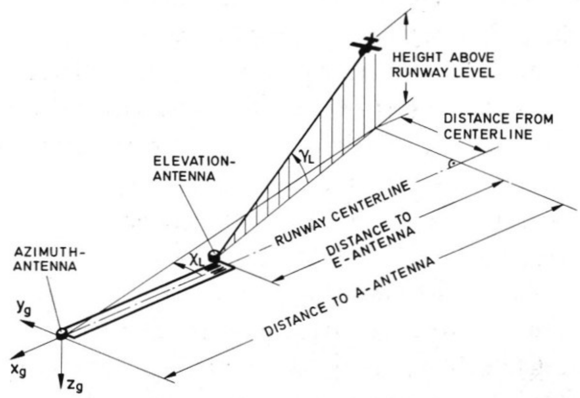


Fig. 3: MLS-Parameters for Determination of Aircraft Position

Consideration earns the fact that the flown approaches were curved in azimuth as well as in elevation. Figure 4 shows a typical flight profile. Curved approaches provide advantages for future STOL- and military applications.(2) They allow to avoid densely populated areas and obstacles safely, provide noise abatement, and increase efficiency.

In inertial navigation systems for example, it is assumed that the inertial velocity, the true airspeed, and the wind vector lie in the horizontal plane and that the aircraft is not banking. (3) For cruise conditions at high speeds this holds true, and the wind computation may be approximated by taking the difference of true airspeed and inertial velocity in the horizontal plane. During descend in the presence of horizontal or vertical winds or during flight manoeuvres the true airspeed and inertial velocity vector do not coincide and do not lie in the horizontal plane (See Fig.2).

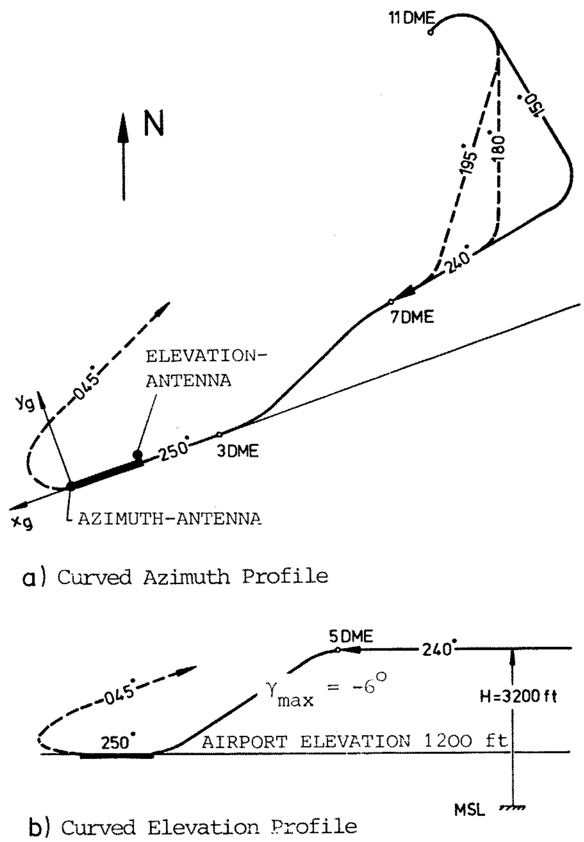


Fig. 4: Typical Approach Profiles

This is the case during curved flight profiles. A simplification in wind determination to the horizontal plane is no longer valid. (4) The following set of equations represents the determination of wind components along and across centerline, u_{Wg} and v_{Wg}. Also included is the transformation of true airspeed into the earth-fixed coordinate system. Determination of wind with respect to wind direction and -magnitude has been performed by R. Hankers. (5) Unfortunately the side slip angle could not be recorded during flight test due the high priority of other data which had to be recorded for the Guidance and Control Unit evaluation. Therefore the side slip was assumed to be zero during the computer calculations.

General vector equation:

$$\underline{V}_W = \underline{V}_K - \underline{V} \tag{1}$$

Components in the earth-fixed coordinate system:

$$\begin{bmatrix} u_W \\ v_W \end{bmatrix}_g = \begin{bmatrix} u_K \\ v_K \end{bmatrix}_g - \begin{bmatrix} u \\ v \end{bmatrix}_g \tag{2}$$

True Airspeed components:

$$\begin{aligned} u_g = |V| \cdot \{ & \cos\alpha \cdot \cos\beta \cdot \cos\theta \cdot \cos\psi \\ & + \sin\beta \cdot (\sin\Phi \cdot \sin\theta \cdot \cos\psi - \cos\Phi \cdot \sin\psi) \\ & + \sin\alpha \cdot \cos\beta \cdot (\cos\Phi \cdot \sin\theta \cdot \cos\psi + \sin\Phi \cdot \sin\psi) \} \end{aligned} \tag{3}$$

$$\begin{aligned} v_g = |V| \cdot \{ & \cos\alpha \cdot \cos\beta \cdot \cos\theta \cdot \sin\psi \\ & + \sin\beta \cdot (\sin\Phi \cdot \sin\theta \cdot \sin\psi + \cos\Phi \cdot \cos\psi) \\ & + \sin\alpha \cdot \cos\beta \cdot (\cos\Phi \cdot \sin\theta \cdot \sin\psi - \sin\Phi \cdot \cos\psi) \} \end{aligned} \tag{4}$$

MLS Inertial Velocity components:

$$u_{Kg} = \dot{x} \approx \frac{\Delta x}{\Delta t} \tag{5}$$

$$v_{Kg} = \dot{L} \approx \frac{\Delta L}{\Delta t} \tag{6}$$

where:

α	=	angle of attack
β	=	side slip angle
θ	=	pitch angle
Φ	=	bank angle
ψ	=	heading angle
x	=	runway centerline distance (distance to elevation antenna)
L	=	lateral distance from runway centerline

III.

Requirements for Data Computation and Acquisition

In order to perform the described wind determination on-line on board the aircraft, there is the need to equip the aircraft with a digital processor. At the time of the flight tests such a processor was not available to us. Therefore the wind calculations were restricted to off-line computations. For future on-line research the Skyservant is now operated by the Technische Universität Braunschweig. A digital multipurpose computer and an INS-system are currently being installed.

Using the described method for an off-line determination of wind components and its statistical properties requires a flight data acquisition system which permits the recording of numerous parameters for a long period of time. In addition the acquisition equipment has to satisfy the specific demands of flight test concerning shock, vibration, reliabity, precision, mobility, and adaptibility to different sensors. These specifications are met by a modern flight data acquisition unit using the Pulse-Code-Modulation (PCM) technique. Such a PCM-System is available at the Lehrstuhl für Flugmechanik at the Technische Universität Braunschweig.

The special features of the system are: simple operation, very low zero drift with constant adjusting, no problems in adapting sensors with different sensitivities, and 12 bit resolution. The recording part of the system consists of a modulator for 32 analog channels, tape recorder, time generator and power supply (See Fig. 5). Total mass of the system is less than 20 kg, and it is particularly suited for missions in light aircraft. For the data transfer into a digital computer the PCM-data is available at a demodulator in digital form including channel address, real time marks, and synchronization. All channels are also available in analog form at the demodulator. This feature is mainly used for quick look purposes after each flight at the airport. Flight test data can be played back at higher tape speeds in comparison to recording, therefore only taking a fraction of the actual flight test time.

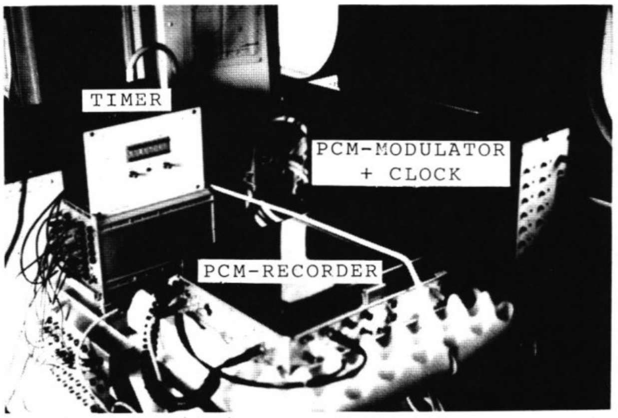


Fig. 5: PCM-Recording Hardware

IV. Disturbed Data

The evaluation of flight data showed that some parameters in the equations listed on page 3 contain disturbances. Two types of disturbances have to be distinguished: one where the sensor itself falsifies the signal and one where the 12 bit quantization of recorded data produces numerical noise.

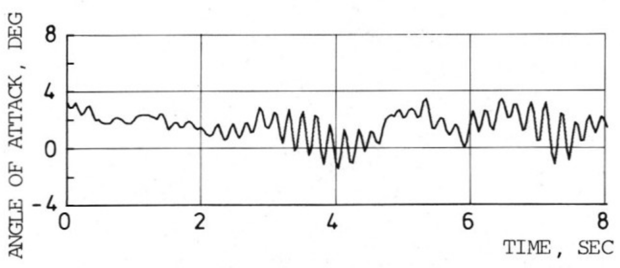


Fig. 6: Angle of Attack Signal

The angle of attack sensor supplied a signal where its dynamics produced undesired signal properties. Figure 1 shows that the vane was placed at the tip of a boom approximately 2 meters ahead of the aircraft nose. The time history illustrates that gusts and the aircraft's short-period response apparently excite the natural oscillation of the vane (See Fig. 6).

Further investigation of the sensor revealed that it responds like a second order system with a damping ratio of about 0.02. The power spectrum of the time signal yields that the natural frequency occurs at about 5 Hz (See Fig. 7).

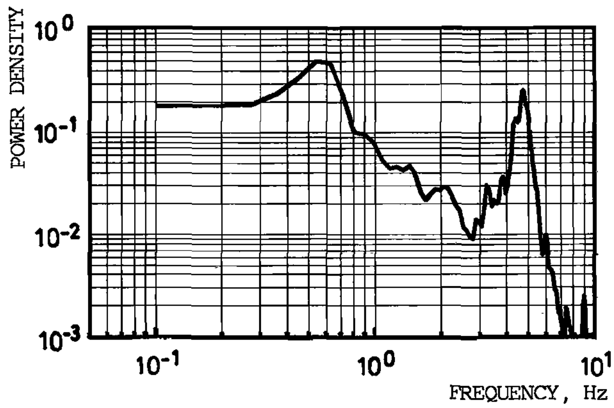


Fig. 7: Power Spectrum of Angle of Attack Signal

Before using the angle of attack signal in the equations transforming true airspeed into the earth-fixed system, the signal has to be filtered in order to eliminate the natural frequency oscillation. This frequency lies well above the frequency range of interest for wind shear detection. Therefore we chose a low pass filter, where non-recursive digital filtering proved to be an adequate method for removing undesired signal properties.[6] The advantage of non-recursive digital filters is that there is a constant phase delay, and for off-line applications as in this case there is no phase delay at all.

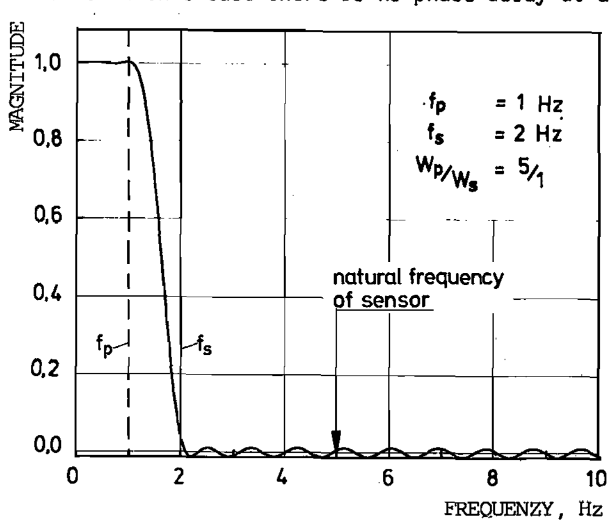


Fig. 8: Magnitude Response for the Digital Low-pass Filter

For filtering the angle of attack signal a filter with 50 constants, a passband frequency f_p of 1 Hz, a stopband frequency f_s of 2 Hz and a weighting ratio of 5 to 1 for passband and stopband tolerances was used.[7] (See Fig. 8).

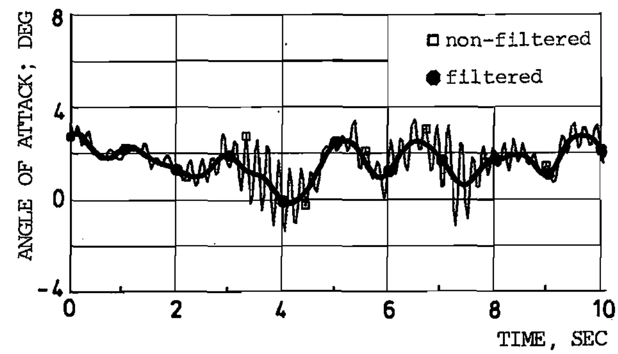


Fig. 9: Angle of Attack before and after Filtering

Figure 9 represents the time history of the angle of attack signal before and after filtering. The power spectrum of the filtered signal clearly demonstrates that the natural oscillation of the angle of attack has been eliminated and that the signal may be used now for further computations (See Fig. 10).

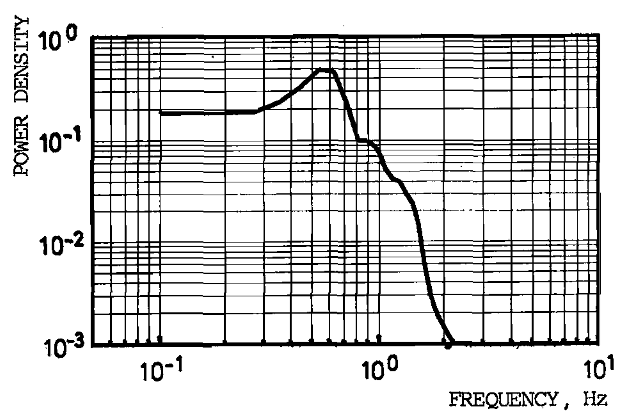


Fig. 10: Power Spectrum of the Angle of Attack after Filtering

Secondly, non-recursive digital filters were employed to eliminate numerical noise. The need for this application arose during the calculation of inertial velocity components by differentiation of PCM-recorded MLS-distances. The distances of up to 40 km were recorded with a 12 bit resolution dividing the measuring range into 4096 steps. In spite of the high resolution of about 10 meters it turned out that the differentiation produced a discrete ground speed result where the step-like time signal could not be used for wind computations (See Figure 11). Differentiation was carried out by differential quotients according to equation 5 using a time increment Δt of 5 seconds.

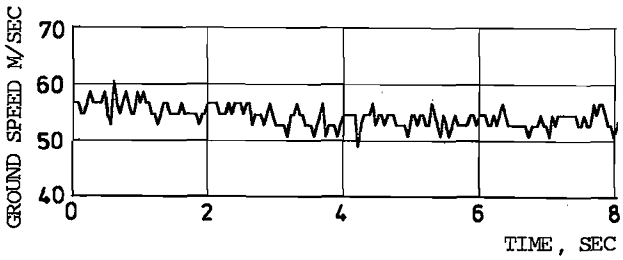


Fig. 11: Inertial Velocity Component along Centerline

By using such a simple method of differentiation, the effectiveness of digital filtering can be demonstrated. Figure 12 shows the frequency response of the filter applied to the inertial velocity component along centerline.

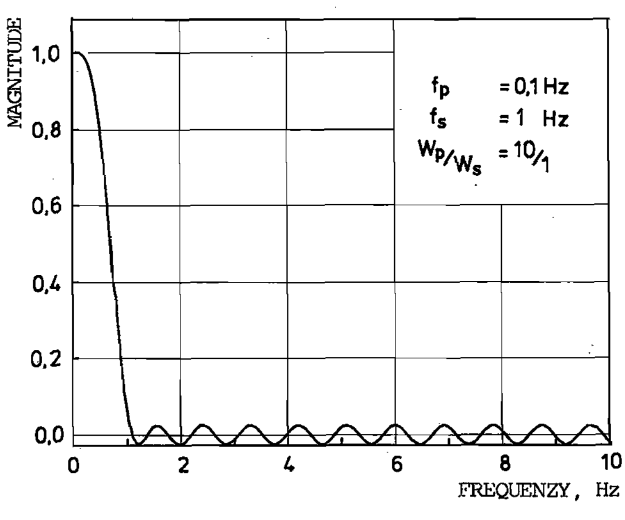


Fig. 12: Magnitude Response for the Digital Lowpass Filter

The outcome is a smooth ground speed signal (See Fig. 13) which permits the wind determination by taking the difference between the true airspeed and ground speed components.

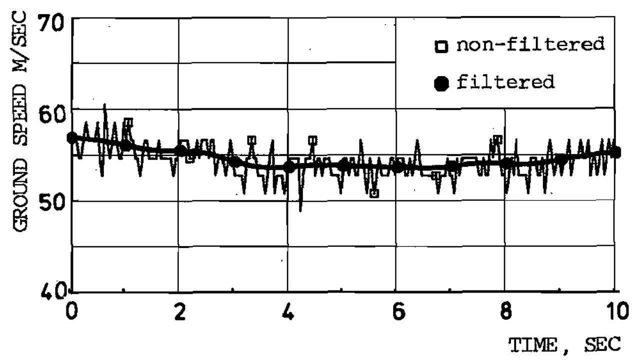


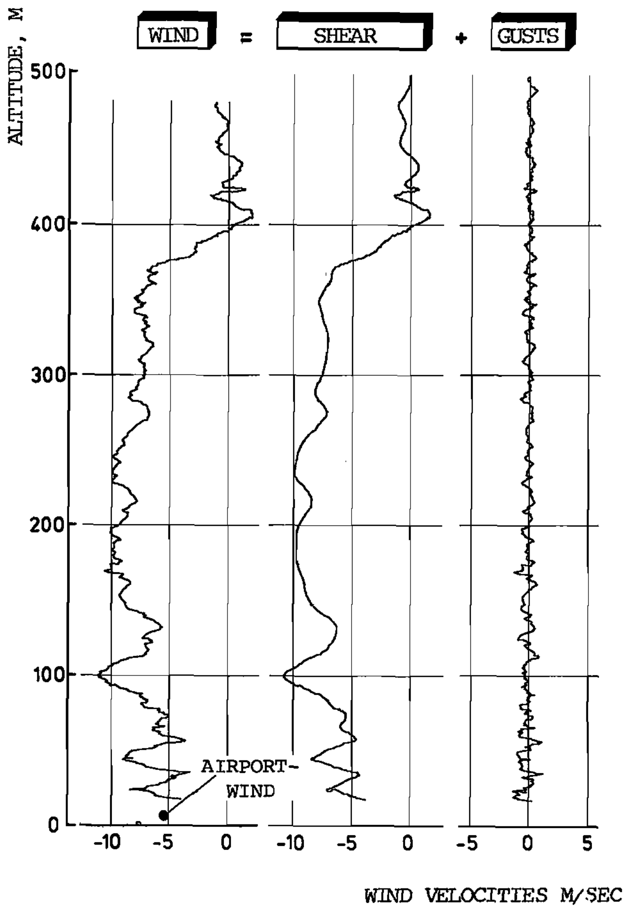
Fig. 13: Inertial Velocity Component along Centerline before and after Filtering

V. Flight Test Results

Test flights were undertaken during various weather conditions. For all flights weather observations were available from the airport weather station at half an hour intervals. This permitted a correlation between calculated and reported winds.

Some flights were tracked by ground radar to insure accuracy of the MLS-position data. A comparison of recorded MLS-position and tracking radar data furnished a fine correspondence. [5]

The following example demonstrates the flight test results for a curved approach flown on August 31st, 1978 at 13:00 GMT. Figure 14 shows on the left-hand graph the calculated head wind component with respect to height above airport elevation where the wind component was computed from recorded and filtered data according to the preceding chapters. The surface wind was reported to be 11 knots from 270 degrees which converts into a headwind component of 5.3 meters per second along centerline. This agrees with the computed wind component in Figure 14.



$$u_{Wg} = \bar{u}_{Wg} + \tilde{u}_{Wg}$$

Fig. 14: Separation of Gusts from Wind Shear

The calculated wind still contains turbulence. For pilot information and autopilot design it is of interest to separate the gusts and turbulence from the low frequency wind. This task was achieved again by using a non-recursive filter, similar to the filter response in figure 12. However, passband frequency was 0.033 Hz and stopband frequency 0.33 Hz. These frequencies were chosen so that all wind frequencies were separated which lie above the break frequency of the Dryden spectrum. The middle part of figure 14 shows the filtered wind component $\bar{u}_{Wg}$ representing the mean, time-variant wind, in which the wind shear information is included. Between 410 and 370 meters a wind shear can be detected where the wind changes from a 2 m/s tailwind to a 7 m/s headwind component resulting in a strong wind gradient u_{Wz} of 0.22 per second causing the aircraft to ascend above the glide path.(9) This wind shear may be attributed to a 4/8 cumulus cloud base reported in 400 meters.

The gusts $\tilde{u}_{Wg}$ on the right hand side of Figure 14 are obtained by subtracting the wind shear $\bar{u}_{Wg}$ from the calculated wind along centerline u_{Wg}. Spectral analysis of the gusts, which contain frequencies above about 0,1 Hz, shows that there is conformity between the slope of the Dryden spectrum and the slope of the gust spectrum (See Fig. 15). An even better conformity may result when using the Karman-spectrum. However, throughout this paper the Dryden spectrum was used for comparitive purposes.

The spectral definition in this paper is the one-sided Dryden spectrum:

$$S_u(\omega) = \frac{\sigma u^2}{\pi} T \frac{2}{1 + (T_u \omega)^2} \qquad (7)$$

with

$$\sigma_u^2 = \int_0^\infty S(\omega)\, d\omega \qquad (8)$$

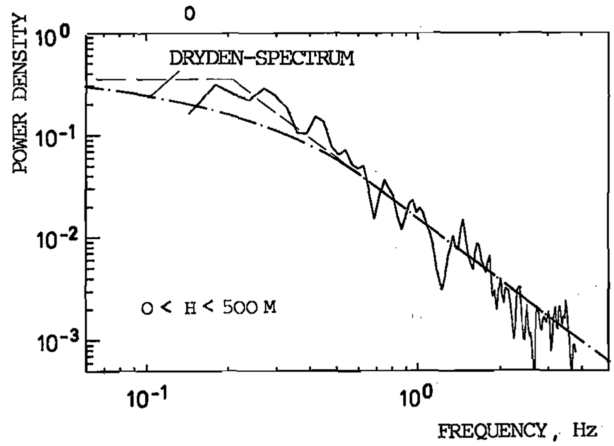


Fig. 15: Gust Spectra

The Dryden spectrum drawn for reference in Fig. 15 implies a time constant T of about 0.8 seconds, which was derived from the autocorrelation of the time signal. By applying Taylor's hypothesis ($L_u = T_u \cdot V$) this corresponds to an integral length L_u of 56 meters at an approach speed of 70 m/s. It has to be pointed out that it is an average constant for the descent height from 500 meters down.

The fine correspondence in spectral slope encouraged trying to calculate the longitudinal spectrum including the low frequency range. For this purpose a straight-in approach on centerline was analyzed. For the spectral evaluation only the flight portion was used where the aircraft approached at the constant height of 600 meters above airport elevation for a period of 353 seconds. These factors insured the validity of the computations.

The computed longitudinal wind component u_{Wg} possesses a mean headwind of 8.26 m/s and a standard deviation of 1.21 m/s, which can be classified as moderate turbulence (See Fig. 16).

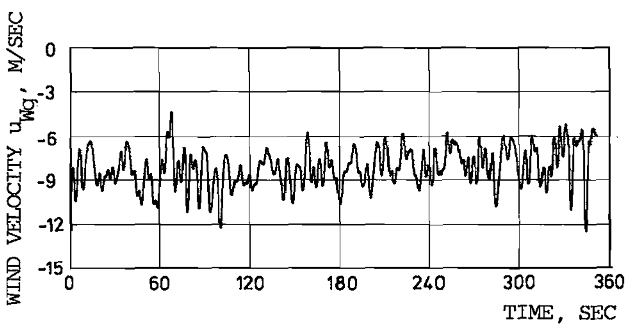


Fig. 16: Time History of Longitudinal Wind Components

The assumption of a Gaussian distribution is verified by the probability density of the longitudinal wind component (See Fig. 17). In this figure the Gaussian probability density is included for comparison. As during PCM-recording, the sampling rate of the calculated wind component was equal to 92 Hz. However, for estimating the gust spectrum at low frequencies, the sampling rate had to be reduced. Before lowering the rate to 5.8 Hz (See Fig. 16), the data was filtered by a non-recursive filter in order to avoid aliasing.

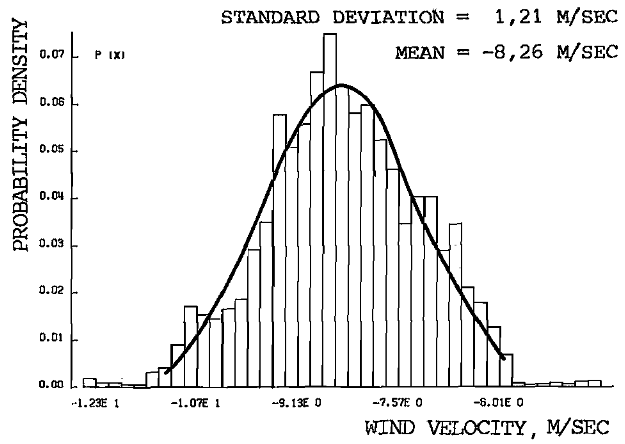


Fig. 17: Distribution of Wind Velocity

The spectral calculations were performed by a Fast Fourier Transformation in two blocks of 1024 sampling points each, where the mean value of each block was substracted from the time signal. Fig. 18 shows the resulting gust spectrum which has been smoothed by a Hamming filter.

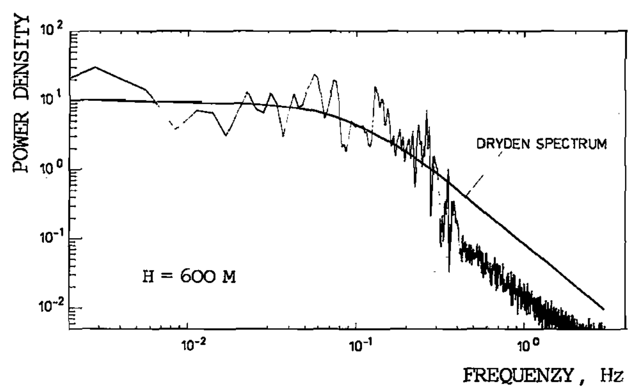


Fig. 18: Gust Spectrum

This spectral result verifies the horizontal tangent of the Dryden spectrum below the break frequency. The first frequency estimate was taken at 2.8×10^{-3} Hz which at an approximate approach speed of 70 m/s corresponds to the longest wavelength of 25 kilometers.

In figure 18 the Dryden spectrum for the longitudinal wind component is included. The time constant for the Dryden spectrum was computed from the normalized autocorrelation of the gust signal (See Figure 19). Integrating the autocorrelation in the time domain yields a time constant of about 1.7 seconds or an integral scale L_u of 120 meters. This is a typical integral scale found in neutral atmospheric conditions. Such a condition may have existed because the measured temperature gradient was - 0.005 °C/m.

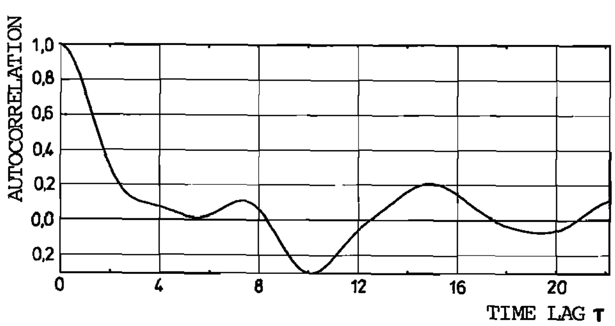


Fig. 19: Normalized Autocorrelation of Gust Signal

VI. Summary

This paper presents a view into the theoretical principles of wind determination during curved MLS-approaches. Data was recorded by a PCM-data aquisition system suited for light aircraft. Disturbed data was processed with the application of non-recursive digital filters. The methods used for off-line wind determination and wind shear detection may be applied in future on-line wind computations. For the longitudinal wind components the gust spectrum was calculated including the frequency range below the break frequency.

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