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A NEW METHOD OF ANALYTICAL EVALUATION OF HELICOPTER TRUE AIRSPEED

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by

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1. Summary

Due to rotorinduced downwash and limited resolution the classical air data computation utilising pressure differential and temperature measurements is not applicable for the helicopter low airspeed range ($|v| < 20$ m/s).

In order to overcome this problem, several approaches have been made in the past resulting in systems with external sensors like LASSIE[1] and LORAS[2] and without external sensors, the so called analytical systems like VIMI[3]. As VIMI has not been designed to meet the accuracy requirement of 2 m/s 95% probability a new analytical method for the new generation of military helicopters has been recently developed using specific helicopter control features.

The validity and accuracy of this new analytical method has been verified by a series of flight trials which have demonstrated that an accuracy of 2 m/s (95%) can be achieved.

2. Introduction

The classical air data computation based on temperature and pressure differential measurements by fixed mounted sensors is not applicable for the helicopter low airspeed ($|v| \leq 20$ m/s) regime. This is caused by the following three reasons:

a) The resolution threshold of standard pitot-tubes available is about 15 m/s. This value results from basic equation (2.1) substituting the pressure difference term by a standard deviation of 100 PA.

$$v = \frac{\sqrt{2RT(p_o - p_s)}}{p_s} \qquad (2.1)$$

R: gas constant T: temperature p_o: total pressure p_s: static pressure

[1] Low Airspeed Sensing and Indicating Equipment |KA81|

[2] Low Range Airspeed System |ON83|

[3] Vitesse Indiqueè par Moyens Internes |DU74|

b) Compared to fixed wing aircrafts rotorcrafts have two additional degrees of freedom, i.e. along the lateral and the vertical axis. In the case of fixed mounted tubes the velocity components along these axes can not be evaluated (fig.2-1)

c) During hovering and within the low speed regime the downwash prevents a precise measurement due to the unavoidable turbulences in that air stream.

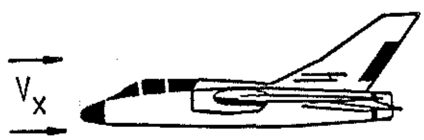
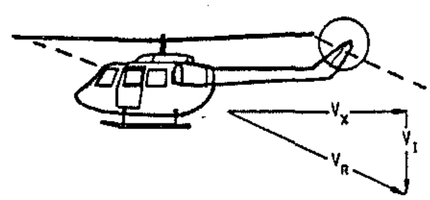
	Fixed Wing Aircraft	Rotorcraft
Wind Conditions		
Resultant Velocity	$V_R = V_X$	$V_R = \sqrt{V_X^2 + V_Y^2 + (V_Z - V_I)^2}$
Velocity Range	$V_X > 50$ m/s	-17 m/s $< V_X <$ 110 m/s -14 m/s $< V_Y <$ 14 m/s -15 m/s $< V_Z <$ 15 m/s

Figure 2-1 Basic Conditions for TAS-Evaluation

Basically there are two concepts to determine helicopter true airspeed in the range $|v| < 20$ m/s.

The first one is to extend the classical air data determination by using temperature and pressure differential measurement probes. This can be referred to as the "classical" mechanical solution, but the deficiencies mentioned under a)-c) must be avoided by specifically mounting the probes on the outside of the helicopter. Presently two of such systems are available, LORAS and LASSIE.

LORAS lowers the threshold mentioned before by using a rotating arm above the main rotor with tip-mounted venturi tubes and thus measuring pressure differentials around a bias depending on the rotational speed of the venturi tubes mounted on the rotating arm.

LASSIE has a swivelling pitot tube mounted on a horizontal arm outside the helicopter and a temperature probe. At low speeds the angle of the swivelling tube is used to determine TAS. At high speeds the classical TAS determination is used.

Due to the various shortcomings as e.g. weight, uncertainties due to downwash turbulences and, in the case of LORAS, extended suszeptability for doppler radar detection and lock on, these systems are not very attractive for military applications.

As at the helicopter used for the flight tests described in chapter 5 LASSIE was installed, this system was part of the evaluation.

The second approach makes use of specific properties of helicopter flight dynamics and therefore the control inputs to the main rotor to command magnitude and direction of speed are the criteria to determine TAS in the low speed regime. This method is referred to as the "analytical" solution of the TAS determination problem. The term "analytical" is perhaps misleading, because the TAS determination is based on measured inputs as well as the method utilising pressure differential and/or probe angle measurements.

With the exception of sensors for static pressure and temperature which are on a helicopter anyway the TAS determination method developed by LITEF does not require externally mounted sensors. This method is called LAASH[4] and does not suffer from the disadvantages mentioned above. It is therefore far better suited for military helicopters.

The LAASH system represents the first working "analytical" low airspeed system for helicopters. Its development is based on a series of flight trials in the BO-105 helicopter at DFVLR[5]. Table 2-1 below gives the LAASH flight test overview.

Helicopter	Test Purpose	Time Span
BO-105	Data Collection	Feb.÷March1985
BO-105	Calibration	Sept.÷Oct.1985
BO-105	Verification	May÷ June 1985

Table 2-1 LAASH Flight Test Overview

3. System Fundamentals

3.1. Collective Pitch

At constant rotor speed, the collective pitch angle Θ_0 is a measure of the power of the rotor which must overcome induced, profile and parasitic drag. Figure 3-1 demonstrates that in the low speed regime the latter two types of drag forces are almost constant. On the other hand the induced drag however decreases with increasing speed. The reason for this is associated with direct incident air flow that reduces the proportion of the air which is induced by the rotor's own power.

[4] LITEF Analytical Air Data System for Helicopters |HA85|

[5] Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt

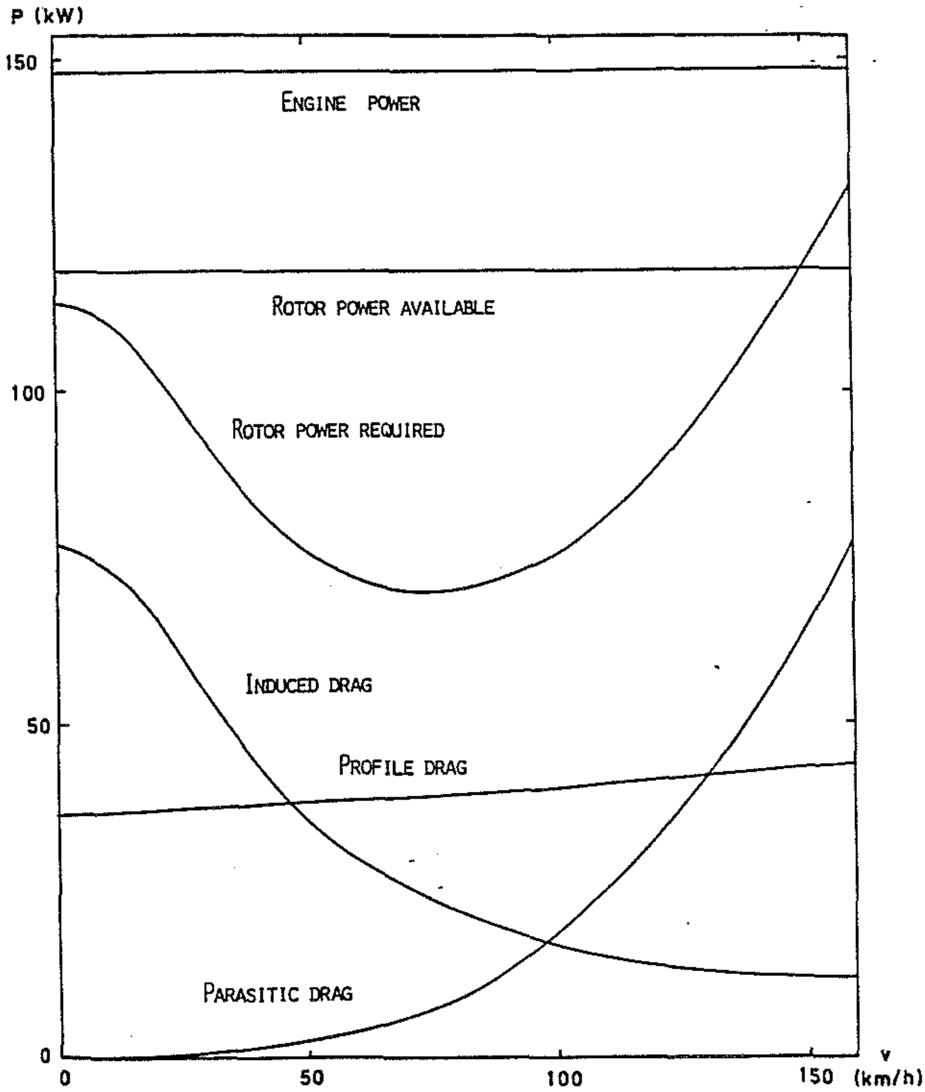


Figure 3-1 Helicopter power versus Horizontal Speed, Bell 47G[6]

At higher speed parasitic drag becomes dominant causing an increase of power required thus the true airspeed graph versus power required is approximately parabolic. According to a rule of thumb the minimum value is achieved at approximately $\frac{1}{2}\ v_{max}$. Up to almost 20 m/s the slope of the power graph is nearly identical with the slope of the induced drag. As without noteworthy loss of accuracy the parasitic drag can be neglected in the low speed regime, the airspeed/power behaviour can be utilised for all sideslip angles. This specific feature is used to determine the resultant horizontal speed. Figure 3-2 shows the collective control position of a BO 105 versus speed.

6 see |JU63|

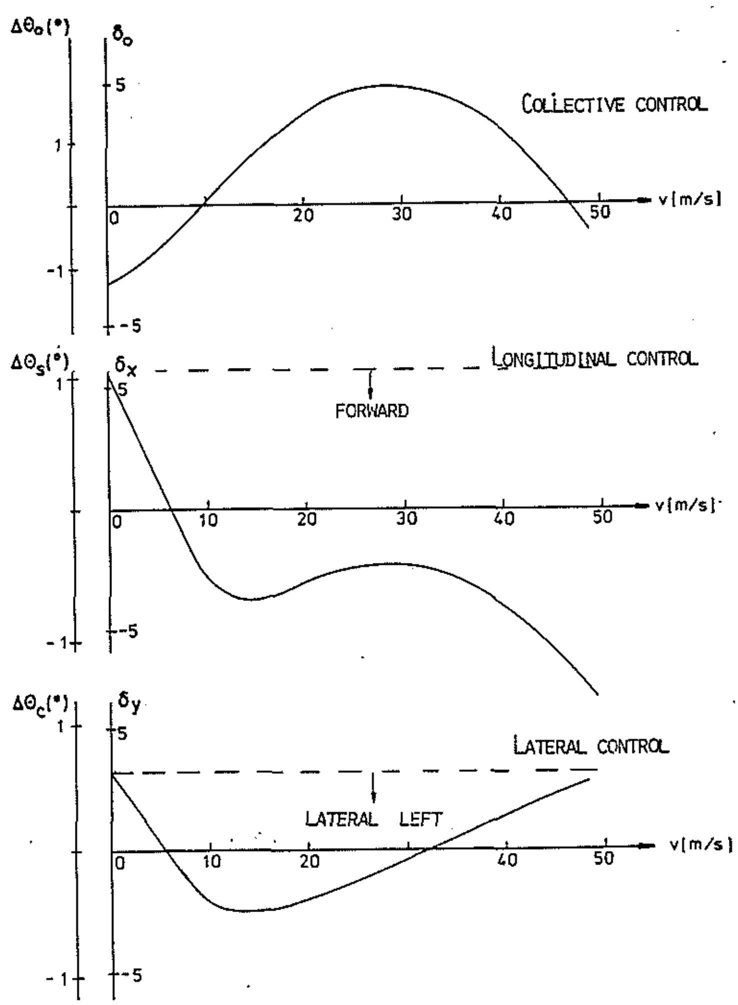


Figure 3-2 Control Positions at Forward Flight, BO 105
Measured in 2/85 at DFVLR

3.2. Cyclic Pitch

A lateral or longitudinal control input causes a variation of the cyclic pitch angles Θ_s, Θ_c. Thus, the rotor disk inclines to the control direction, and as a consequence of the tilt a lateral and/or longitudinal force is produced. This fact is illustrated in figure 3-2 which shows the appropriate BO-105 values of lateral and longitudinal control measured in forward flight. For forward speed command the control stick has to be moved forward and at increasing speed a longitudinal flow gradient arises which results in a flapping of about 270° respectively a roll moment to the right is generated |PA59|. To compensate for this moment the pilot has to move the control stick leftwards. At further increased speeds the longitudinal control curve is characterised by two reversals where the slope changes its sign. Due to the decrease of the flow gradient the lateral control has to be moved back.

The complete control characteristics are shown in figures 3-3a/b. For each sideslip angle one and only one specific function is valid. Through 360°

these functions are periodic. In the case of a given flight direction, e.g. 90°, the lateral control signal indicates, as expected, a deflection to the right, whereas due to the flow gradient the longitudinal stick position is forward. Consequently, the helicopter flow conditions require the angular displacement of longitudinal and lateral control functions. This is an important fact used in the LAASH procedure explained in the following chapter.

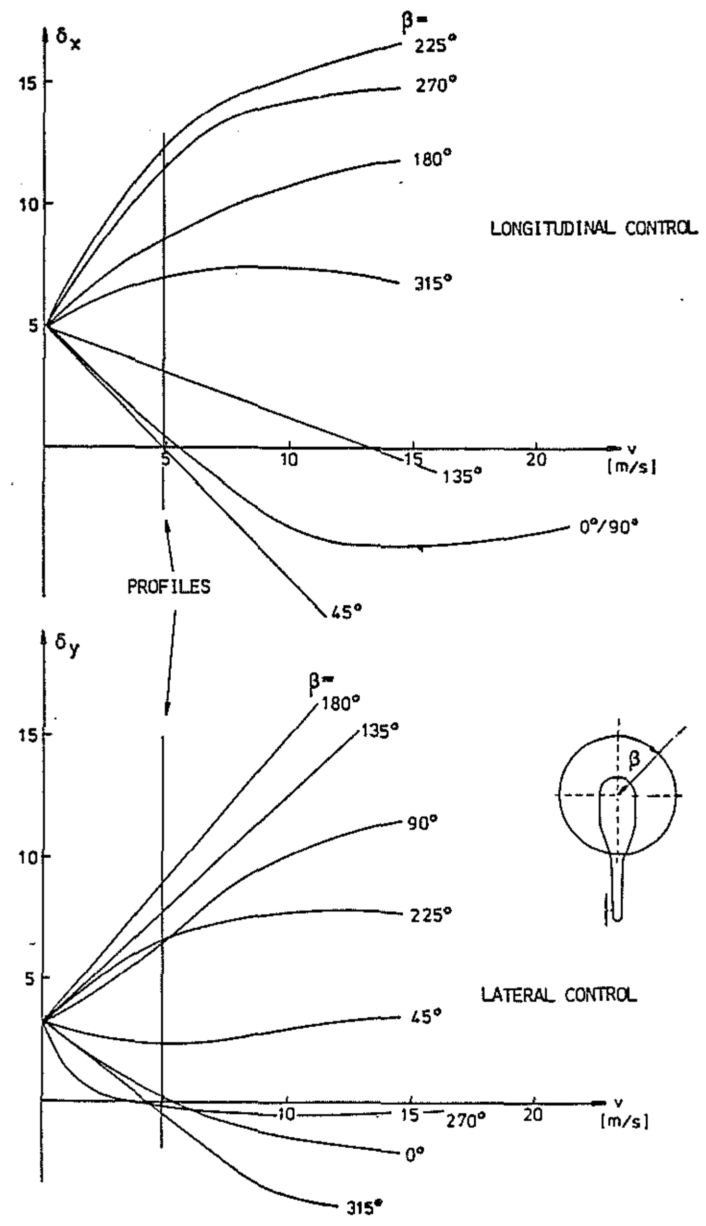


Figure 3-3 Measured Control Characteristics of the BO-105

4. LAASH-System

4.1. General

The system LAASH developed by LITEF essentially consists of a polar measurement utilising the control functions

- collective pitch - longitudinal control - lateral control

Furthermore the parameters

- mass - temperature - static pressure

are required to compensate the model for mass and air density corrections.

4.2. True Air Speed Determination

As explainedin chapter 3.1 in the low speed regime the collective pitch is a measure of horizontal true air speed. The corresponding function is approximately linar. Therefore and because of the sideslip invariance the airspeed collective pitch relationship is generally given by the simple expression

$$\delta_o = c_m + Sc \cdot v_h \tag{4.1}$$

c_m: additional term, depends on helicopter mass and air density
Sc: scale factor
v_h: horizontal true airspeed

Hence, the resultant is calculated by

$$v_h = \sqrt{v_x^2 + v_y^2} = \frac{\delta_o - c_m}{Sc} \tag{4.2}$$

4.3. Sideslip Determination

In chapter 3.2 the characteristic of the cyclic control has been described. The relationship between TAS and longitudinal resp. lateral control has shown to be periodic with an angular displacement due to the flow gradient. LAASH uses this feature to determine the sideslip angle.

At first the value v_h computed according to equation (4.2) is substituted into the sets of curves figure 3-3, which are available e.g. in the form of a table in the computer thus generating two profiles (figure 4-1). These profiles represent two discrete functions with which the relationship between longitudinal respective lateral control and sideslip angle is determined under the condition of v_h being constant. In the next step the sampled values δ_{x_i} and δ_{y_i} are plotted in a δ_{x_i}, δ_{y_i} frame forming an octagon (figure 4-2). The task to be solved is optimally fit the actual pair of the values $\delta_{x,N}$ and $\delta_{y,N}$ into the polygon. For that it is advantageous to observe the joints from the center of measuring values computed as an average along the two coordinate axes and to perform a direction interpolation. In this manner also measuring points near the joints are well-defined.

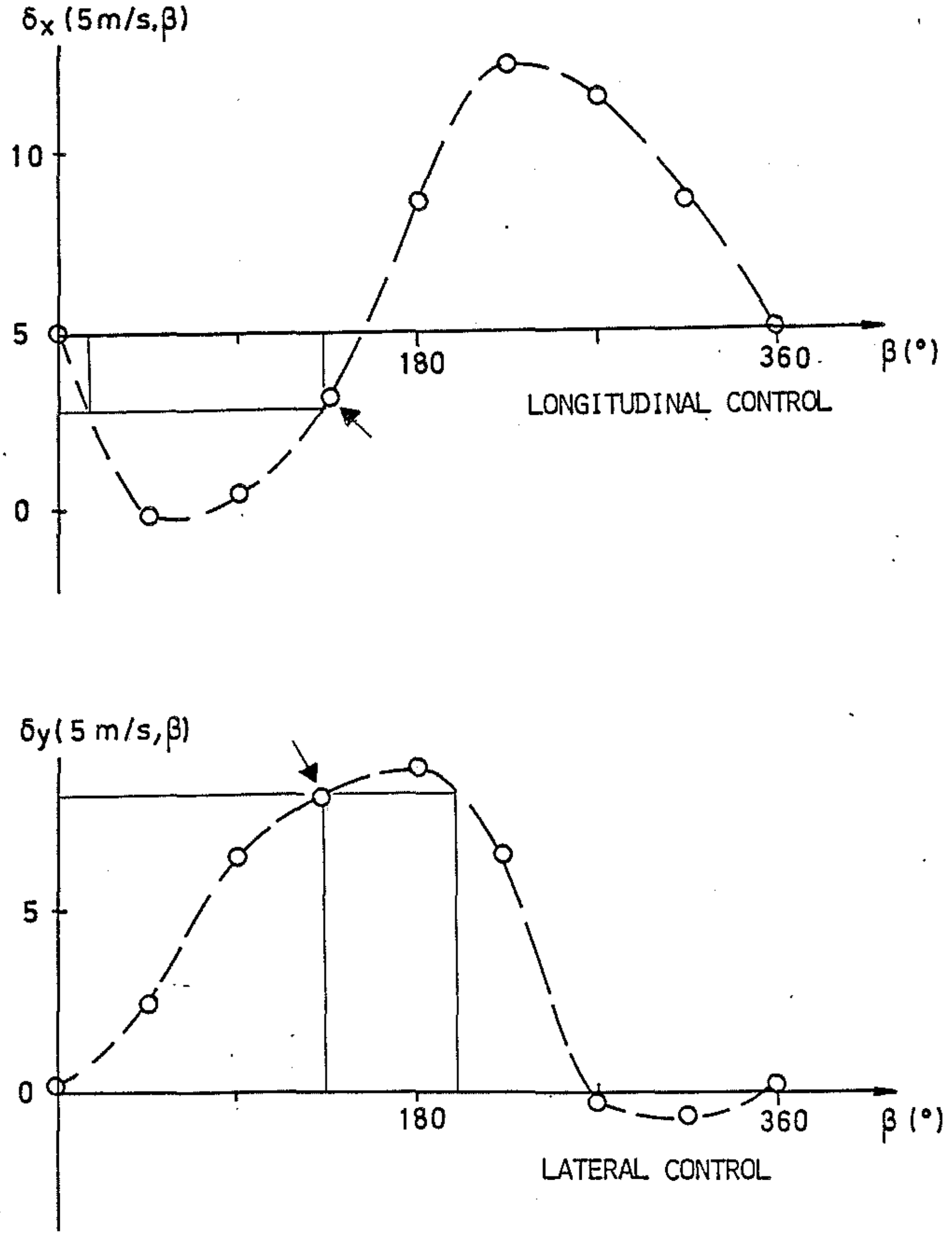


Figure 4-1 Control Profiles at 5 m/s True Airspeed, BO-105

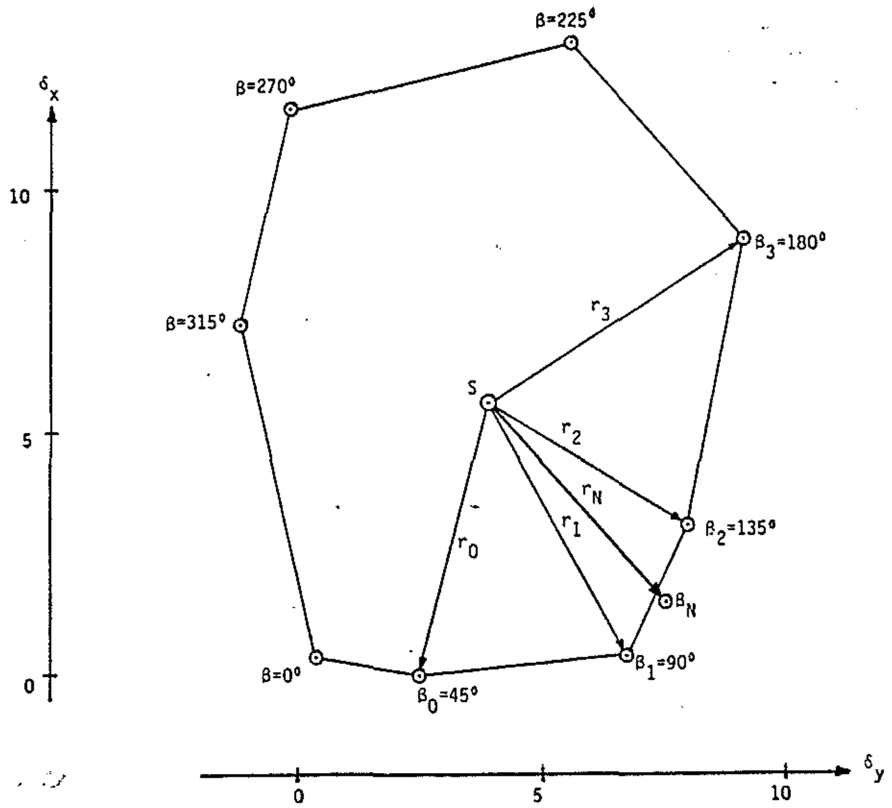


Figure 4-2 Octagon for Sideslip Interpolation

Newton's procedure has been chosen as interpolation algorithm. The corresponding rule is applied as follows:

$$\beta_N = a_0 + a_1 (r_N - r_0) + a_2(r_N - r_0)(r_N - r_1) + \\ + a_3 (r_N - r_0)(r_N - r_1)(r_N - r_2) \tag{4.3a}$$

$$a_0 = \beta_0 \tag{4.3b}$$

$$a_1 = [r_1 r_0] = \frac{\beta_1 - \beta_0}{r_1 - r_0} \tag{4.3c}$$

$$a_2 = [r_2 r_1 r_0] = \frac{[r_2 r_1] - [r_1 r_0]}{r_2 - r_0} \tag{4.3d}$$

$$a_3 = [r_3 r_2 r_2 r_0] = \frac{[r_3 r_2 r_1] - [r_2 r_1 r_0]}{r_3 - r_0} \tag{4.3e}$$

The horizontal speed v_h and the sideslip angle β_N evaluated according to (4-2) and (4-3) are the polar elements to calculate the body-related true airspeed. Its components result in

$$V_{X,N} = V_h \cos\beta_N \tag{4.4a}$$

$$V_{Y,N} = V_h \sin\beta_N \tag{4.4b}$$

4.4. LAASH-Procedure

A general overview of the LAASH procedure is given by diagram 4-3. The procedure is divided into the following sequential steps:

1. measurement of $\delta_{O,N}$, $\delta_{X,N}$, $\delta_{Y,N}$
2. computation of the resultant true airspeed V_h by substituting $\delta_{O,N}$ into the calibration equation for collective pitch
3. octagon-determination by means of tables providing control characteristics
4. Interpolation on Newton's algorithm yields the sideslip angle β_N
5. Polar - rectangular transformation provides noisy components $V_{X,N}$ $V_{Y,N}$
6. Filtering result in $\overline{V}_{X,N}$, $\overline{V}_{Y,N}$ smoothed

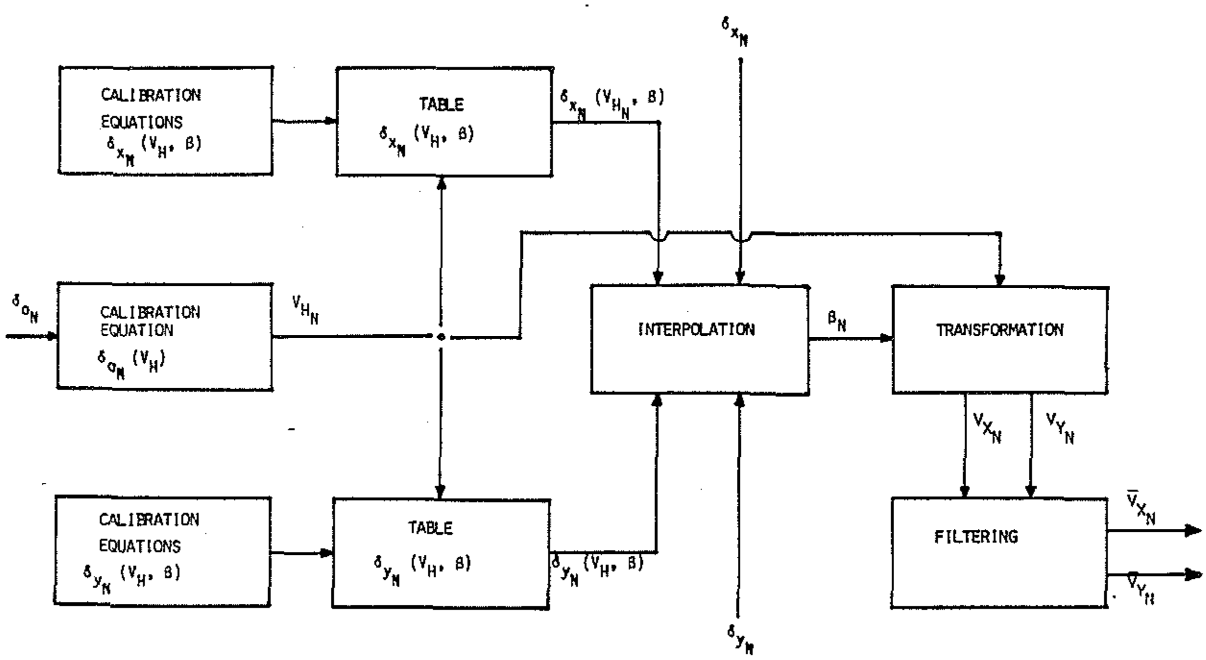


Figure 4-3 Block Diagram of the LAASH procedure

5. Flight Trials and Tests

5.1. General

In order to demonstrate the validity of the analytical system LAASH a series of flight tests has been carried out by LITEF in close cooperation with the DFVLR in their centers at Braunschweig and Oberpfaffenhofen. At the DFVLR

Braunschweig a properly equipped MBB helicopter type BO-105 was available (figure 5-2) The total flying time amounted to about 70 h. According to the development status the trials were divided into three parts, i.e. tests to collect data concerning the relationship of the helicopter control functions to airspeed, calibration flight tests and system verification flight tests.

5.2. Instrumentation and Parameter Selection

As there was no operable analytical systems to begin with, type and number of the parameters required could not accurately be defined prior to the first part of the trials. All those quantities have therefore been measured which the authors thought that they could contribute to solve the task of TAS determination with the required accuracy of 2 m/s 95% probability. Figure 5-1 delineates the block diagram for the first part of the trials and table 5-1 shows a synopsis of all the parameters acquired.

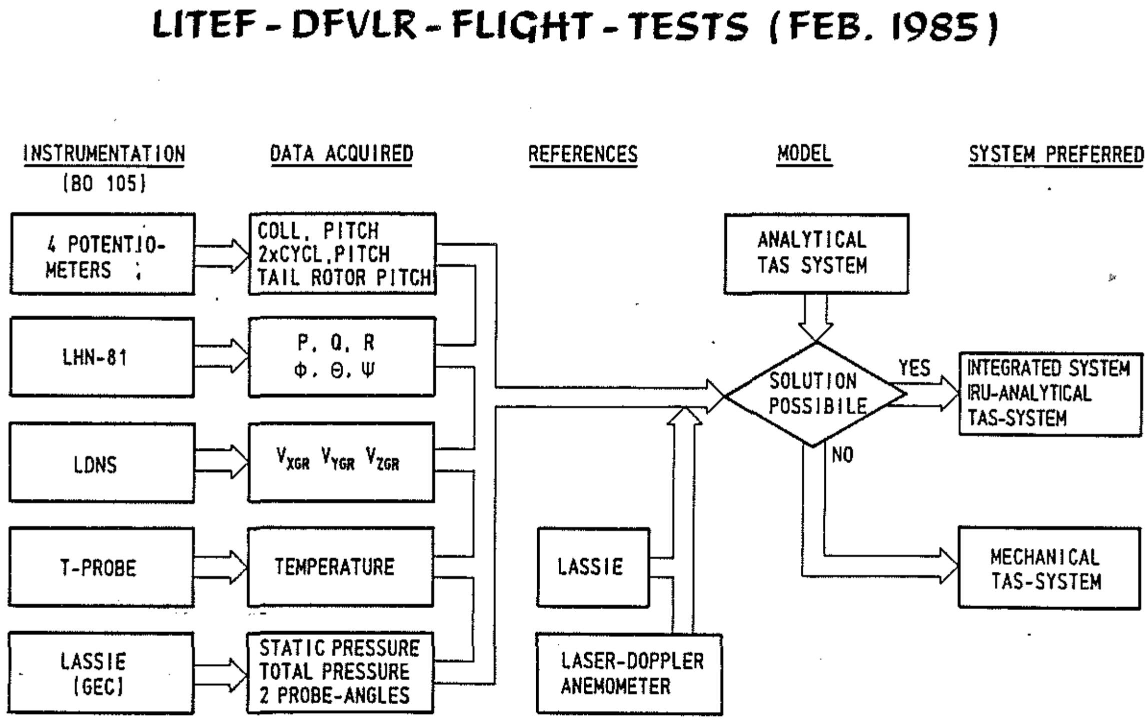


Figure 5-1 Block Diagram Data Collection

Parameter	Symbol	Instrumentation	Acquirement
Collective Control	δ_o	Potentiometer	permanent with 10 Hz
Longitudinal Control	δ_x		
Lateral Control	δ_y		
Pedals (tail rotor)	δ_H		
Roll Angle	ϕ	LHN-81	
Pitch Angle	θ		
Heading[1]	T		
Rollrate	p		
Pitchrate	q		
Yaw Rate	r		
Velocity (east)[2] (with respect to ground)	v_E		
Velocity (north)[2] (with respect to ground)	v_N		
Temperature	T	Resistance measurement	
Baro Altitude	h_B	LASSIE	
Indicated Airspeed	IAS		
Sideslip Angle [Probe]	β_L		
Angle of Attack [Probe]	α_L		
Weight[3]	M	three point balance	as single event
Center of Gravity	S	three point balance	
total pressure reduced to sea level	QNH	Tower Info/LDA[4]	irregular intervals
Wind Velocity [average]	V_W		
Wind Direction [average]	ψ_W		

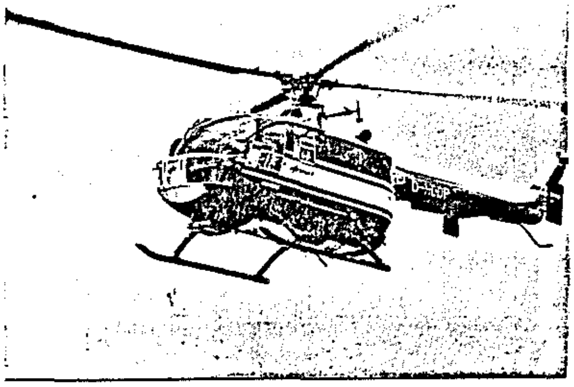
1.) MSU augmented

2.) augmented by Doppler Radar RDN 80B (ESD) / AN/ASN 128 (SK)

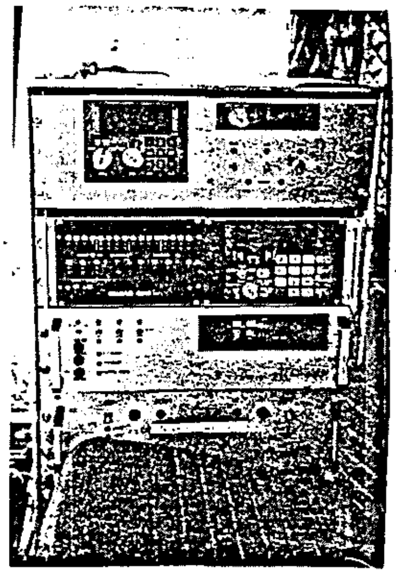
3.) updated by fuel indicator reading

4.) Laser Doppler Anemometer

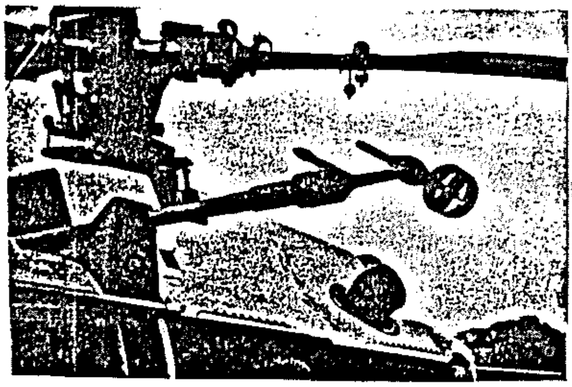
Tab. 5-1 Parameter Selection and Instrumentation



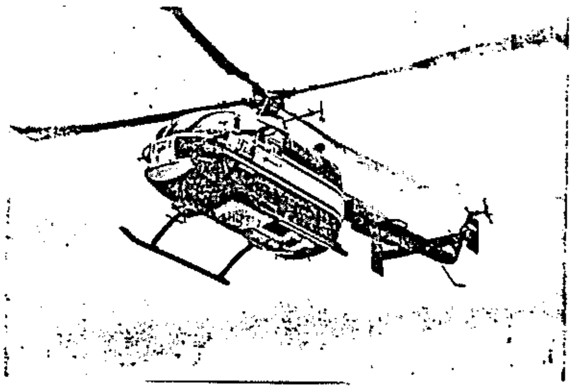
a) Helicopter BO 105



b) Control Display Unit



c) True Airspeed LASSIE



d) Doppler Radar Antenna
RDN 80 B (ESD)

Figures 5-2 a ÷ d

The most important parameters - the control inputs - were acquired by potentiometers mounted at the control lever arms. A helicopter inertial reference unit LHN-81[7] augmented in heading by means of a standard flux valve (KEMS 802-1) and for velocity by means of a doppler velocity sensor (RDN 80B-ESD resp. AN/ASN 128-SK) (figure 5-2c) provided attitude, heading, angular rates and ground speed components.

In order to update the air density value (collective function!) temperature was acquired by means of a resistive probe. The static pressure was taken from LASSIE which was used as airspeed reference as well (figure 5-2d). For a short period of time a Laser-Doppler-Anemometer (LDA) at DFVLR Oberpfaffenhofen could be used as reference system as well. All data provided by the afore mentioned equipment have been sampled with 10 Hz. For on-board signal acquisition the MUDAS[8]-System on board of the test vehicle was used. It provides all data in the ARINC 429-format recorded on a cassette. For quick look purpose the most important signals were sent via the telemetry in parallel to the recording. The helicopter parameters weight and center of gravity are measured only once and the weight change due to fuel consumption has been calculated off line using the readings of the fuel indicator. QNH, wind speed and wind direction were available at irregular intervals from the tower resp. the Laser Doppler Anemometer.

5.3. Flight Test Phases

Due to the fact that there was neither an operable analytical TAS system nor reliable results of the control characteristics of the test vehicle available the first trials were structured to determine the characteristics of the BO-105 by adequate measurements. Appropriate flight profiles have been defined for that purpose in close cooperation with the DFVLR test pilots.

After having analysed the data collected during the first part of the trials and subsequently having developed LAASH, the second part of the trials was dedicated to the calibration of collective, longitudinal and lateral control against true airspeed resp. sideslip angle. The lever calibration could be made by using a predetermined sideslip angle and varying the velocity in the relevant range such that with a sideslip interval of 45° eight profiles could be obtained (figure 5-3). For the sake of redundancy most of the profiles were obtained several times.

As mentioned above the flight trials were carried out at the DFVLR area. The majority of the individual flights have been flown at a flight level of 50 feet above the runway to avoid ground effects and possibly to use the runway as reference line for sideslip determination. All data recorded during this phase of the trials have been analysed off line.

The third test phase comprised the complete system verification including software implementation and on-line computation. The corresponding algorithm had been integrated into the LHN 81 software. As the model has been amended with proper cut-off-algorithms the accuracy for dynamic flight phases could be very much enhanced.

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[7] LITEF Helicopter Navigator 81 see |LI86|

[8] Modular Universal Data Aquisition System

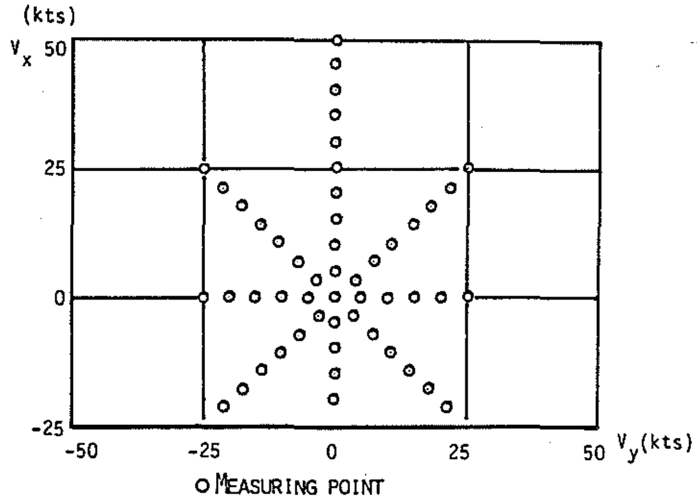

Fig. 5-3 Velocity Diagram-Testphase 2

5.4. Flight Test Results

As seen in figure 3-3 the measured values are symmetrically distributed. Probably a complete description of the control lever characteristics is provided. The discrete collective data reduced to standard values have been plotted in figure 5-4. The solid line represents the result of a linear approximation via an adjustment, at what the linearity of that function has been proven before by a so called identity test. In the same way the air density resp. weight influence on the collective control has been tested. Computations show little sensitivity to changes of weight and/or air density such that the collective equation (4.1) has to be corrected if the helicopter's weight has been changed by approximately 75 kg or the flight level by 350 m.

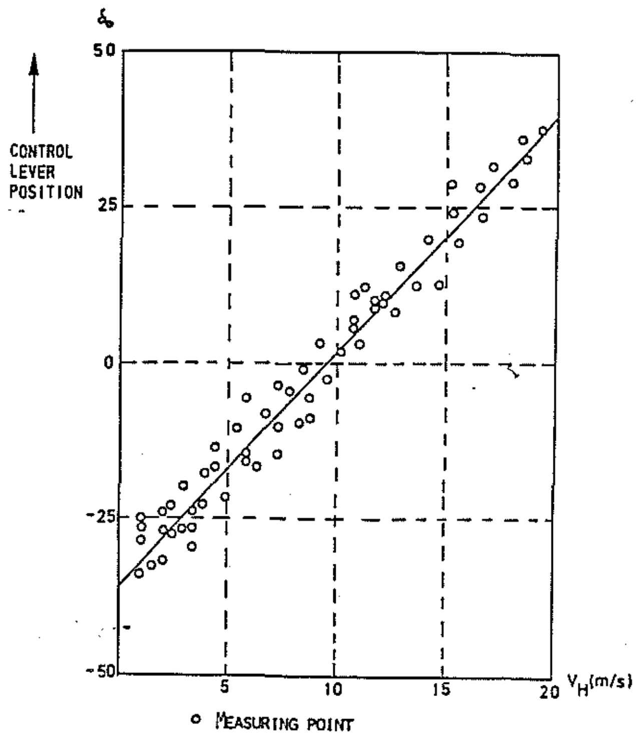

Figure 5-4 Approximation Collective versus
True Airspeed / BO 105

The attitude could possibly contribute to an analytical system. Figure 5-5 disapproves this idea because the pitch angle Θ versus speed proves not to be sensitive enough. The useful sensitivity range of the roll angle is limited to ± 5 m/s. Outside this range the roll angle does not provide information which could be used for TAS determination. It is insensitive as is the pitch angle.

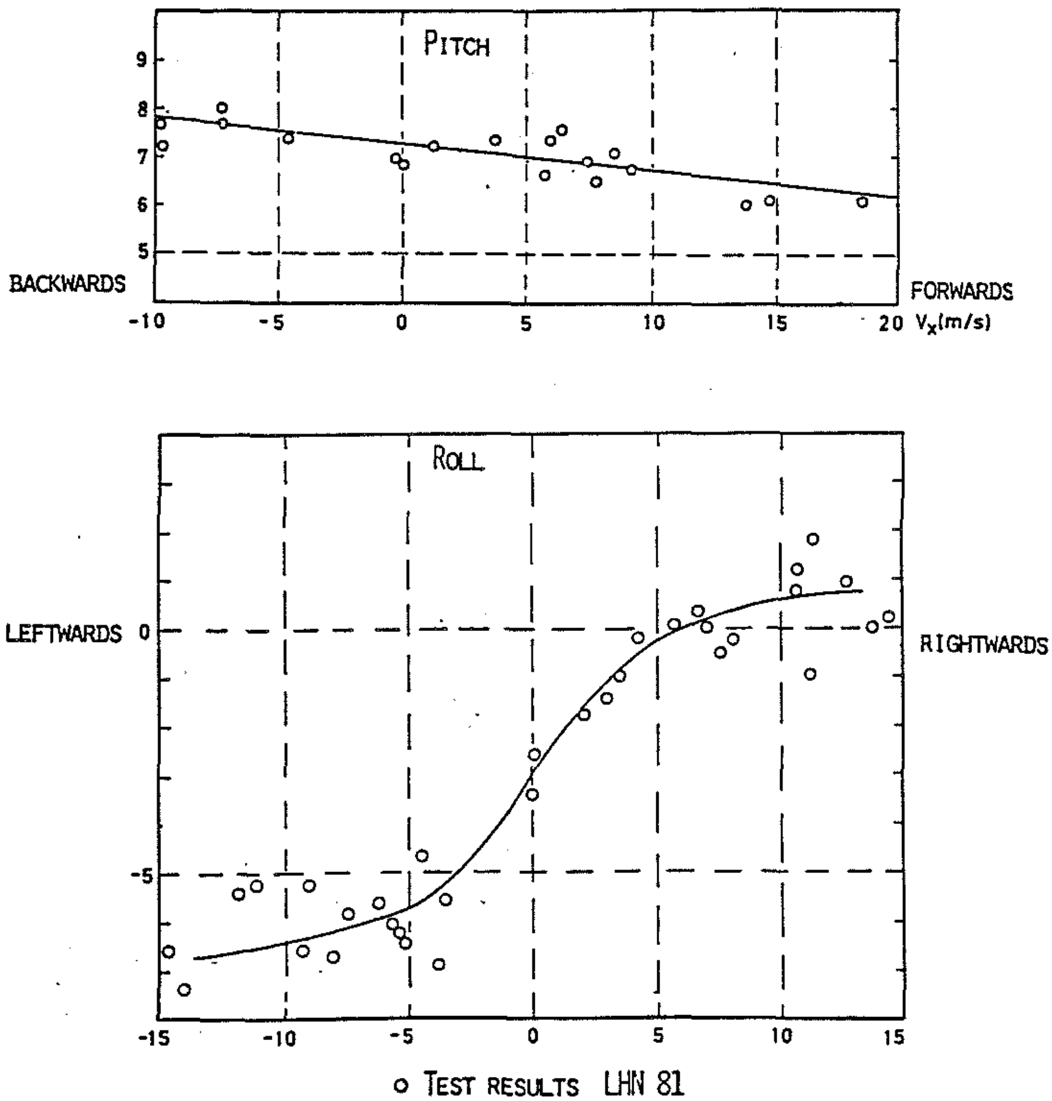

Figure 5-5: Helicopter Attitude / BO 105

The validity and accuracy of LAASH has been demonstrated under various conditions. Figures 5-6 a-d illustrates estimation errors during arbitrary steady state flight periods. Generally the error is less than 2 m/s. Based on all steady state flights the LAASH accuracy can be stated to be within 2.5 m/s (95%). Due to the occuring noise it is advisable to smooth the output data by a properly designed filter.

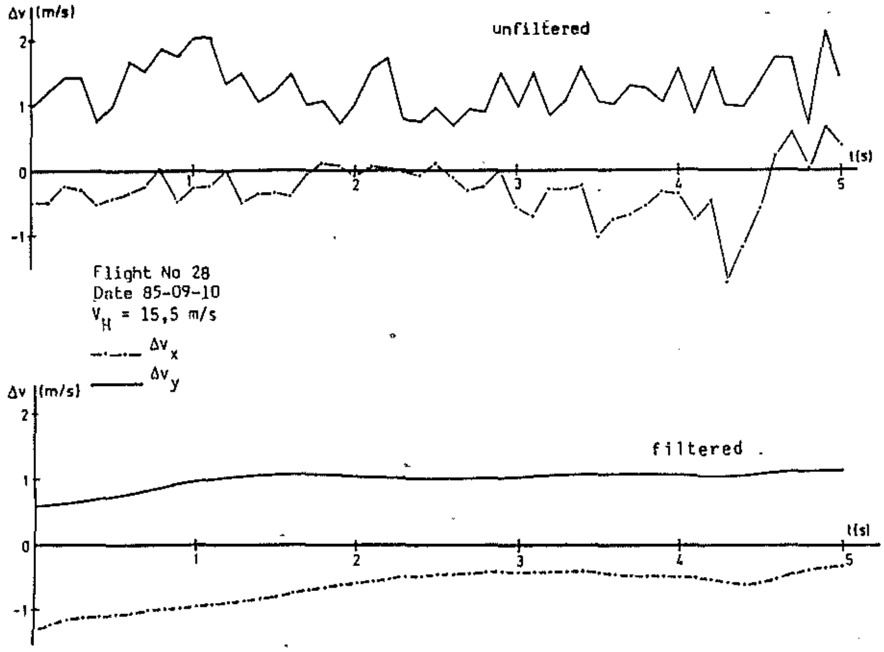

Figure 5-6a LAASH Performance 0° Sideslip

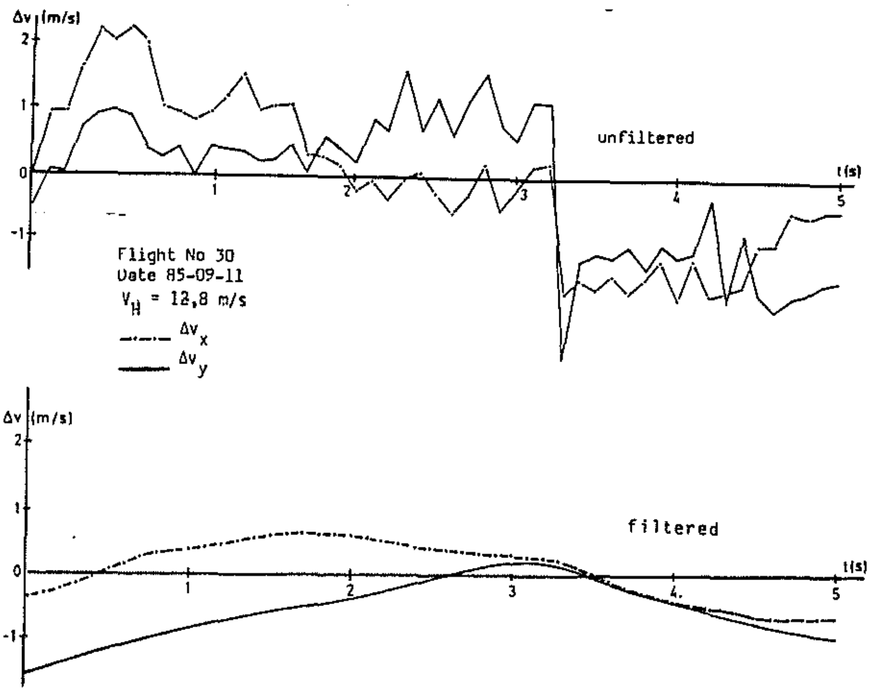

Figure 5-6b LAASH Performance 90° Sideslip

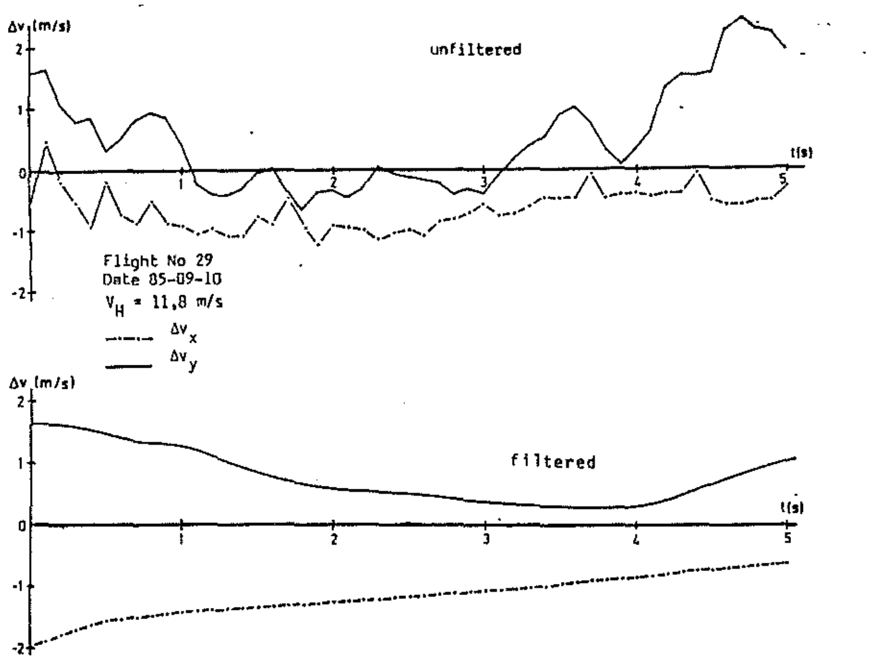

Figure 5-6c LAASH Performance 180° Sideslip

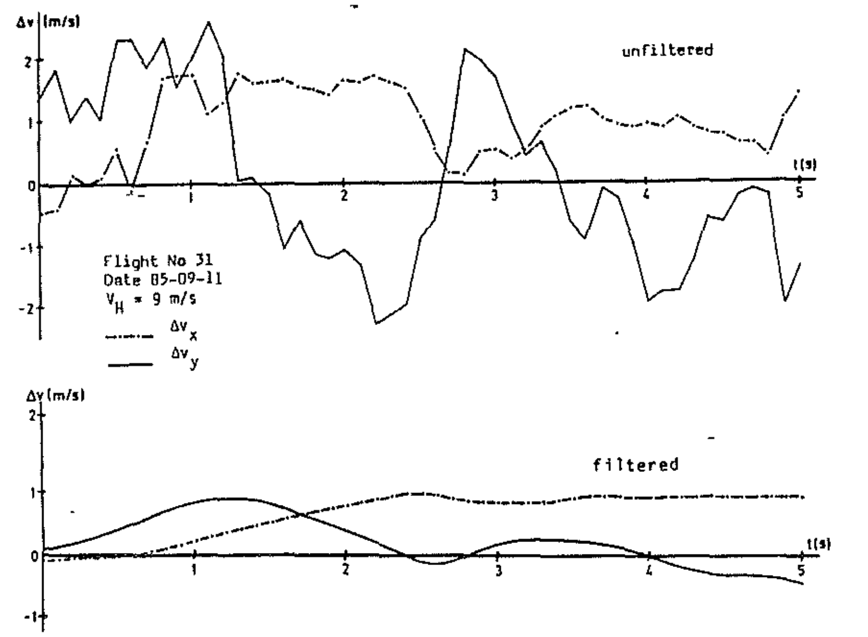

Figure 5-6d LAASH Performance 270° Sideslip

Figure 5-7 demonstrates the LAASH accuracy and validity under dynamic and high speed conditons. If the speed however exeeds 20 m/s this is detected and the normal LAASH algorithm is interrupted for the time of excursion and the TAS calculation is then substituted ground speed and last remembered wind.

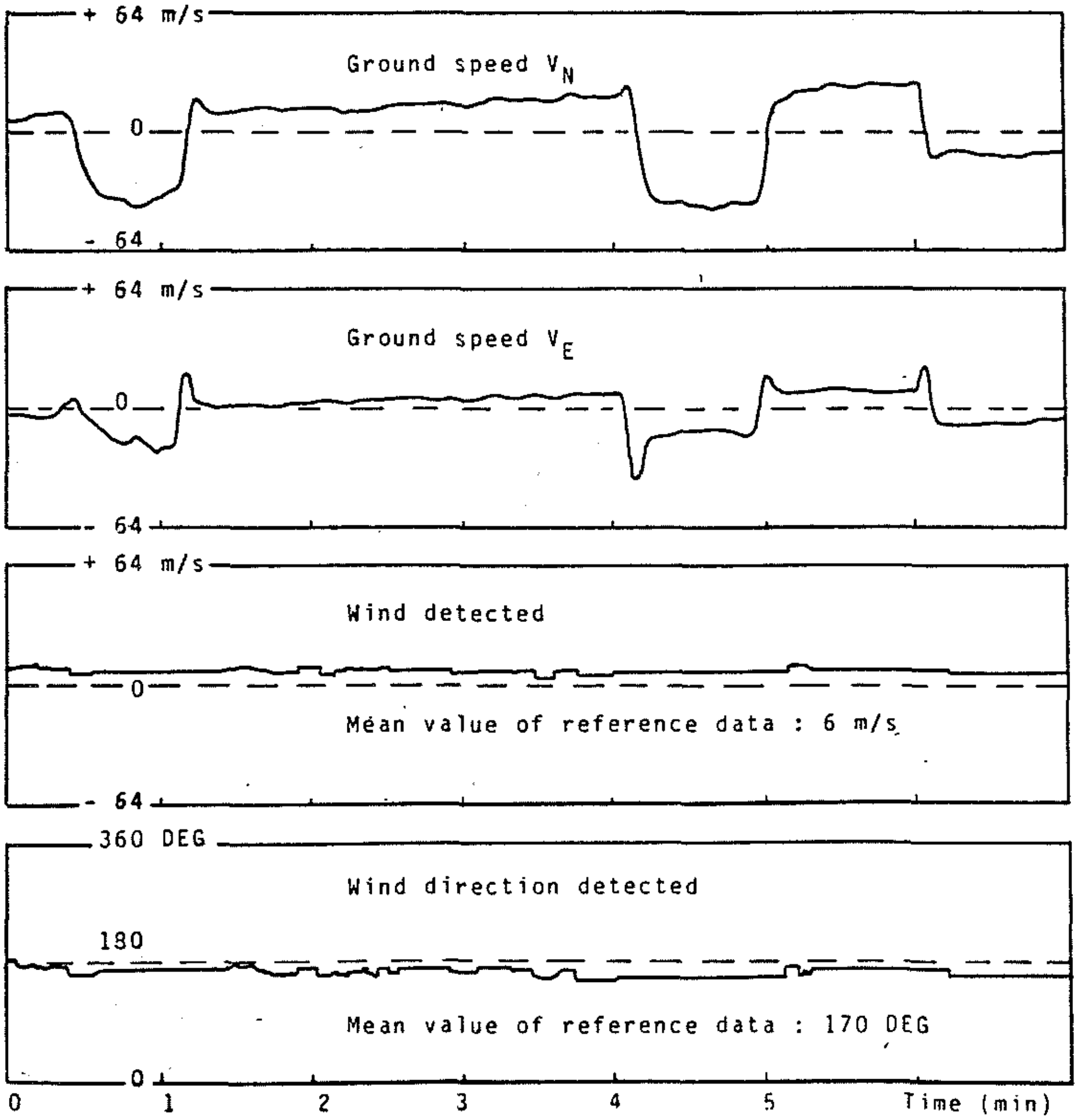

Figure 5-7 LAASH Results under Dynamic Conditions / BO 105

6. Conclusions

A new method of TAS determination for the low speed regime of helicopters has been designed and the validity and accuracy of the method developed has been verified by a series of flight trials.

7. Acknowledgements

The authors wish to express their thanks to all participants of the various flight test campaigns and especially to the involved members of the Institut für Flugführung der DFVLR in Braunschweig and the Institut für Optoelektronik der DFVLR in Oberpfaffenhofen.

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