THE DESIGN AND EVALUATION OF THE EH101 MERLIN HELICOPTER SIDESLIP CALCULATION MODULE

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Abstract

This paper details the design and evaluation of a sideslip calculation software module specifically developed for the EH101 Merlin helicopter. The sideslip module is used in the calculation of wind speed and direction. This wind information is vital to enable the pilot to hover and carry out Anti Submarine Warfare (ASW) missions whilst operating in adverse weather conditions at sea.

Introduction

With the ever advancing integration of avionic systems, software algorithms can be used to condition and calculate a much wider scope of information than has previously been possible. In some instances use of software algorithms makes it possible to replace certain sensors with software code embedded in an Aircraft Management System (AMS).

Initial investigation into the use of an omni-directional air data sensor highlighted that the aerodynamic characteristics of a large airframe, the size of the EH101 helicopter, was not fully compatible with such external sensors. The sensor was designed to provide longitudinal and lateral True Air Speed, (TAS-X and TAS-Y). The TAS-Y element being important to minimise non-wind sideslip errors in the Wind calculation. Thus an alternative wind speed and direction calculation method was required which only relied on TAS-X from a conventional digital Air Data System (ADS), and fixed Pitot tube. The question then was how could the required accuracy of wind calculation be achieved without a sensed lateral airspeed (TAS-Y)? After further investigation it was found that a software driven approach would be the most appropriate.

Helicopter Flight dynamic Model

The initial step to formulate a workable algorithm, was to use a mathematically defined model of the EH101 helicopter. This model is capable of simulating the flight characteristics of the helicopter, by computing the forces and moments that act on the helicopter. These forces and moments are computed in absolute terms to provide a fully representative model capable of continuous operations over a limited flight envelope.

Basic Equation Reference Frames The basic operation of the model utilises a set of 'fixed in space' reference axes. These axes permit six degrees of freedom, (three translation and three rotational) with its origin at the helicopters centre of gravity. A second movable axis can be superimposed onto this reference axis. Onto this movable axis fundamental equations of motion are applied. To represent aircraft forces specific aerodynamic effects, accelerations, velocity, rotor effects, airframe drag and aircraft control laws are applied. By applying these dynamic forces to the movable axis, and monitoring the change in 'spatial position' as compared with the reference axis the 'effects' of these applied force can be monitored.

The helicopter equations described above

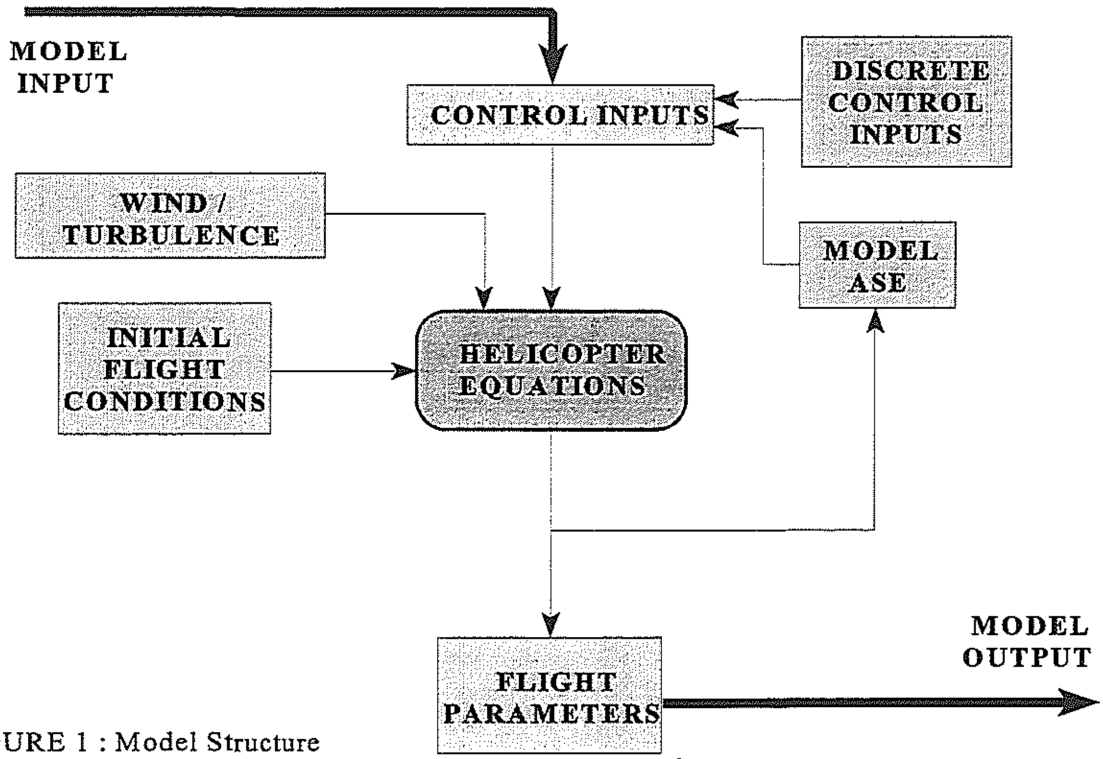


FIGURE 1 : Model Structure

are contained within the models structure as shown in figure 1. Additional effects are applied, including discrete control inputs and model auto-stabilization to account for realistic helicopter flight dynamics and provide certain simulated conditions.

Limiting Factors During a limited amount of flight scenarios, the flight dynamics of the helicopter may become non-linear in nature. The model can not account for this behaviour, therefore to maintain accuracy the model was limited to simulate the helicopter in trimmed straight and level flight with small angular and linear accelerations and limited pitch and roll and be above 60 knots of airspeed.

Model Data Output The output from the computer model yielded vast amounts of data. After an extensive assessment period a complex algorithm emerged. This algorithm, which contained a large amount of terms and dependancies could be used to produced an accurate solution for TAS-Y. However, in its present form, it was not suitable for implementation into the AMS and would require simplification.

Each data term and dependancy was therefore evaluated to establish its individual influence and significance on the algorithms output accuracy. After an initial sensitivity analysis of a small number of cases, combined with advice from the Aerodynamics department the parameters with the most affect on TAS-Y output accuracy were:-

a) All-Up-Weight (AUW) of the aircraft (in the range of 11500 Kg to 14290 Kg).

b) Centre of Gravity (Fore/Aft and lateral), (CofG).

c) True Air Speed (TAS). Investigated in the range of 60 to 180 knots. These ranges are the minimum and maximum TAS values of the model.

d) Relative Air Density (σ). Investigated in the range of 950 to 1040 mbar. This σ range incorporates the extreme operation limits of the EH101.

Rationalization of the Algorithm The output from the sensitivity analysis showed that the four dominant terms, if incorporated, should be able to produce a simplified algorithm suitable for implementation in the AMS. The resulting algorithm should also be within the target accuracy of 2 knots.

In order to combine the four dominant terms, the original computer model algorithm was taken and analysed, but no reduction in its complexity was possible. This eliminated the possibility of using a simplified version of this algorithm.

Matrix of Tests Analysis

A new relationship linking the four terms was required. Using the computer model data the relationships between the four dominant parameters and the sideslip of the aircraft was investigated and an estimation formula for TAS-Y was found.

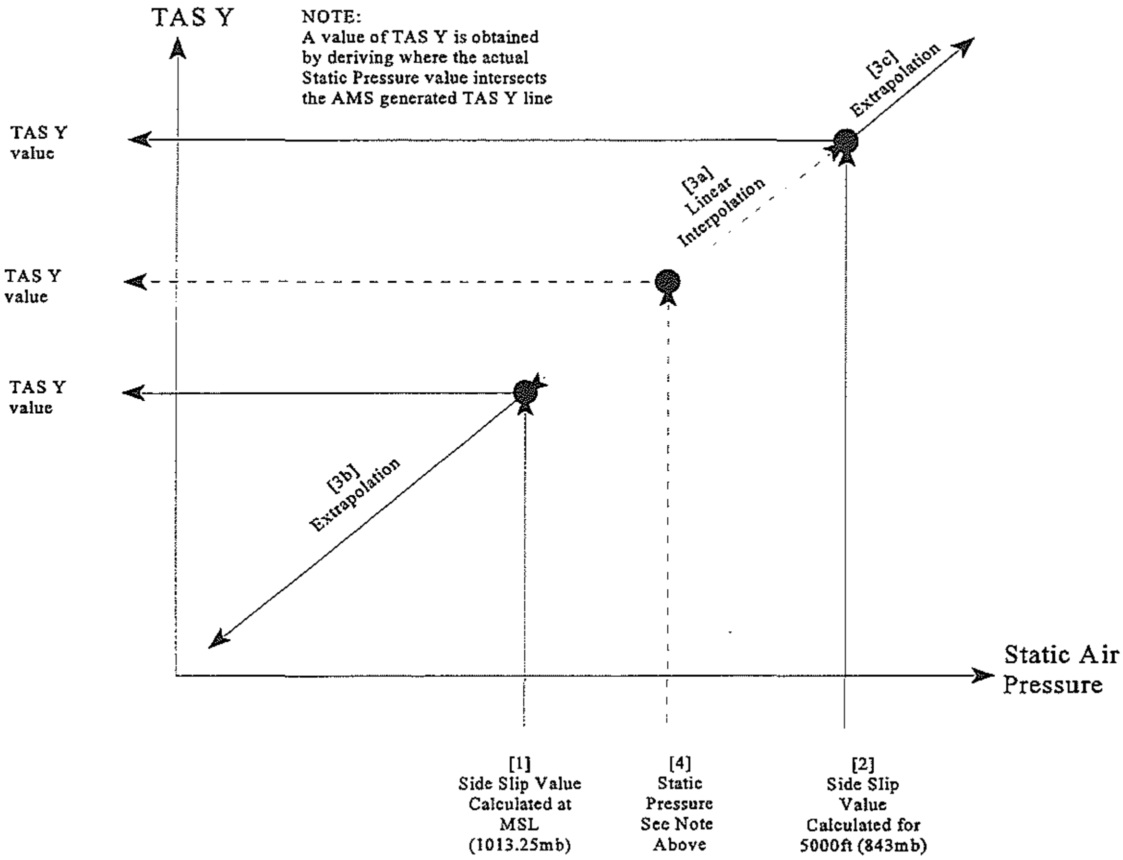
The analysis of the model data was divided into two sections, the un-loaded aircraft case with no external stores fitted and the loaded aircraft case when the aircraft is fitted with external stores in various configurations.

Unloaded Aircraft The first analysis concentrated on an investigation into the aircraft performance when no external stores were fitted. The fore/Aft Centre of Gravity (CofG), on the aircraft centerline was analysed to determine the characteristics of the aircraft without stores fitted.

The data from the model was entered into a Lotus 1-2-3 spread sheet and used to derive an estimation formula which takes into account all the dominant parameters. Initially altitudes up to 15,000 ft were considered, but the variation of TAS-Y at this height is difficult to model. The upper altitude was reduced to 5000 ft. True Airspeeds from 60 to 160 knots were considered initially, but it was found that TAS-Y was difficult to model below 80 knots.

The output graphs from this investigation were used to determine the relationship between TAS-Y and each of the dominant parameters. The relationships obtained showed that TAS-Y decreases linearly with increasing AUW except at very high altitudes and the TAS-Y decreases linearly with forward CofG. Also σ increases exponentially with increasing altitude, but as the absolute air temperature rises the increase of σ reduces. Therefore at higher altitudes the TAS-Y was found to be more sensitive to changes in air density.

These relationships were amalgamated but found to require two initial formulae, the first was derived for a pressure altitude at sea level and the second for a pressure altitude at 5,000 ft. The two formulae were derived from the models output data. The data was analysed graphically to assess basic trends. As noted above the relationships between AUW and TAS-Y, CofG and sideslip were linear. Linear regression was used to determine the coefficients for these relationships. Further linear regression yielded cross terms involving TAS, AUW and CofG.



1. Calculated TAS Y value based at MSL
2. Calculated TAS Y value based at 5000ft
3. Calculated TAS Y from either:-
   a) Linearly interploated between values obtained in 1&2
   b) Linearly extrapolate beyond the value obtained in 1.
   c) Linearly extrapolate beyond the value obtained in 2.
4. Actual TAS Y value is obtained by deriving where current Static Pressure value intercepts the generated line.

Figure 2 - Graphical Representation of AMS Generated TAS-Y Calculation

The exponential and polynomial terms in TAS and σ were assessed by eye from graphs produced from the aerodynamics model data. The best fit was found to be a polynomial in TAS^4 and an exponential term of $e^{1.43\sigma}$. Finally the coefficients were fine tuned using least squares residual error reduction with the model data being used as the datum.

To derive an intermediate pressure altitudes the TAS-Y can be calculated by linear interpolation. Outside this range it can be calculated by extrapolation, however at high altitudes the calculation tended to underestimate the actual TAS-Y. After a refinement process the algorithm gave a reasonably accurate predictions of TAS-Y up to 10,000 ft by linear extrapolation and after some adjustments also performs reasonably well down to airspeeds of 60 knots. Figure 2 shows graphically the calculation process.

The resulting equations that are suitable for implementation into the AMS are as follows:-

Mean Sea Level (1013 mbar) ISA conditions

$$\textbf{TAS-Y} = \text{CofG}\{0.03 . \text{TAS} - 1.6\} - \text{CofG AUW}\{3.14 \times 10^{-7} . \text{TAS} - 6.79 \times 10^{-6}\} - \text{AUW}\{3.69 \times 10^{-8} . \text{TAS} + 2.39 \times 10^{-5}\} + \text{TAS}\{2.2 \times 10^{-9} . \sigma . \text{TAS}^3 + 3.0 \times 10^{-5} . \text{TAS} . e^{1.43\sigma} - 0.02\} + 6.77$$

5,000 ft (843 mbar) ISA conditions

$$\textbf{TAS-Y} = \text{CofG}\{0.023 . \text{TAS} - 1.2\} - \text{CofG AUW}\{3.15 \times 10^{-7} . \text{TAS} - 8.0 \times 10^{-6}\} - \text{AUW}\{1.32 \times 10^{-7} . \text{TAS} + 5.4 \times 10^{-6}\} + \text{TAS}\{8.4 \times 10^{-10} . \sigma . \text{TAS}^3 + 7.0 \times 10^{-5} . \text{TAS} . e^{1.42\sigma} - 0.022\} + 4.80$$

Loaded Aircraft The second aircraft performance that required consideration was when external stores and a mission console were fitted. The 'loaded' case was analysed to determine the effects of weapon loads and the stores sponsons. As weapons are placed on the aircraft the lateral CofG changes as well as along fore/aft CofG as for the unloaded aircraft case.

To establish how the aircraft TAS-Y was affected by its external stores, additional information was enter into the model, ie weight and drag coefficients of the stores and stores sponsons. Typical stores investigated included Stingray and Depth-charge. It was found that the drag characteristics of the Royal Navy (RN) stores were negligible although a small aerodynamic drag was produced by the stores sponsons.

After investigation of the basic unloaded aircraft equation it was found that an additional drag constant would have to be included for the fitment of the store sponsons.

For the loaded aircraft the basic computer model was again used, with the addition of a lateral displacement of the CofG away from the aircraft centerline, to represent weapon loadings, and some aerodynamic drag due to the stores sponsons. An additional correction was also required to account for the change in CofG when a mission console was fitted. A number of conditions were run on the model and it became clear that, for fixed TAS, AUW, Fore/Aft, CofG and σ, TAS-Y varied linearly with the moment of weight about the aircraft centerline. In addition to this it was noted that the AUW and position of the Fore/Aft CofG did not affect the gradient of the moment of weight - TAS-Y line.

Further linear interpolation and least squares error calculation produced the following correction. This should be added to the TAS-Y calculated for the unloaded aircraft when the store sponsons and stores are fitted as these contribute to the AUW of the aircraft:-

Correction = $(1.21 \times 10^{-6} . TAS + 0.00015 . \sigma - 0.00055) \times$ moment of weight.

Initial Verification of TAS-Y algorithm

To initially test that the TAS-Y output would provide the required accuracy under aircraft flight conditions, data from three flights were used to verify the TAS-Y algorithm and also to tests the likely accuracy of the overall Wind module. The flights used were not dedicated flights although the opportunity was taken to gather the data for off-line analysis. The main development Merlin helicopter was used to conduct these flights which took place over Lyme Bay, Dorset and at the Aberporth range, Wales.

To obtain a reference source of airspeeds the original helicopter probe was used. This probe provides both TAS-X and TAS-Y. During the flights, additional data was also monitored including groundspeed, heading, attitudes, temperature and pressure. To provide an external surface wind speed and direction reference, different datum's were used during each flight. During the Lyme bay flights, a visual estimate of the surface wind speed and direction was used from the pilot, whilst during the Aberporth range trials, meteorological weather buoys situated throughout the test location were used.

It should also be noted that the accuracy of the several reference wind speed and direction source used during the flights was at times un-reliable. This unfortunately reduced the amount of data that was available for analysis.

Off-line Analyses of Flights The gathered flight parameters were input into the TAS-Y algorithm and the results were then combined and compared with the reference data.

To determine the aircraft's wind speed and direction the aircraft's ground speed was subtracted from its true airspeed. Using earth referenced axes as the common reference frame the wind direction and magnitude was determined.

To convert the aircraft wind speed and direction to the surface wind speed and direction, a simplified form of an Eckman Spiral windshear algorithm was used. This is used to estimate the direction and strength of the wind at the surface from wind values calculated at the aircraft altitude. This Spiral is also dependent upon the latitude and height of the aircraft. The complete algorithm is very complicated with many terms. For implementation in the AMS this was simplified. This simplification was used in the wind calculations although slight errors may be introduced as the algorithm does not account for changes in weather systems.

Initial Trials Conclusions From the three flight trials conducted to establish the accuracy of the TAS-Y, a reasonable correlation in results was observed that was within the design specifications. Analysis of the wind data from the flight trials showed that from the limited data available, the overall Wind module output would be capable of providing the required design accuracy if it was implemented in the AMS. The results also indicated that with an improved datum wind speed and direction measurement technique the observed error will probably reduce. It was therefore recommended that dedicated flight trials be performed to assess the Wind Module accuracy.

Software Implementation of the Wind Module The results from this initial testing phase showed that the TAS-Y calculation is capable of providing the wind module with an accurate source of TAS-Y to enable the wind speed and direction to be calculated. These calculations were conducted off-line using recorded aircraft parameters. It was therefore necessary to implement the Module into a 'real' AMS and flight test it. The final Wind Module implementation is shown in figure 5 at the end of the report.

The TAS-Y wind calculation was implemented into the wind module in the Italian variant EH101 AMS. Initial Full System Integration Rig (FSIR) testing showed that several 'bugs' existed in the initial software release. These problems were fixed and implemented into flight worthy AMS software.

In order to evaluate this software release, a second FSIR testing session was conducted. The results of these tests indicated that the TAS-Y algorithm was functioning correctly and after initial evaluation of the complete Wind module it appeared to be functioning in accordance with the Software Requirement Specification.

Dedicated Wind Module Accuracy Trials

To evaluate the accuracy of the overall wind module, dedicated aircraft trials were conducted in Northern Italy. In order to provide an accurate wind datum on which to assess the wind modules outputs the trials were conducted using a ground station consisting of a highly accurate ground base wind profiler to determine wind at altitude and a standard anemometer and wind vane mounted on a 5 metre pole to determine surface wind. The wind profiler can determine the average wind speed and direction up to a maximum height of 3 km. The anemometer and wind vane provided instantaneous surface wind speed and direction measurements.

Dedicated assessment flight were conducted on an Italian variant of the EH101 on 30th July and 1st August 1996 respectively. The EH101 helicopter was flown above this wind profiler at varying speeds and heights in an elongated "figure of eight" profile. Aircraft and wind ground station data output was captured and logged during these manoeuvres ready for analysis post flight.

The aircraft's data was recorded using an onboard data acquisition system. This system stores aircraft data in time slices, between event markers, which contained aircraft data relating to a specific run.

Reference Wind Datum The datum test equipment consisted of a REMTECH wind profiler for wind direction and speed measurements at altitude and a Weather Wizard III system which provided surface wind speed and direction measurements. To provide a radio link from the ground station to the aircraft a suitable V/UHF radio set was used. To synchronize the

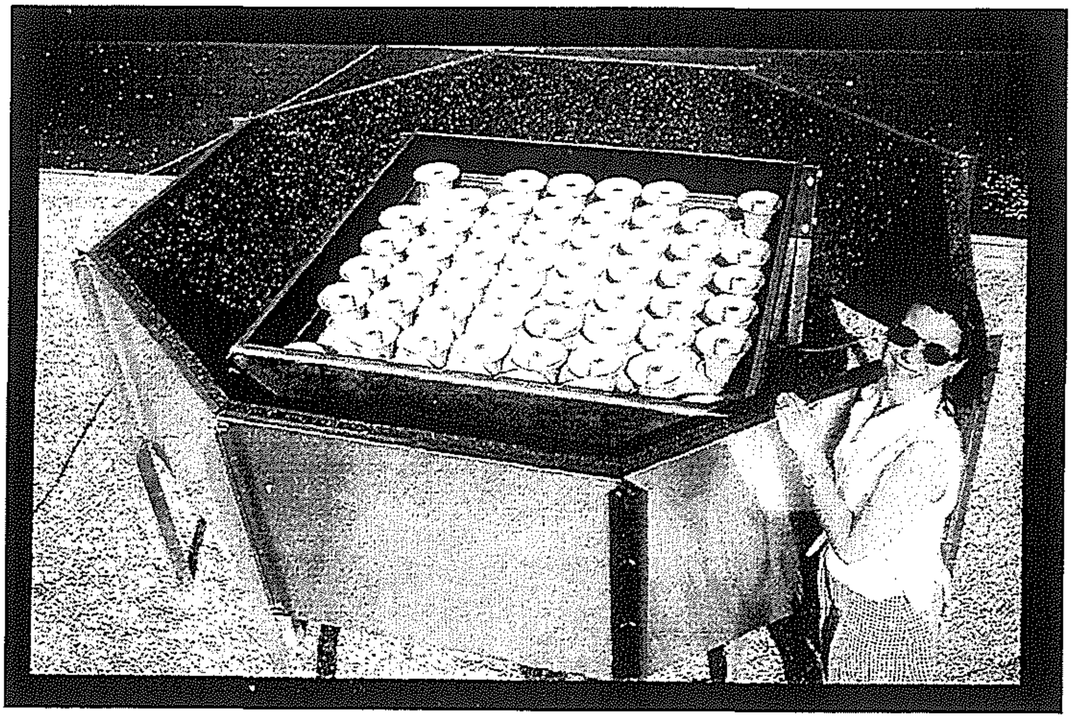


Figure 3 : REMTECH PA1-LR

datum measurements with the aircraft's acquisition data, the aircraft's GPS and a hand held Magellan GPS were used to provide UTC time.

The REMTECH PA1-LR, shown in figure 3, measures wind speed and direction, vertical motions and turbulence at the test area at user defined height intervals up to a maximum height of 3000 metres. This is accomplished by emitting a strong acoustic pulse into the atmosphere. The frequency shift of the echo varies according to the wind speed. By processing this frequency shift the wind direction and velocity can be measured at different altitudes, giving a wide range of parameters. The wind profiler consisted of two main parts:- a single antenna (phase array type) and an electronic cabinet containing the computer, transceiver and power amplifiers.

The antenna uses a single / multicellular antenna composed of 52 elements whose beams are steered electronically. Using these steerable beams both the horizontal and vertical components of the wind velocity can be found.

In order to reduce background noise, the transmitted pulses are coded into five frequencies in the pulse. Using software the return signals can be decoded, thus reducing background noise.

Weather Wizard III The DAVIS INSTRUMENTATION Weather Wizard III system combines the use of an anemometer, wind vane and temperature sensor to provide a comprehensive surface weather station. The measurement sensors are mounted on a standard 5 metre pole to minimise ground shielding effects. The heart of the system is the control display and computer which integrates the outputs from the measurement sensors and combines this information into a readable display. This control unit can be connected to a laptop computer so its data can be recorded.

Location of Trials A suitable location was to be found to perform the tests. This test site, the Cameri aircraft Base, just north of Milan was a large, flat, open space, with predicted low levels of background noise. This location was chosen to gain the best performance from the reference wind equipment.

The wind profiler was initialised prior to the trial and data was gathered 3 hours prior to the aircraft arriving. This data was used as a bench mark for the trial and once initialised data was gathered every 30 minutes.

Surface wind speed and direction data was gathered using the Weather Wizard III system, instantaneous measurements were gathered during the trials, although surface wind speed and direction was logged every 1 minute throughout the day.

also seen that several results indicated large wind directional errors. These large errors were not obtained during a specific test period, although it was noticed that during these measurement periods large variations in the wind speed and direction had occurred. As the wind profiler produces an average wind speed and direction measurement for a 15 minute period, if large variations in the wind speed and direction had occurred during this averaging period, the aircraft's instantaneous calculated wind could have a 'perceived' error in this measurement. It was further noticed that during the trials, there was large periods, especially in the mornings, of thundery showers. As mentioned earlier, weather fronts are not

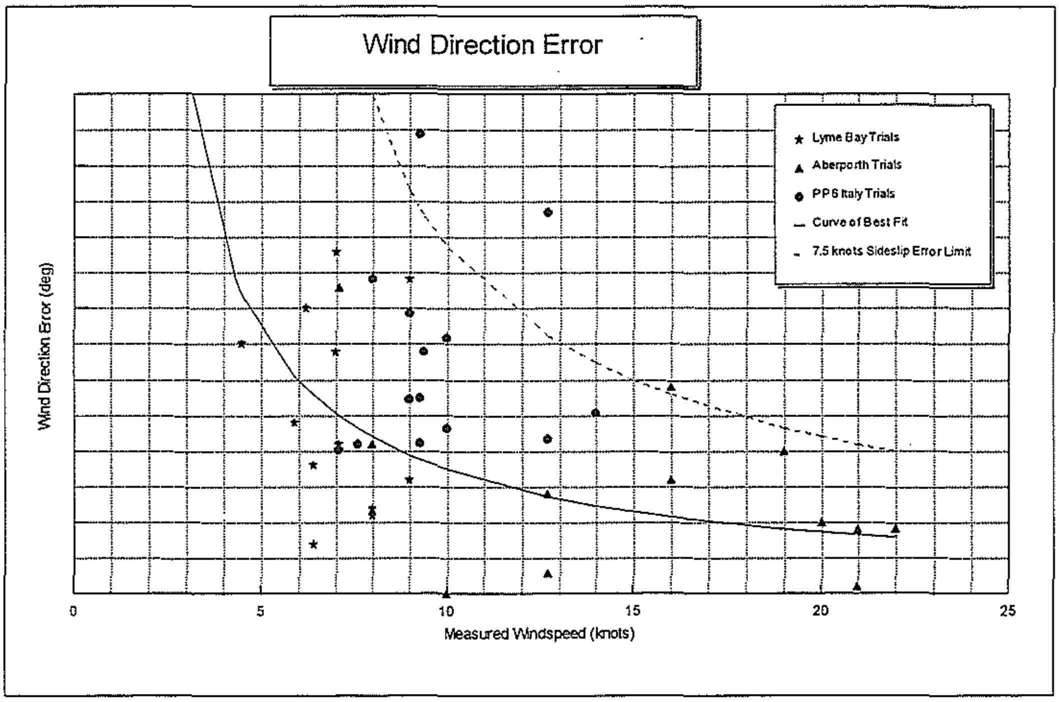


Figure 4: Overall Wind Results

accounted for in the Eckman spiral conversion which could have caused an additional error.

<u>Results and Accuracy of the Wind Module</u>

The results from the dedicated wind trials in Italy were analysed. Generally they showed a good correlation to the previously obtained flight data, indicating that generally the calculated wind was comparable to the measured wind. It was

All the results from the Lyme Bay, Aberporth and Italian trials were combined into the graph shown in figure 4. This shows a good correlation to the measured surface wind speed and direction.

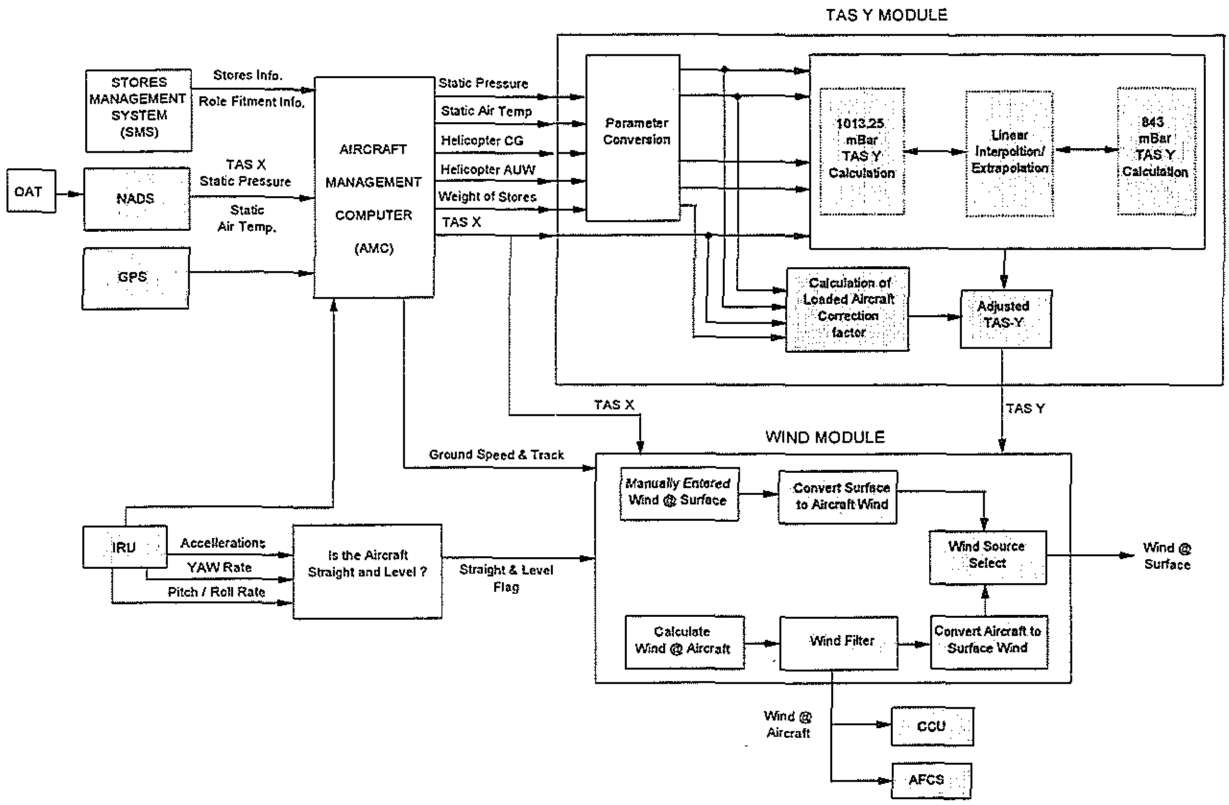


Figure 5 : Final Wind Module Implementation

Conclusion

On comparison of the data the datum wind speed and direction data correlated well with the wind module outputs and were within the defined accuracy limits. This confirmed that the TAS (Y) algorithm was accurately calculating the sideslip of the helicopter within its specified operating limits.

Concluding Remarks

This paper has highlighted several wind measurement techniques used to monitor the behaviour of the wind for use as a datum on which our measurements have been based. From the test conducted, the absolute measurement of the wind has proved difficult to obtain, thus to a large extent the results obtained from the Wind Module assessment have lead to a 'good correlation' with the wind references. Therefore within the wind measurement limitations our assessment of the wind module has proved successful, although the absolute accuracy of its output is still unknown.

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