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EVALUATION OF THE HELICOPTER LOW AIRSPEED SYSTEM LASSIE

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Abstract

To evaluate the airspeed sensing capability and the dynamic response characteristics of the Marconi Avionics helicopter low airspeed system LASSIE, both, flight tests and wind tunnel tests were conducted. The system uses a swivelling pitot static probe designed to operate within rotor downwash in the low airspeed regime and out of downwash for higher speeds. Due to nonlinearities in the sensor transition phase an accurate system characterization is necessary to obtain reliable airspeed data.

Flight tests that were conducted to characterize the system for a BO 105 helicopter are described. The evaluation method and results, showing uncalibrated and calibrated data are discussed in detail.

To investigate the dynamic behaviour of the system, dynamic tests in a wind tunnel equipped with a gust generating system were conducted. LASSIE transfer functions were measured for four different wind tunnel speeds. Representative results are shown and discussed.

1. Introduction

The DFVLR research center in Braunschweig is operating its own MBB BO 105 helicopter (Figure 1). To fulfill the requirements of various research projects the helicopter is basicly instrumented with conventional sensors to measure rigid body accelerations, rates and attitudes, control deflections and performance data. The sensing of airspeed, however, caused some difficulties. Conventional sources of air data, like vanes and pitot static systems cannot be used in the low speed regime and in hover, when the dynamic pressure approaches zero and the fuselage becomes immersed in rotor downwash.

During the recent years various attempts have been made to solve the low airspeed and flow direction measurement problem [1 to 6]. However, only a few systems have been made available as production units. One of these systems, the Marconi Avionics Low Air Speed Sensing and Indicating Equipment (LASSIE) was installed on the DFVLR BO 105 helicopter. (Initially a prototype unit was used which meanwhile has been replaced by a production unit). As the system was only roughly calibrated [7], flight tests were conducted to obtain a more detailed and accurate calibration. A radar tracking system was used as a reference system to measure the actual helicopter position and speed. The flight conditions were level forward flight (from about - 15 to

60 m/sec) at sideslip angles up to 30 degrees.

This report first of all gives a description of the LASSIE system and its principle of operation. Then flight test set-up and data handling are described. The evaluation method and calibration results are discussed in detail. Finally some results are presented that were obtained from an investigation of the dynamic behaviour of the LASSIE system.

2. System Description

The following is a description of the prototype unit that was used for the calibration tests. The production unit has a newly designed smaller sensor and is equipped with a digital computer. A detailed description of this system is given in [8].

The low airspeed system includes a swivelling pitot static probe, an analogue computer (Air Data Converter) and three indicators that present forward, lateral and vertical speed components to the pilot.

The pitot static probe (Figure 2) consists of a standard pitot static pressure head and a tail assembly. It is mounted on two perpendicular sets of bearings. The angular positions of the probe are measured by two synchro resolvers and fed to the Air Data Converter. In addition the total and static pressure are piped to pressure transducers in the converter. Based on these four measured variables the computer calculates forward and lateral airspeed (both, calibrated and indicated), height, height rate, total airspeed at the probe, and the probe angles with respect to the fuselage. The signals are available as electrical signals and can be used for cockpit indicators and any data processing and recording system.

The pitot static probe is mounted on a boom below the main rotor as shown in Figure 3 and 4. It can rotate freely around the pitch axis and it can move around the yaw axis up to ± 60 degrees. Thus the probe is able to align with the resultant flow at the probe location for all flight conditions. This resultant flow is either the aircraft velocity itself for the high speed regime or it is the sum of the aircraft velocity and the rotor induced velocity for the low speed regime when the LASSIE sensor is within the rotor downwash.

3. Principle of Operation

Corresponding to the sensor location within or out of rotor downwash, two basically different flow conditions at the probe must be distinguished:

1. LASSIE sensor out of downwash (Figure 5)

It can easily be visualized that the probe will point into the flight direction and measure the total airspeed $\overline{V}$. Without sideslip the forward and vertical speed components in a fuselage fixed axis system are:

$$u = \overline{V} \cos\alpha$$

$$w = -\overline{V} \sin\alpha$$

With sideslip these equations are extended to:

forward speed $u = \overline{V} \cos\alpha \cos\beta$

sideward speed $v = \overline{V} \sin\beta$

vertical speed $w = -\overline{V} \cos\beta \sin\alpha$

where α and β are the probe angles.

2. LASSIE sensor within rotor downwash (Figure 6)

In the low airspeed regime and at hover standard pitot static systems rigidly fixed to the fuselage fail to work mainly for three reasons

- the dynamic pressure becomes small and is difficult to measure
- the dynamic pressure changes only slightly with speed
- for helicopters the probe is deeply immersed in rotor downwash which renders the measurement unusable.

In contrast to these rigidly fixed probes the swivelling LASSIE sensor is designed to also utilize the rotor downwash because it always aligns with the local flow. This arrangement has the advantage that the sensor will not be required to measure small dynamic pressures.

Figure 6 demonstrates that the helicopter forward speed is given by

$$u = \overline{V} \cos\alpha - V_i \sin i$$

where V_i is the induced rotor velocity

and i is the rotor incidence angle.

The second term $V_i \sin i$ cannot be measured. However, at low airspeed the incidence angle i is small and at high airspeed the induced velocity is small. Consequently, the product $V_i \sin i$ can be neglected and the equation becomes

$$u = \overline{V} \cos\alpha$$

Considering also sideslip the corresponding equations are

forward speed $u = \overline{V} \cos\alpha \cos\beta$

sideward speed $v = \overline{V} \sin\beta$

When the probe is within the downwash it is not possible to measure the vertical airspeed. Therefore LASSIE provides a height and height rate signal, calculated from the static pressure measurement.

Although the equations to calculate the speed components are identical for both sensor positions there is a major difference in the importance of $\bar{V}$ and α (or β). Figures 7 and 8 show the dependence of the dynamic pressure ($P_{dyn} = \frac{1}{2} \rho \bar{V}^2$) and the probe angle α on helicopter forward speed: When the sensor is within the downwash changes in the dynamic pressure with respect to forward speed are relatively small in comparison to changes in the probe angle with forward speed. For the high speed regime the situation is opposite: the probe angle is almost constant but there is a significant change in the dynamic pressure with speed. This indicates that the low speed measurement is mainly based on the probe angle signal whereas higher speed is measured using mainly the dynamic pressure signal.

As a consequence of this fact and, in particular, of the complex flow in the downwash, there are three essential LASSIE characteristics that become obvious when speed components, obtained from LASSIE, are plotted versus reference speed data, obtained from radar tracking: (Figure 9)

1. There is a significant discontinuity when the LASSIE sensor enters or leaves the downwash (sensor transition phase).
2. The slope of the LASSIE versus reference speed curve is different for the low speed and high speed regime.
3. Both, the speed where the discontinuity occurs and the slope of the speed curve depend on the combination of helicopter forward and sideward speed.

When the LASSIE speed calculation is only based on the above given equations large errors particularly in the sensor transition phase cannot be avoided and it is necessary to apply additional corrections. In order to determine these corrections a flight test program to "characterize" the LASSIE system was conducted.

4. Flight Tests and Data Handling

For the flight tests a matrix of various steady state level flight conditions was defined by varying helicopter speed and sideslip angle. The speed was changed from -15 up to 60 m/sec in steps of about 5 m/sec and the sideslip angle was varied from -30 to +30 degrees in steps of 10 degrees. To conduct the tests the helicopter followed a straight and level flight path.

The requested flight condition was adjusted by the pilot. Each run (matrix element) was flown at least twice in opposite directions to evaluate or partially compensate wind influences. About 200 runs were flown with an average run duration of about 30 seconds.

Data recorded on magnetic tape were obtained from two sources:

1. Data measured on board the helicopter were transfered to the ground by telemetry. These were in particular: helicopter heading, pitch and roll attitudes, aircraft rates and linear accelerations and all data provided by LASSIE.

2. A ground-based radar was used to measure helicopter position.

Data were sampled at 20 Hz; the radar data, however, could only be measured with a sampling frequency of 1 Hz.

Wind speed and direction were measured with a recording anemometer. In order to reduce wind influences an attempt was made to conduct the tests when there was practically no turbulence and wind speed did not exceed 5 kts.

The main data processing steps for both, LASSIE and radar data are shown in Figure 10:

1. LASSIE data
   a) Helicopter speed components were calculated from LASSIE measurements using the above equations (helicopter body fixed axis system).
   b) LASSIE probe angles were extracted from their measured sine and cosine functions.

2. Radar data
   a) Helicopter speed components in an earth fixed axis system were calculated from position measurements.
   b) Speed components were transfered to the helicopter body fixed axis system.

Originally it was planned to correct the air data for wind influences. However, wind measurements and the analysis of flights, flown in opposite directions, showed that no significant wind or turbulence influences could be detected.

Each run was divided into 4 seconds segments (Figure 11). For these segments the mean value for each variable was calculated and stored for further evaluations. Thus the amount of data decreased and the effect of scatter in the radar data was reduced. (The LASSIE data proved to be practically constant within a run).

5. LASSIE Characterization

The objective of the LASSIE characterization is the elimination of systematical measurement errors. They are mainly due to different characteristics in the low and high speed regime, leading to the discontinuity in the sensor transition phase and to different characteristics with increasing sideslip.

Therefore the characterization includes three major steps: The determination of the sensor position with respect to the downwash, the error analysis, and the correction of the measurements.

5.1 Determination of the sensor position with respect to downwash

In Figure 9 it has already been shown that there is a significant discontinuity in the speed measurement during the sensor transition phase. Therefore data obtained from the LASSIE probe have to be treated separately according to the sensor position with respect to the rotor downwash. A method to determine if the sensor is within or out of downwash is based on LASSIE measurements $\overline{V}$, α and β:

Small successive ranges of β were defined. For each of these ranges $\overline{V}$ was plotted versus the probe angle α. Figure 12 demonstrates that two different sets of data can be distinguished:

a) $\overline{V}$ changes significantly whereas α is almost constant. Consequently the probe is out of downwash.

b) $\overline{V}$ changes slightly and there is a large α range. Obviously the sensor is within downwash.

It proved to be relatively easy to identify the sensor transition phase in terms of α and β from these plots. (For higher sideward speed corresponding plots of $\overline{V}$ versus β must be used). The results obtained are summarized in Figure 13.

5.2 Error analysis

As the combination of different helicopter forward and sideward speed also influences the errors of the LASSIE speed measurement, errors have to be analysed for various flight configurations. To evaluate the forward speed the following technique was used: small successive ranges of LASSIE sideward speed v were selected. For each of these ranges LASSIE forward speed u was plotted versus reference (radar) speed u_R. Simultaneously, these data were separated into two groups, using LASSIE α and β measurements:

1. Data obtained from the sensor within downwash

2. Data obtained from the sensor out of downwash.

For each of these groups a first order regression analysis was calculated. From these, a set of equations for $u = f(u_R)$ was obtained. Considering that without any errors the speed obtained from LASSIE must be identical to the radar measured speed, the errors of the equations $u = f(u_R)$ can be calculated. Each of the resulting error equations belongs to a specific (uncorrected) LASSIE sideward speed and to a LASSIE sensor location (with respect to rotor downwash).

The analysis of sideward speed measurements is conducted in a corresponding way.

5.3 Measurement corrections

The obtained error equations are used to correct the basic LASSIE calculated speed. An example of corrected data is presented in Figure 14. In comparison to Figure 9 it is demonstrated that the discontinuity in the sensor transition phase as well as differences in the slope could be removed.

6. LASSIE Characterization Results

The LASSIE characterization was conducted for level forward flight with sideslip angles up to 30 degrees. The described method to determine if the sensor is within or out of rotor downwash was applied successfully without any problems. This is also true for the calculation of the error equations and the final corrections of the measured data. For the longitudinal and lateral speed Figures 15 and 16 compare corrected LASSIE data with radar measurements. All data segments (about 2300) are considered. It can be seen that the three main objectives of the LASSIE characterization could be reached:

1. To determine the probe position with respect to downwash.
2. To eliminate the discontinuity in the sensor transition phase.
3. To obtain a constant slope, independent from sensor position and sideslip.

However, there is a relatively high scatter in the data. It is caused by inaccuracies of, both, radar measurement and LASSIE signals. To determine the accuracy of the LASSIE system the standard deviations of the LASSIE speed components were calculated using all data segments. In addition the standard deviations were computed separately for both sensor positions, within and out of rotor downwash. After correcting for the known radar error standard deviation of 1.75 m/sec the following results were obtained (numbers in brackets are without radar error correction):

	forward speed	sideward speed
sensor out of downwash	1.88 (2.57)	1.79 (2.5)
sensor in downwash	1.71 (2.45)	0.97 (2.0)
all data	1.81 (2.52)	1.46 (2.28)

Table 1 LASSIE error standard deviation (in m/sec)

A comparison of the standard deviations shows that the accuracies of both the LASSIE and the radar system are of the same order. However, it is desirable that the reference system be of a significantly higher quality than the system under test itself. When a better reference system is available it should be possible to reduce the high scatter in the data and to further improve the LASSIE accuracy, e.g. by using higher order polynomials for the correction equations.

7. LASSIE Probe Dynamics

The LASSIE characterization was based on steady state flight conditions. In order to also investigate the dynamic behaviour of the sensor, tests were conducted in the DFVLR 3 x 3 m low speed wind tunnel. Two gust generator flaps, driven by an electro hydraulic actuator, were installed at the tunnel outlet. They allowed the generation of various types of vertical gust profiles with different amplitudes and frequencies in the test section.

7.1 Test set-up and conduction

The objective of the tests was to measure the frequency response for the LASSIE probe angles α and β at different gust amplitudes and tunnel speeds. Therefore the LASSIE sensor was installed in the test section together with a differential pressure probe as a reference system (Figure 17). The test conditions included three different gust amplitudes (1.5, 3, and 5 degrees) and four wind tunnel speeds (18, 27, 38 and 50 m/sec). A flow chart of the test set-up is given in Figure 18. During each test the selected tunnel speed and maximum flap angle were held constant. A computer controlled frequency analyser fed a sine wave with a defined frequency to the hydraulic actuator to move the flaps. Both, LASSIE and differential probe measurements of the resulting gust profile were recorded on tape and also fed back to the analyser. After 10 cycles, amplitude and phase relationships of the two measured variables were calculated and stored. Thus 25 different frequencies ranging from 0.2 up to 7.5 Hz were used sequentially. Finally, the obtained frequency response was printed out and plotted in the form of Bode diagrams.

7.2 Wind tunnel tests results

The dynamic behaviour of the LASSIE sensor was investigated separately for the probe angles α and β. However, no major difference in the sensor response could be detected. The following figures are based on β measurements but they are practically identical to those obtained from α measurements.

Figure 19 shows the influence of different gust amplitudes (maximum gust angle 1.5, 3, and 5 degrees) on frequency responses, when the tunnel speed is held constant. Except of some small deviations for the low amplitude (gust angle 1.5 degrees) there is a good agreement which proves that the LASSIE dynamics are virtually independent from gust amplitudes.

Frequency responses obtained from 4 different tunnel speeds are given in Figure 20. The maximum gust angle was 3 degrees. The resonance frequency significantly increases with speed and the peak amplitude increases slightly. The reasons for the relatively high phase shifts of the sensor still have to be investigated. This is especially true for the influence of friction in the bearing and aerodynamical effects on the stabilizing ring of the probe.

Summarizing some of the main results Figure 21 presents three characteristic frequencies and their dependence on airspeed:

- the frequency f_1 where the amplitude response exceeds 3 dB
- the resonance frequency f_R
- the cutoff frequency f_c where the amplitude response becomes smaller than -3 dB.

For the frequencies smaller than f_1 the LASSIE system certainly can be used without restrictions. But for higher frequencies it has to be taken into account that the sensor is underdamped. Speed changes due to the helicopter motion itself are usually in the lower frequency range where the LASSIE dynamic response is satisfactory. Turbulence influences, however, exciting the sensor motion at higher frequencies can deteriorate the measurement.

8. Conclusions and Future Aspects

Flight tests with a BO 105 helicopter were conducted to evaluate the capability of a LASSIE system and to obtain an accurate system characterization. Only steady state level flight conditions with different forward speeds and sideslip angles were evaluated. Calibrations for the LASSIE aerodynamically measured longitudinal and lateral speed were completed. To investigate the dynamic characteristics of the LASSIE probe , tests were conducted in a wind tunnel equipped with a gust generating system. The following conclusions were found:

8.1 LASSIE characterization

- When only the basic equations for the calculation of the speed components are applied large errors especially in the LASSIE sensor transition phase will occur.
- Using an appropriate characterization method it is possible to determine the sensor position with respect to the rotor downwash and to calculate correction equations.
- The error standard deviation of the corrected LASSIE data was less than 2.0 m/sec. However, it seems to be possible to further improve this accuracy when a more accurate reference speed measurement is available.
- A complete LASSIE characterization needs extensive flight testing because various combinations of longitudinal and lateral speed must be flown. In addition a highly accurate reference speed is absolutely necessary.
- The system characterization is only valid for the helicopter type under test and it is also only valid for the specific sensor location.

8.2 LASSIE dynamics

- The LASSIE probe frequency response is virtually independent from gust amplitudes.
- The resonance frequency of the sensor increases with speed. It ranges from 1.9 Hz at 18 m/sec up to 5.5 Hz at 50 m/sec.
- Near to the resonance frequency the system is significantly underdamped.

8.3 Further remarks

- Although only prototype indicators were used in the cockpit and only the LASSIE calculated speed (without corrections) could be displayed, the pilots gave satisfactory ratings. The LASSIE speed information proved to be very helpful in particular in the low speed regime and for sideslip control.
- The LASSIE system was installed on the DFVLR helicopter BO 105 in July 1978. It has been operating now for 490 flying hours. During this time it never had any failures nor caused any problems.

8.4 Future aspects

Additional tests with the LASSIE system should be conducted to address the following problem areas:

- The sensitivity of LASSIE measurements to helicopter weight, C.G. position and vertical speed.

- Definition of the sensor transition phase when the sensor is

  a) on the side of the advancing rotor blade
  b) on the side of the retreating rotor blade

  because it may be easier to accurately define the transition phase when the sensor is on the side of the advancing blade.

- Improvement of the dynamic response of the sensor, in particular with respect to the damping characteristic.

9. References

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10. Acknowledgement

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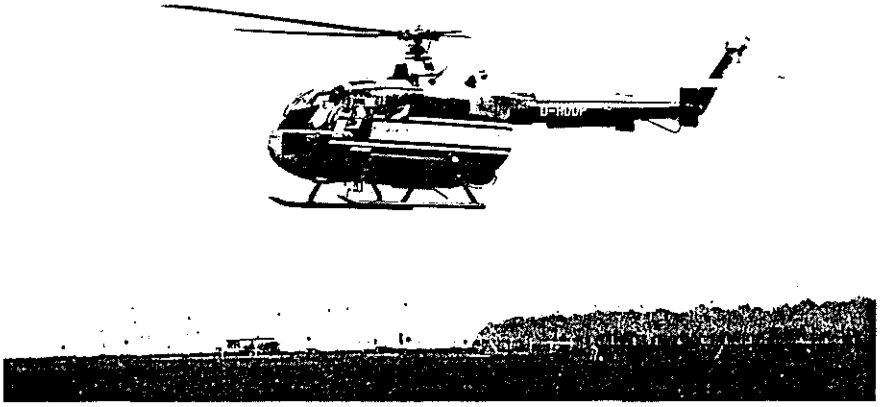


Fig. 1 DFVLR research helicopter BO 105

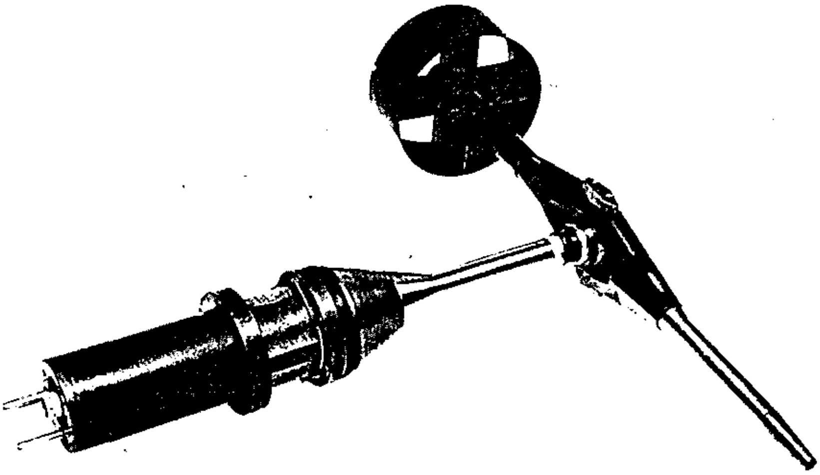


Fig. 2 Sensor of the Low Airspeed Sensing and Indicating Equipment LASSIE (prototyp unit)

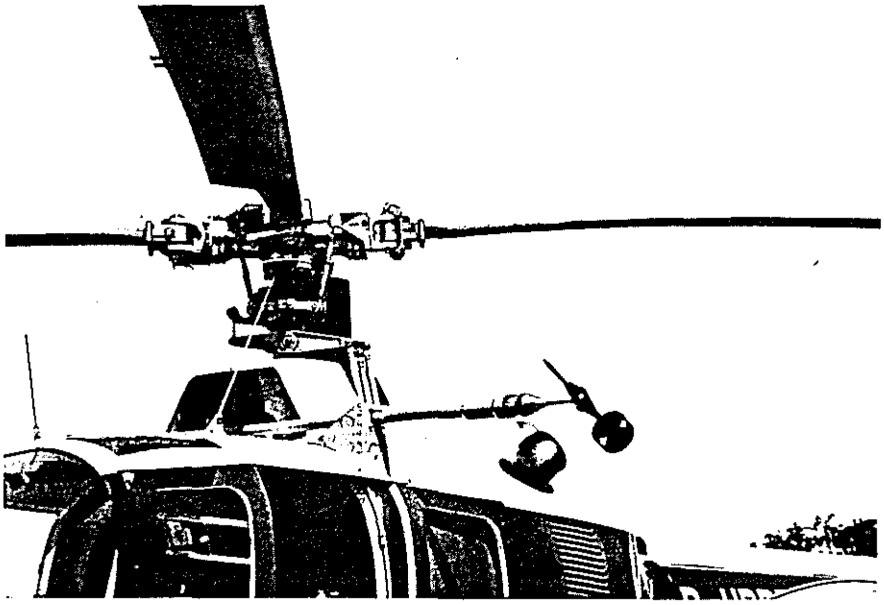


Fig. 3 LASSIE sensor installation

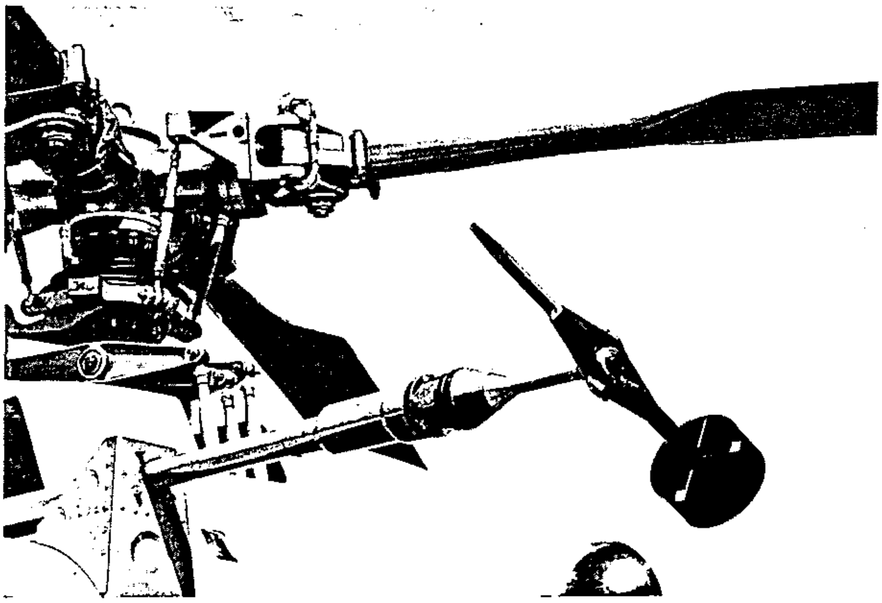


Fig. 4 LASSIE sensor installation

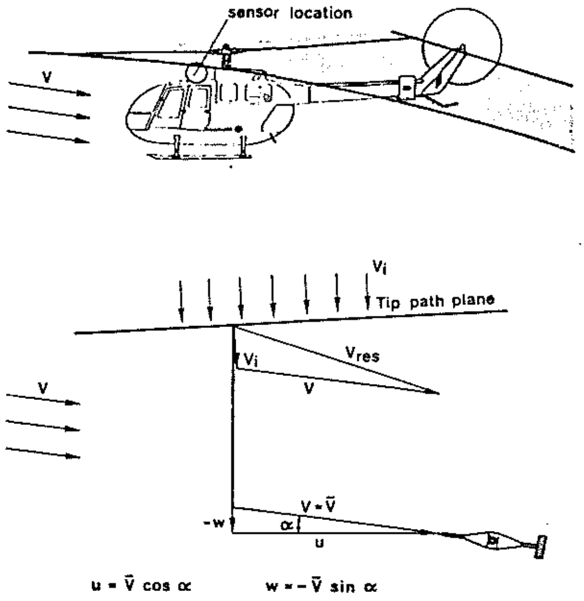


Fig. 5 LASSIE principle of operation: sensor out of rotor downwash

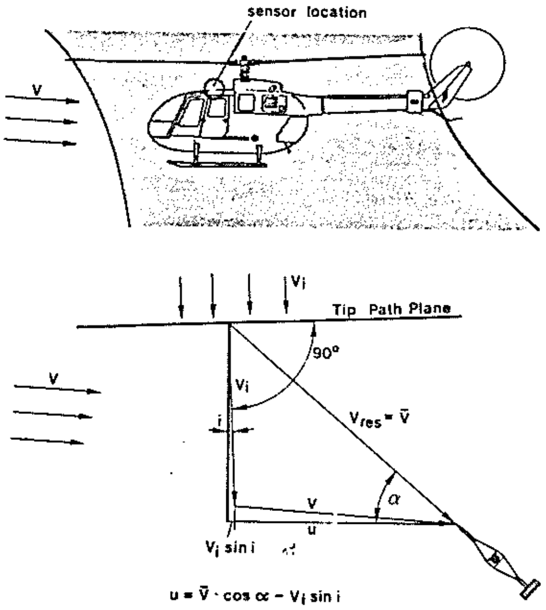


Fig. 6 LASSIE principle of operation: sensor within rotor downwash

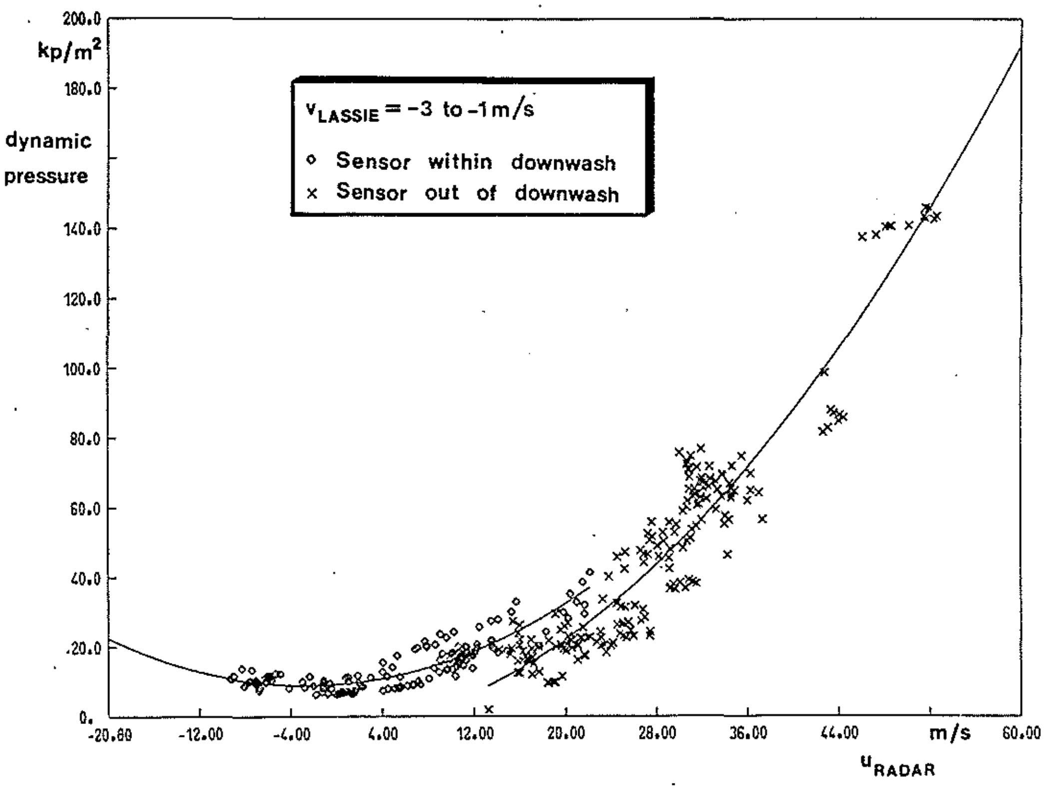


Fig. 7 Variation of LASSIE dynamic pressure with helicopter speed

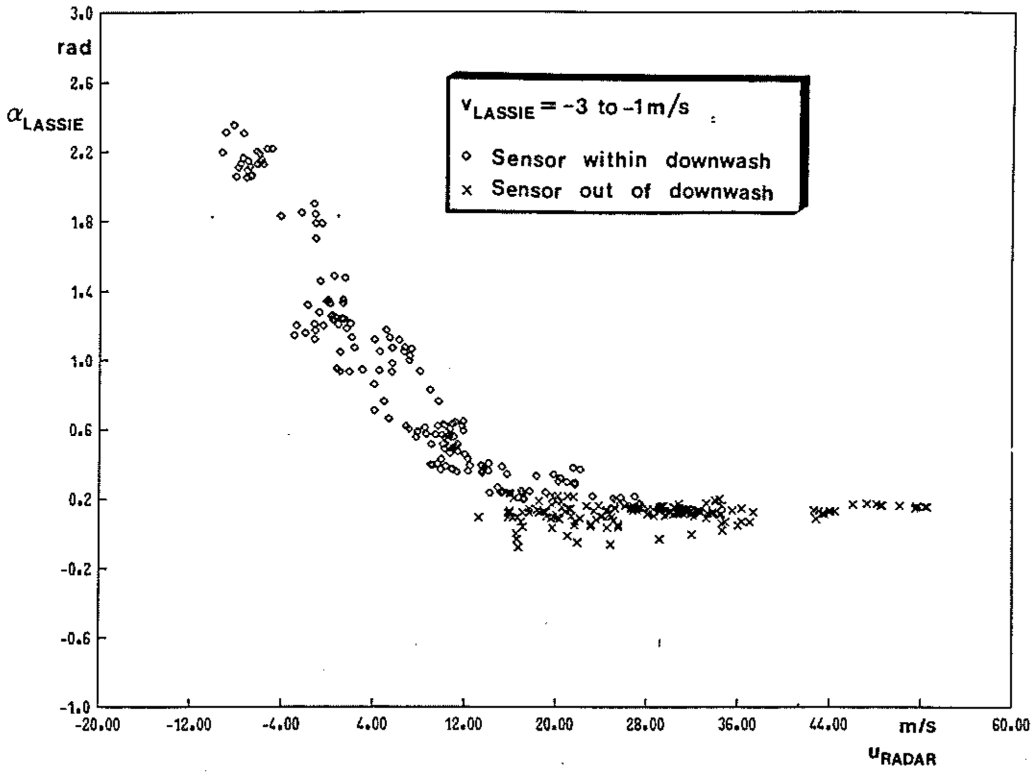


Fig. 8 Variation of LASSIE probe angle α with helicopter speed

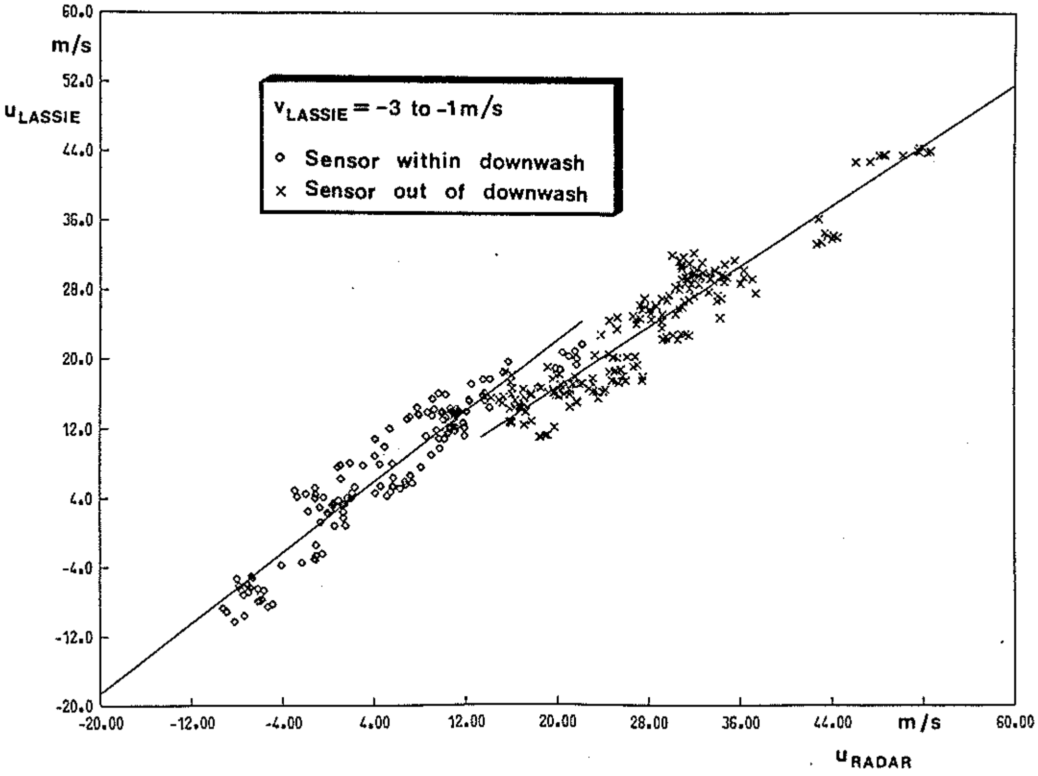
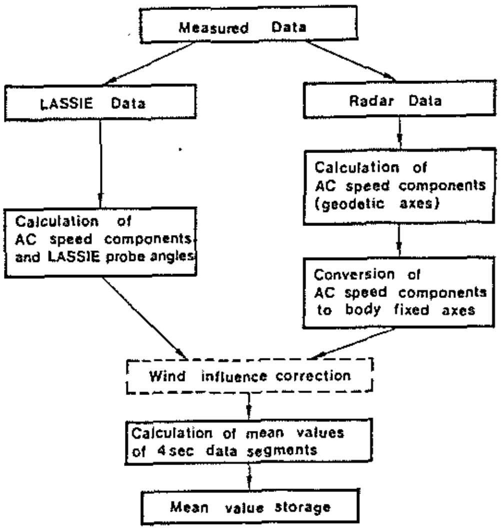


Fig. 9 LASSIE measured forward speed versus radar measured forward speed (without LASSIE characterization)



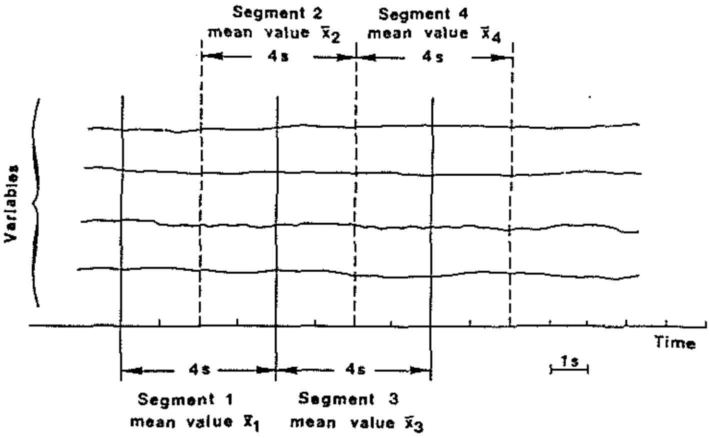


Fig. 11 Definition of flight test data segments

Fig. 10 Data processing

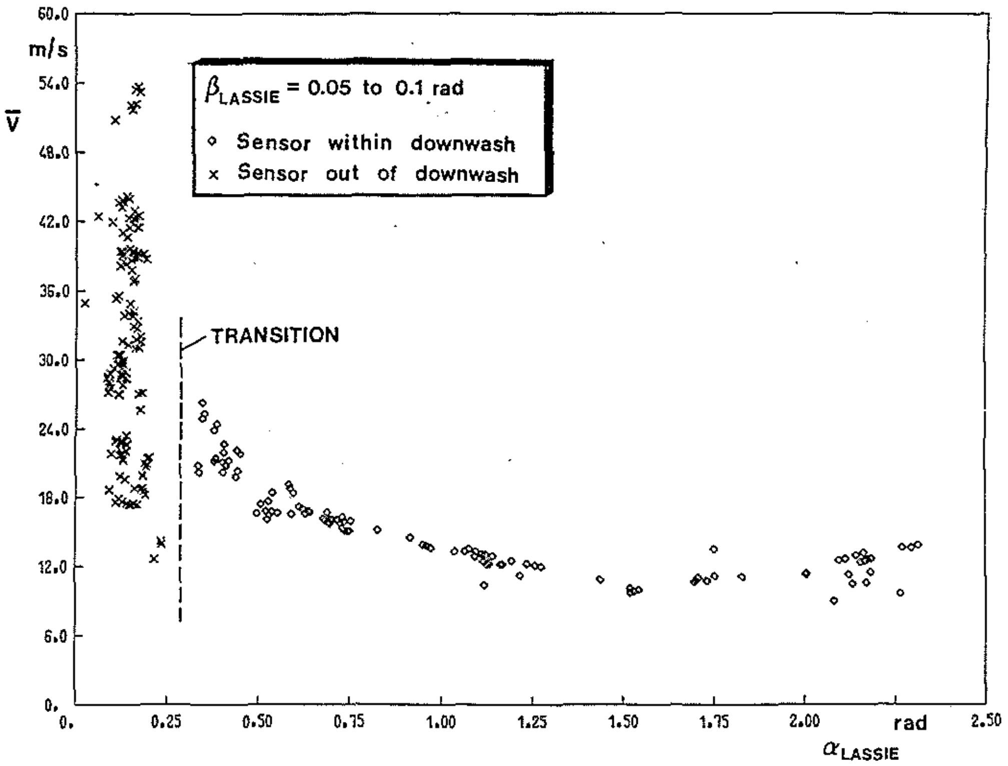


Fig. 12 Determination of LASSIE sensor transition phase

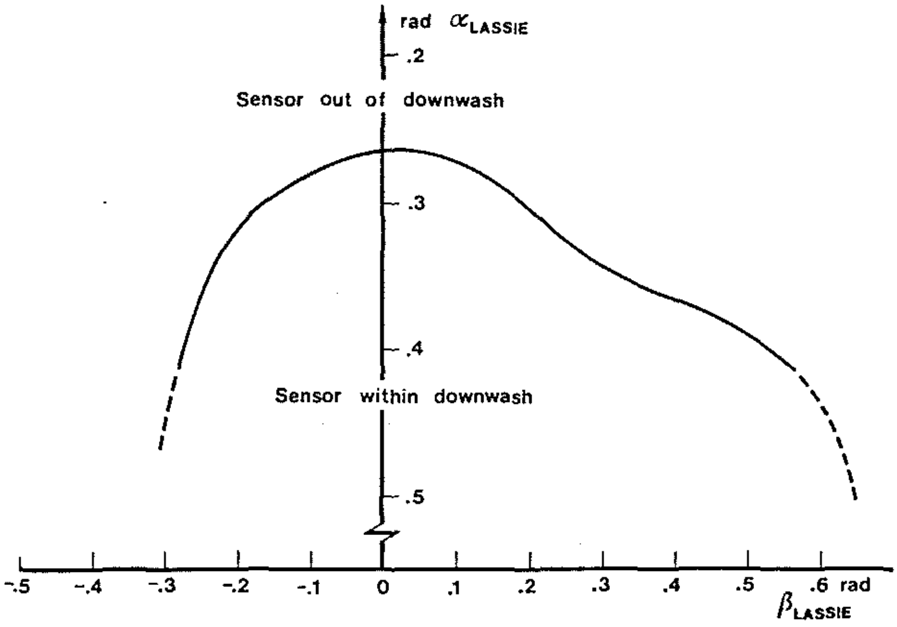


Fig. 13 Definition of LASSIE sensor position with respect to rotor downwash

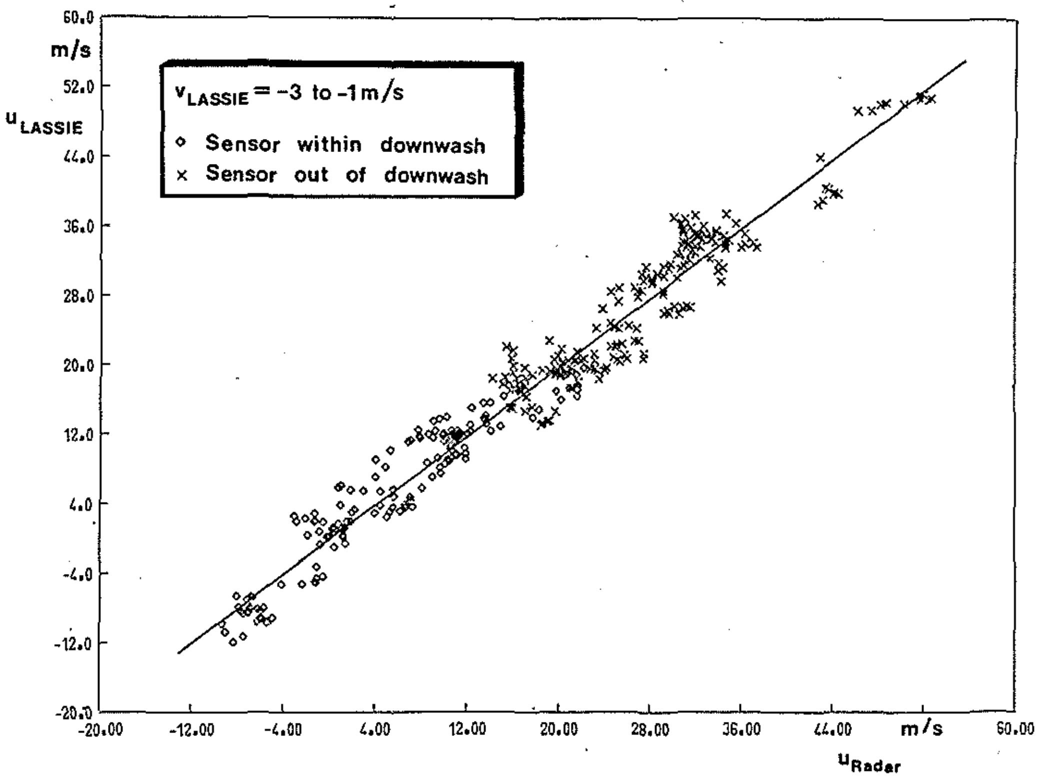


Fig. 14 LASSIE measured forward speed versus radar measured forward speed (with LASSIE characterization) - compare with Fig. 9 -

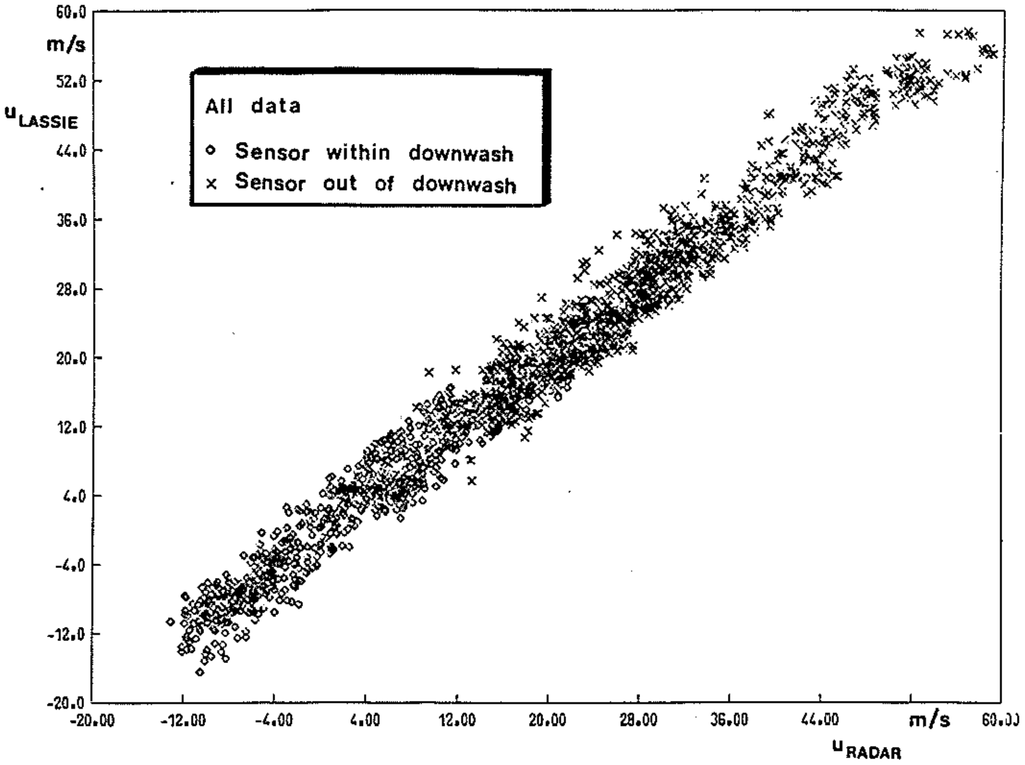


Fig. 15 LASSIE measured forward speed versus radar measured forward speed (with LASSIE characterization)

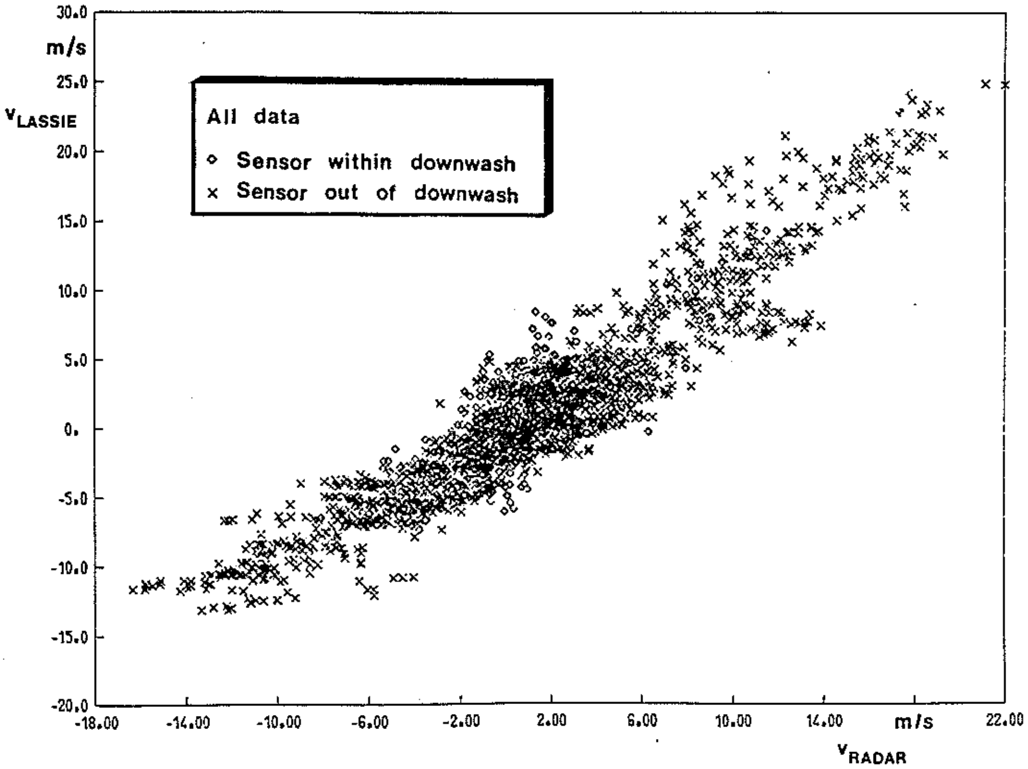


Fig. 16 LASSIE measured sideward speed versus radar measured sideward speed (with LASSIE characterization)

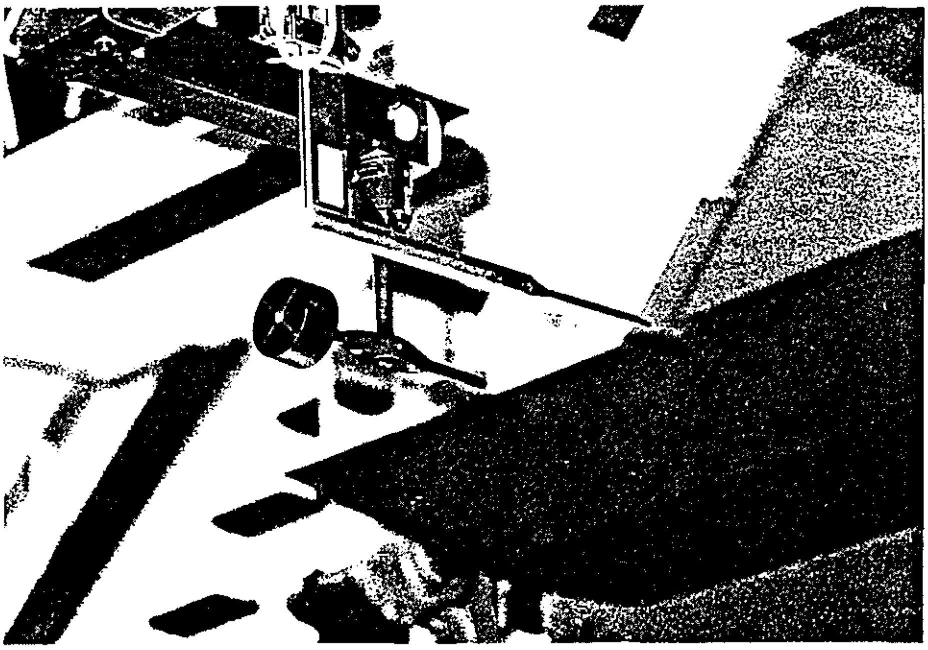


Fig. 17 LASSIE sensor (production unit) and differential pressure probe in the wind tunnel equipped with gust generating flaps

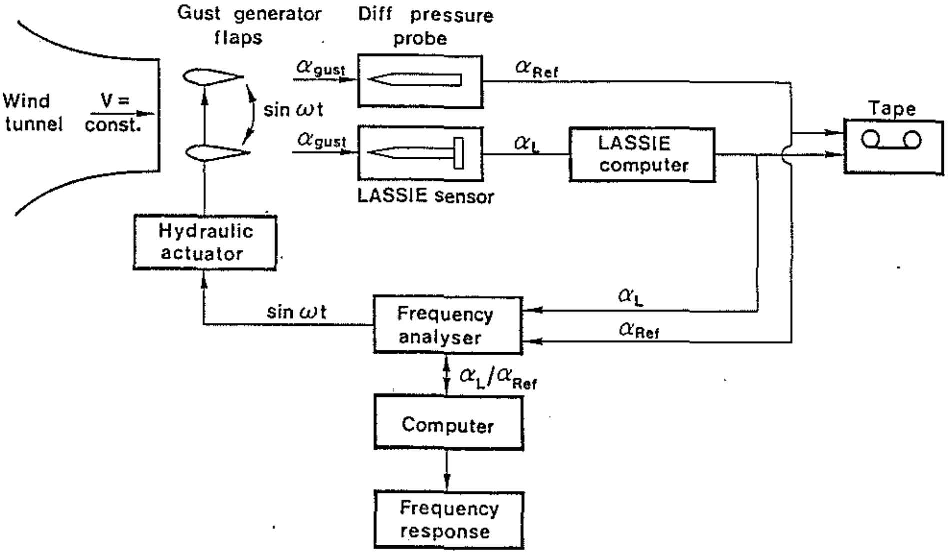


Fig. 18 Flow chart of the wind tunnel tests

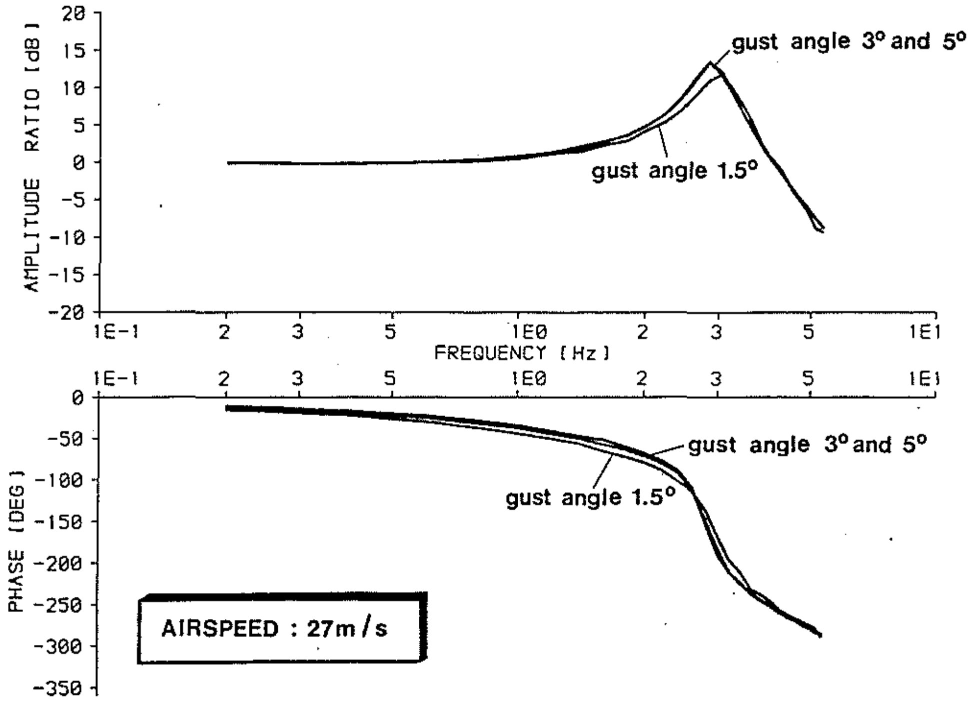


Fig. 19 Influence of gust amplitudes on LASSIE frequency response

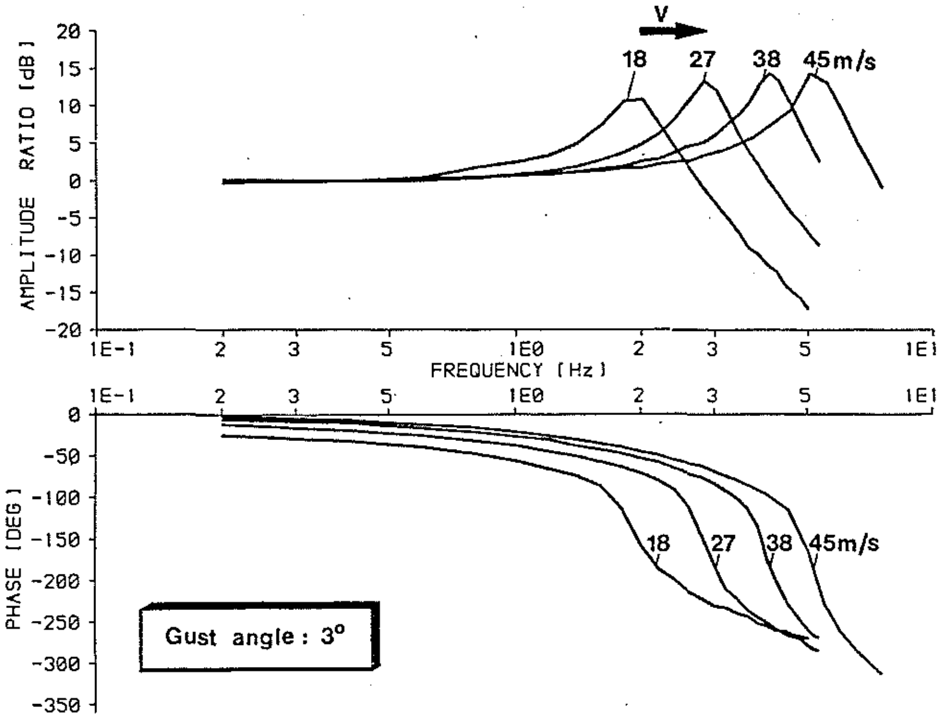


Fig. 20 Influence of wind tunnel speed on LASSIE frequency response

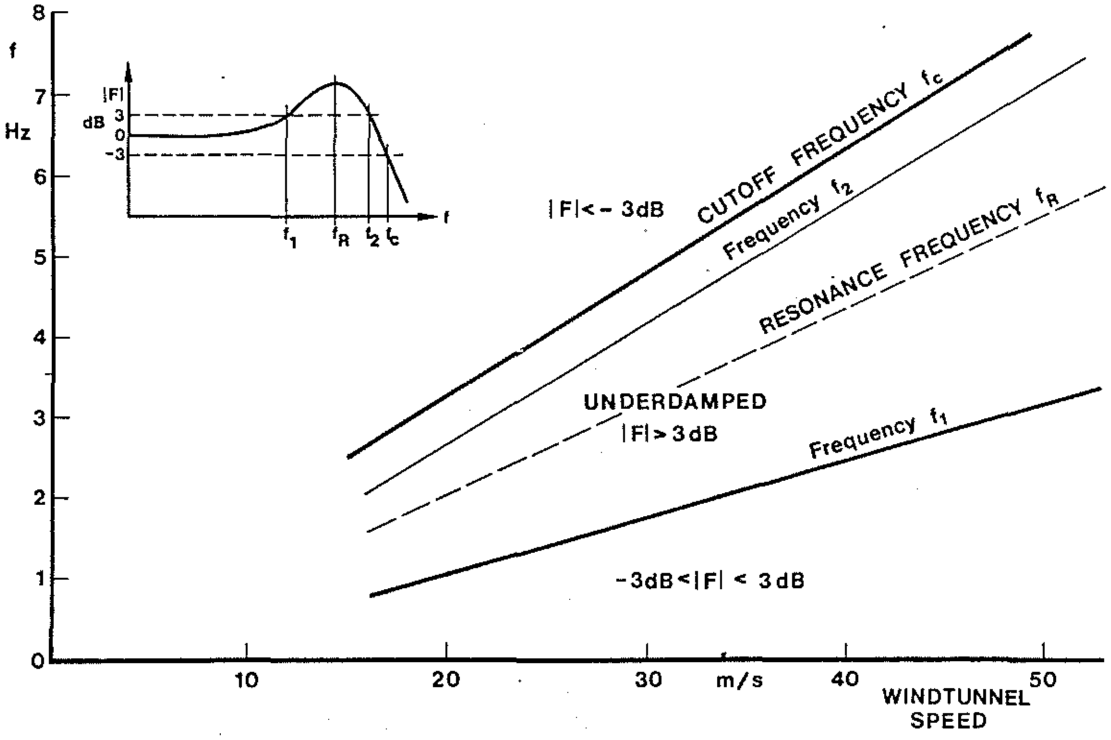


Fig. 21 Main characteristics of LASSIE dynamic behaviour