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FLIGHT PATH MEASUREMENT OF HELICOPTERS USING A STRAP-DOWN NAVIGATION SYSTEM

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Abstract

The determination of velocity, used distance and altitude of a helicopter during hover and transition is difficult, time consuming and costly. Currently several systems are being used to acquire this type of data, for example kinetheodolites, radar, laser and so on.

In aircraft STRAP-DOWN Navigation Systems are usually used for guidance and control. It seems to be obvious to use these systems also for flight path measurements. However, to obtain the required accuracy there exist time limitations, and an optimisation of the test flight maneuvers is necessary. On the other side, tests can be carried out at any place without special ground equipment.

The installation described in this paper was especially developed by MBB.

Measurements of helicopter motions with this system were performed for:

- Translatory movements in all directions
- Cat A and Cat B start and landing process
- H/V Tests, upper point and knee point
- Cat A vertical takeoff profile from a platform

1. Introduction

I would like, first of all, to show a picture of the BO 105 LS at Leadville/Colorado (~ 10000 ft altitude) in August 1983. The helicopter is performing a sideward flight along the runway accompanied by a pace vehicle.

Fig. 1 Test Flight with BO105 LS at Leadville/Colorado (9927 ft Altitude)

FAA certification officials were in both, the helicopter and the pace car. Tests were being performed to demonstrate controllability and maneuverability according to FAA Part 27.143 (c).

The speedometer of the pace car had been calibrated prior to testing and the vehicle was then used to provide pace speed reference for the helicopter.

Naturally there are other ways of low speed helicopter or flight profile measurement. Normally velocity and altitude is obtained at high helicopter speeds using a calibrated pitot static pressure system. As we all know such systems are not suitable for measurements of low speeds and maneuvers near the ground.

For these reasons theodolites, laser or precision radar instruments are often used to measure flight profiles or low speeds. None of these methods were available in Leadville. Neither a radar nor laser was available and it was not possible to install a theodolite.

It is possible to measure altitude and speed using an onboard radar installation which functions like a radar altimeter or doppler. However, suitable sights must be found on the helicopter for installing the antenna. Furthermore, the measurements of the flight profile are relative to the traversed area so that a perfectly horizontal test site is required when measuring for example the height above ground.

This is not always available and is rarely available where the certification flight tests must be demonstrated under extreme conditions, for example high altitude or low temperatures.

Fig. 2 High Altitude Tests in Chile with BO105 LS (Area Elevation 15900 ft)

An ideal installation would be an inertial system which could be placed in any helicopter with no need for additional modification such as antennas, with no connection to any ground station and with self-contained and complete data measurement and recording capabilities.

In aircraft, inertial navigation systems are usually used for guidance and control.

Two types of systems are available:
- The gimbaled platform where the sensors are mounted on an attitude stabilized platform and
- the STRAP-DOWN system, where the sensors are strapped directly to the aircraft and measure body rates and accelerations.

Both systems could be used for flight path measurements. However, to obtain the required accuracy even with very precise instruments, time limitations exist and an optimization of the test flight maneuvers is necessary. On the other hand, tests can be carried out anywhere without special ground equipment (for example: High Altitude Tests).

2. System Requirements and Description

2.1 General

The installation described in this paper was specially developed by MBB with the following features:
- STRAP-DOWN system with very precise dry-tuned rate gyros and accelerometer
- Schuler tuned navigation system
- on/off selectable barometric altitude damping
- an integrated airdata system
- computer system with multi microprocessors Z8002
- STRAP-DOWN software using high order language "C"
- PCM data output
- analog and digital inputs and outputs
- integrated servoloop controller for up to 3 actuators

Measurements of helicopter motions with this system were performed for:
- Translatory movements in all directions
- Cat A and Cat B start and landing profiles
- H/V Tests, upper point and knee point
- Cat A vertical takeoff profile from a platform

Offline data were evaluated and plotted by computer. In particular these are the translatory velocities vx, vy, respectively v-ground, as well as v-vertical and the flight altitude (height above start point) against distance or time.

During a test these data are also displayed in the cockpit; digital on a CRT-Display and vx, vy on an analog cross indicator.

2.2 Sensor Performance Requirements

STRAP-DOWN means:

Measurements in 3 axes of
- body angular rates and
- body accelerations

and calculation from this data of:
- attitude
- velocities
- distance
- altitude

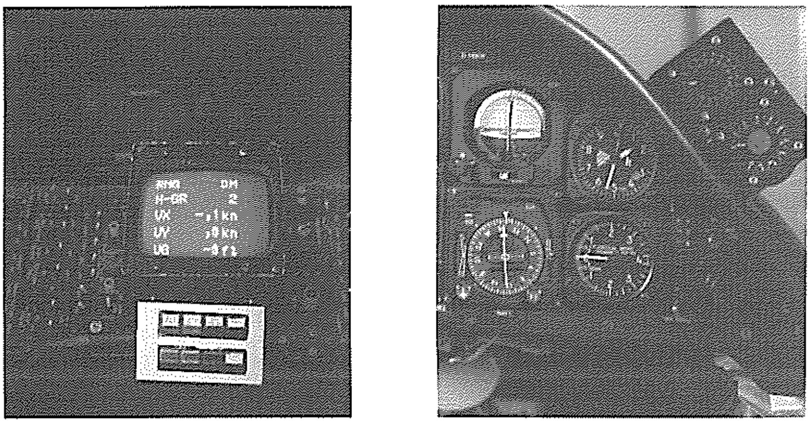

Fig. 3 CTR Display and Analog Crossindicator in the Cockpit

The mathematical solution has been known for a long time and presents no problem with the powerful microcomputers available today. But obtaining required accuracies in the presence of sensor errors, especially under the environmental conditions of a helicopter, is challenging.

As a simple example, if we have a measurement error in acceleration, the short time velocity error will be

$v = a \times t$ and the distance error $d = 1/2\ a \times t^2$

This means, an error of only 0.0001 g or 100 micro g gives the following:

time	velocity	distance
1 min	0.1 kt	6 ft
2 min	0.2 kt	24 ft

This example shows the importance of minimizing the measurement time, because a reduction of measurement error gives only a linear reduction of the distance error against the squared time influence.

Errors in acceleration have two main sources:

First are the various kinds of accelerometer sensor errors such as bias, temperature drift of bias and scale factor, non-linearity, crosscoupling, conversion errors into digital data, etc.

The second error source is the accuracy of determination of the direction of the earth gravity vector. This is a problem, because earth gravity has to be substracted from the measured accelerations to get the real acceleration of the aircraft.

So a good initial alignment of the calculated attitude to the g-vector is necessary and the measured angular rates have to be very exact over the measurement period to maintain attitude in the arc second range. Thus rate sensor errors have to be kept even smaller than accelerometer errors.

Discussion of the sensor performance requirements shows that the design goals are very demanding. So the design rules have been:

- employ the best sensors available
- design as much as possible in digital electronics
- if analog circuitry is necessary use hybrids to keep temperature drifts small and repeatable.

This led to the following hardware design:

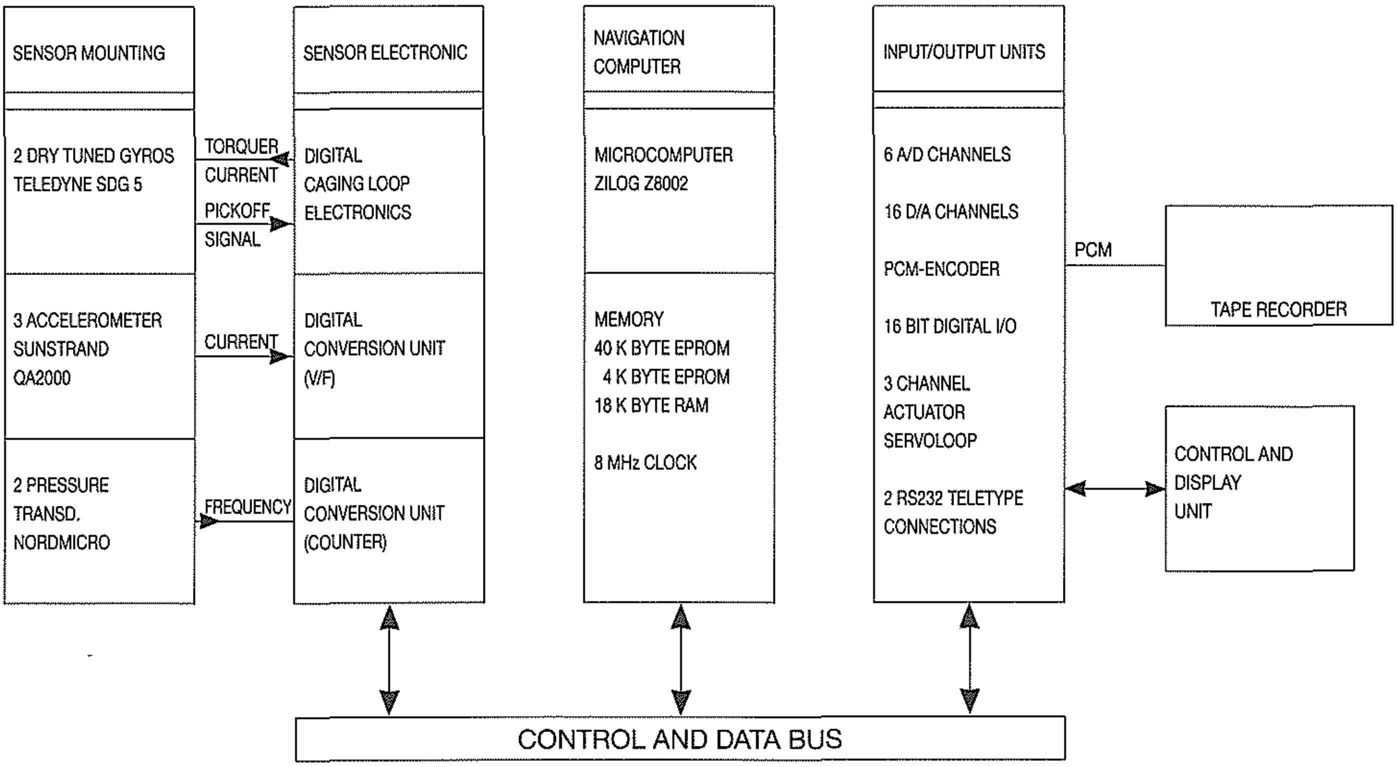

Fig. 4 Block Diagram Flight Path Measurement System

2.3 Hardware Description

The hardware consists of four major components:

- the sensor mounting block
- the sensor electronics
- the navigation computer
- the input and output units

Sensor Mounting Block:

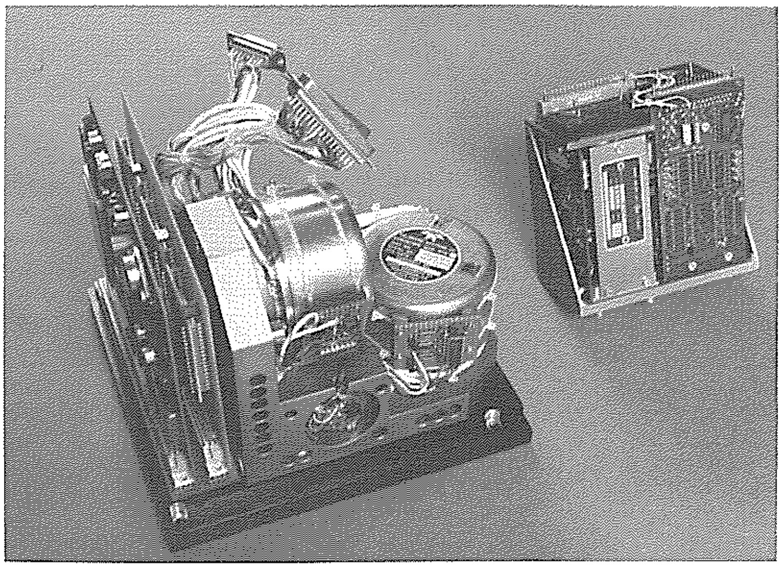

Fig. 5 Sensor Mounting: 2 Gyros – 3 Accelerometers, 2 Pressure Transducers

Because laser gyros were not available in Germany, dry tuned gyros had to be used.

Dry tuned gyros measure rates about two axes, so only two of them are used in a skewed arrangement. Gyro 1 measures pitch and roll movements while gyro 2 is skewed 45 degrees so that each axis measures yaw rate divided by the root of two.

Sensor Electronics:

During development most of the effort was spent in the design of the gyro caging loop and its conversion of torquer current into digital data. A completely new approach to a fully digital microprocessor controlled solution was taken. 3 accelerometers are mounted orthogonally on the sensor block. Their output current is proportional to the acceleration and measured with special voltage to frequency converters.

Very precise air data sensors are also integrated into the system. The output of two pressure transducers is frequency proportional to the input pressure.

The navigation calculations are done in a Z8002 microcomputer with a memory of 40 kbytes EPROM, 18 kbytes RAM and 4 kbytes EEPROM at a clock rate of 8 MHz.

Input- and Output Units:
The following are available for connection to the outside world:

- 6 differential channels A/D (12 bit)
- 16 channels D/A (12 bit)
- 16 channel PCM encoder
- 16 bit digital input or output
- 2 teletype connections

Navigation Computer:

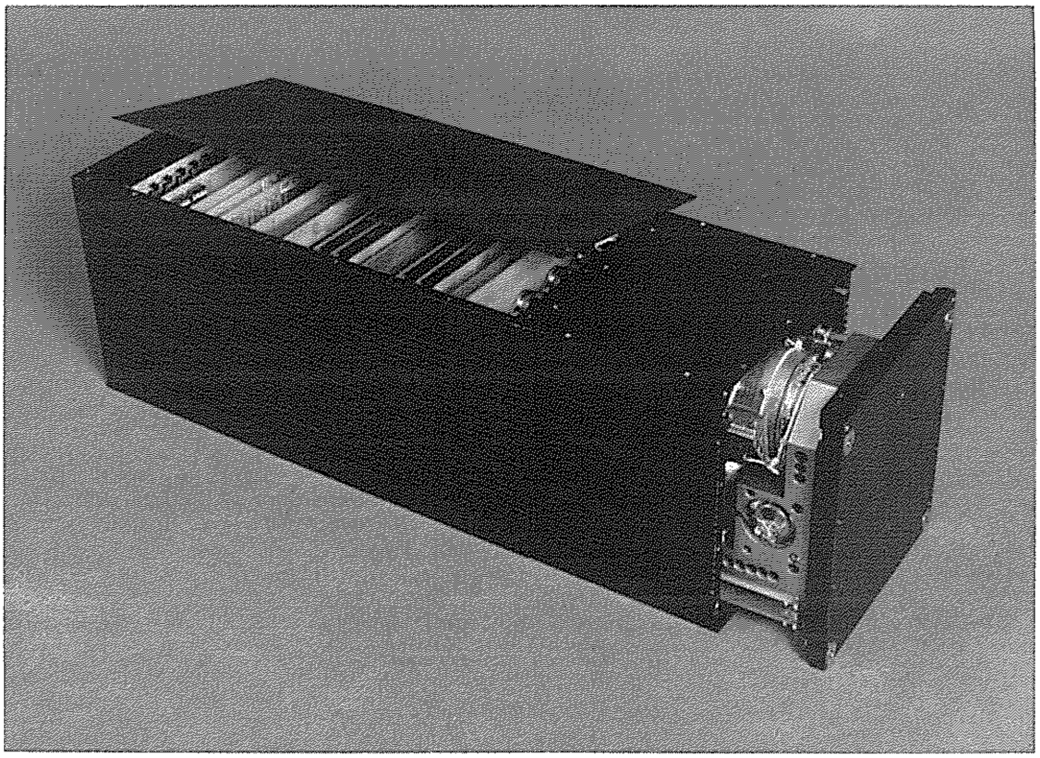

Fig. 6 Navigation Computer

2.4 Software Description

The problems to be solved by software are: First to compute the following from the given measured data representing angular rates and linear accelerations:

- Attitude in pitch, roll and heading
- Velocity vx, vy in body coordinates and vg in earth coordinates
- Position in latitude and longitude and distance from a start point.

Second, compute the following from data representing p-static and p-total:

- barometric altitude
- indicated airspeed

3. Flight Tests and Results

3.1 Installation in Aircraft

The flight tests were performed with a BK117 helicopter. Fig. 7 shows the installation of the equipment in the helicopter. Of particular importance is to insure, that the equipment is perfectly aligned with the helicopter longitudinal axis, and is fixed.

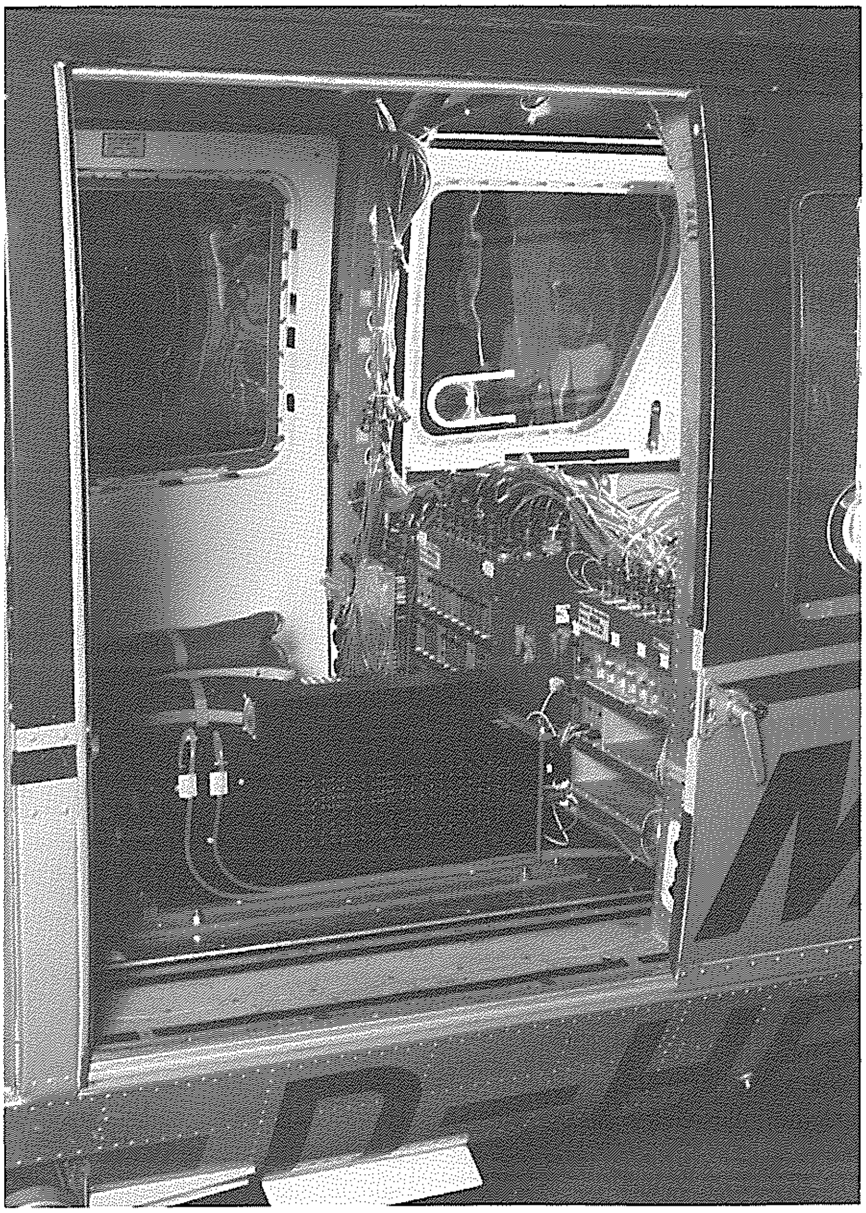

Fig. 7 Installation of the STRAP DOWN Equipment in the Test Helicopter BK 117

3.2 Handling

Operating the equipment should be as simple as possible in order to eliminate errors. A 2-minute alignment phase is performed before each test. This is fully automatic. During this period the helicopter must remain stationary on the ground and the barometrical sensor is used to establish the altitude data. The barometric signal is removed as soon as this referencing phase is complete, since as soon as the collective pitch is increased, errors will be induced in the measured static pressure altitude. As soon as the flight test begins the equipment operates exclusively on inertial signals, i.e. without any time delay.

The pilot is now fully active with the execution of the flight tests and must concentrate his attention on the world outside the helicopter.

The flight test engineer will read and transmit the relevant test data via the Intercom, warn of impending simulated engine failure and start the maneuver. Furthermore, he can put identifiers on the magnetic tapes at appropriate positions in order to ease analysis at a later stage.

I would like here, to bring up 2 important points which are essential to the performance of flight testing using a STRAP-DOWN platform:

Firstly, as previously stated, the measurement accuracy increases as the test time reduces, i.e. unnecessary maneuvers between takeoff and landing should be minimized. For example, it should not be necessary to first of all complete a traffic pattern in order to obtain the start position for a landing, or for the high hover point during a height-velocity-diagram test. It should be possible to obtain the flight state required for the certification test immediately and straight ahead following the takeoff.

Secondly, as soon as the helicopter returns and remains stationary on the ground, the crew is able to check whether the measurements were sufficiently accurate or not. The test engineer is able to read the velocities:

$$vx, vy, vz$$

If no measurement error has occured, these three velocities must be equal to 0, when the helicopter has landed and is sitting on the ground. In order that the test data can be accepted, the displayed values must ly within predefined limits. These limits will themselves depend on the type of tests performed.

This method of checking the test data can be accepted and applied, since the most important errors will increase as a function of the time. This means that the errors integrated during the actual testing will always be smaller than the errors measured during the landing check.

If one of the velocity values given above is larger than the limit then the test must be repeated. For this reason, it is very important and useful to determine the data quality immediately following the test. In this manner, the test personnel can decide whether a particular test point should be repeated without having to wait for a complete data analysis. Because then the required atmospheric conditions, which are essential for the certification testing, are quite likely to be no longer available.

At this point it is worth mentioning, that most of this flight testing must be performed under calm or head wind conditions less than 2 kt. Otherwise windspeed must be added vectorially.

3.3 Flight Tests Performed

The following diagrams have been produced directly from STRAP-DOWN flight test data. They have been plotted using specially developed software and are examples of many possible presentations.

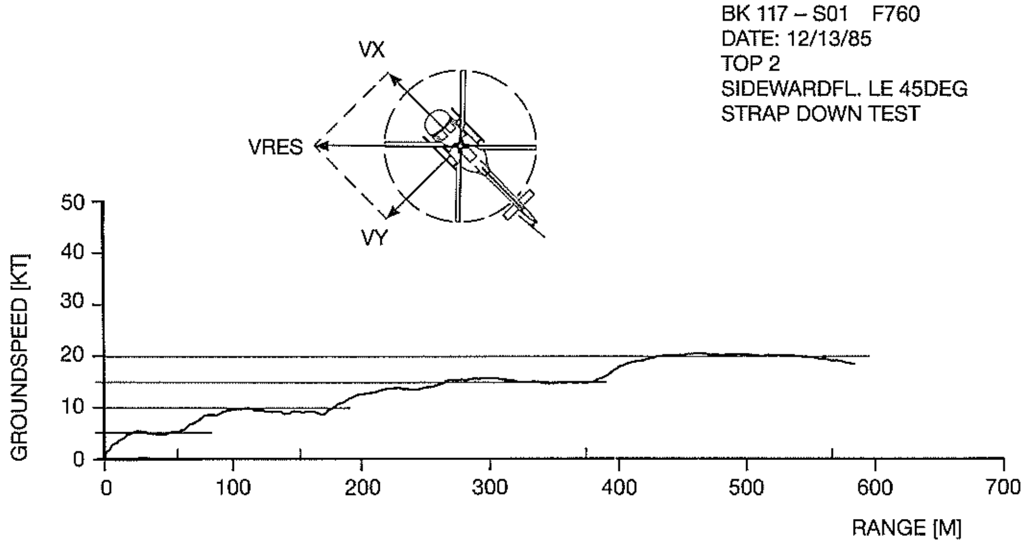

Fig. 8 Groundspeed V_{RES} Versus Range

Fig. 8: Sideward flight to the left/forward, 45°, shows the real speed curve along the test course in steps of 5, 10, 15, 20 kt. It can be seen that the pilot cautiously increased the speeds to the next steps and also how accurately he held the speed once established.
Here of course V_{RES} is the vector-sum of V_X and V_Y, i.e. the speed relative to the ground.

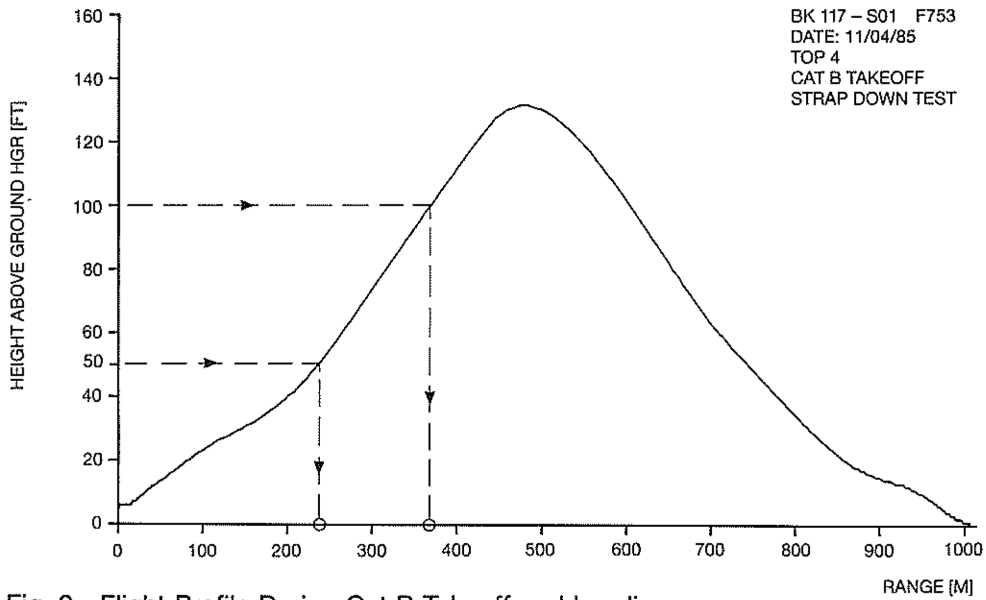

Fig. 9 Flight Profile During Cat B Takeoff and Landing

Fig. 9: Cat B takeoff and landing flight profile. It is quite clear from this diagram to see how the distances can be obtained for the 50 and 100 ft altitudes.

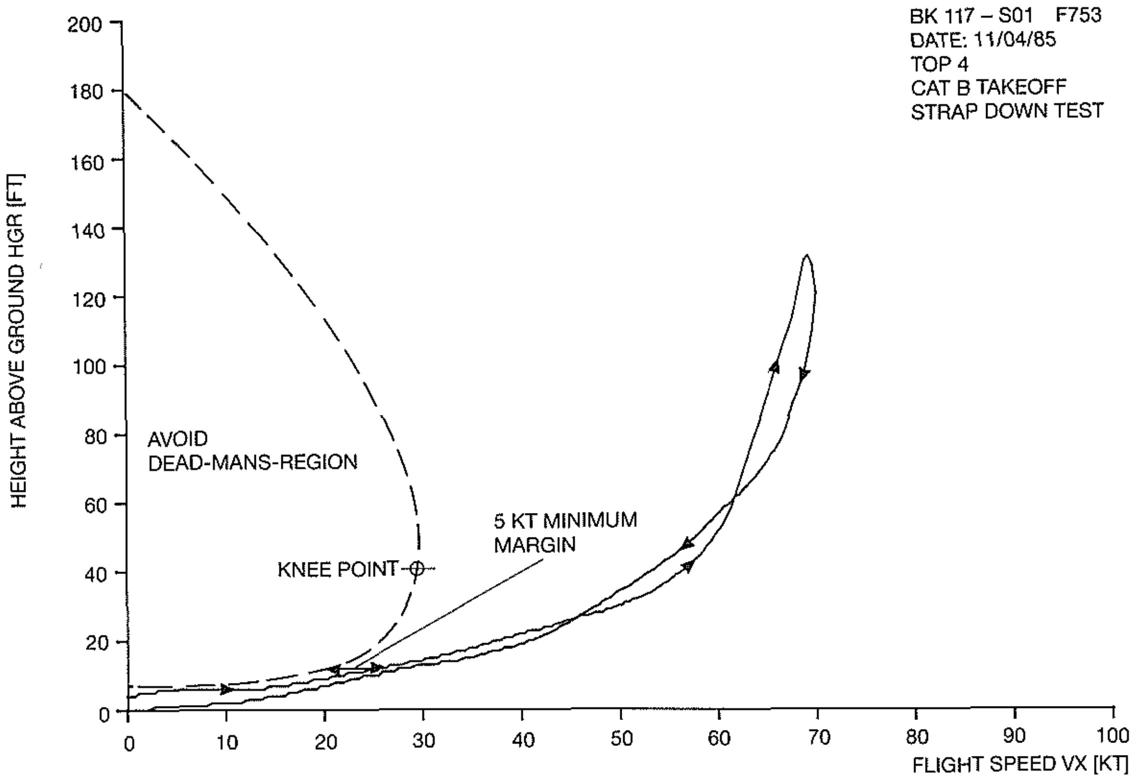

Fig. 10 Flight Profile During Cat B Takeoff and Landing

Fig. 10: This diagram represents the same test as shown in Fig. 9; however, the altitude and flight speed is shown for the takeoff and the subsequent landing.
The same representation is used in the pilot's flight manual in order to inform the pilot of the limiting height velocity envelope for a particular weight-altitude-temperature (WAT-curve) condition.
It can be clearly seen, that during these tests the pilot did not enter the so called "dead man's region" during both takeoff and landing.

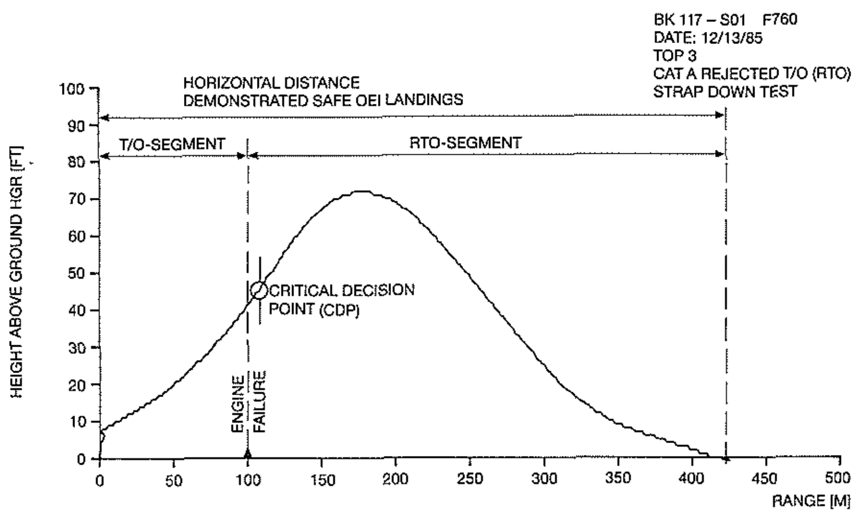

Fig. 11 Flight Profile for Cat A Takeoff

Fig. 11: Cat A rejected takeoff, engine failure before reaching the critical decision point CDP = 45 kt and subsequent landing. Establishing the distance to the landing point is very simple.

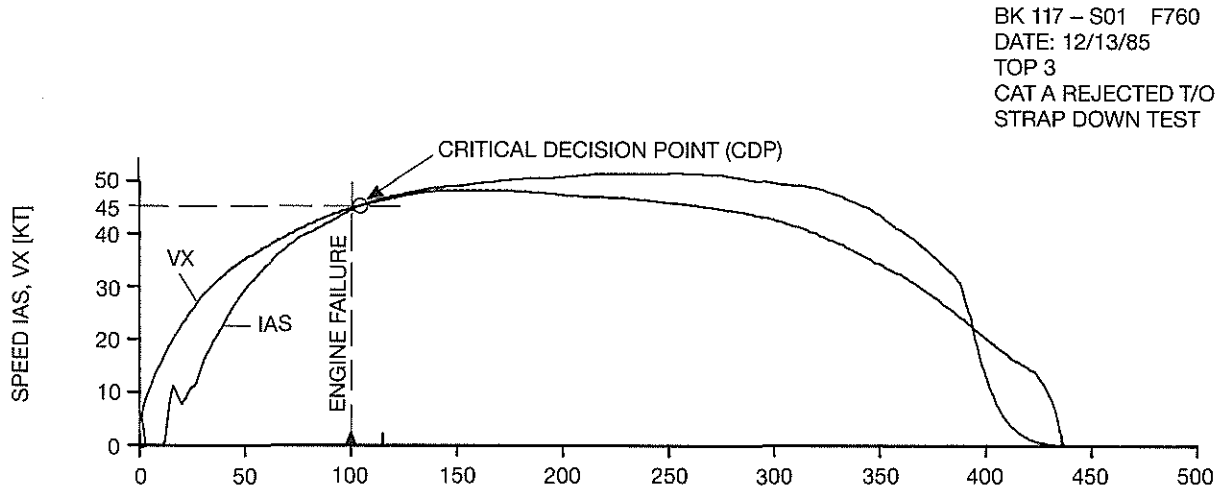

Fig. 12 Comparison Between IAS and V_X

Fig. 12: The same test as shown in Fig. 11. This shows a interesting comparison of IAS and the actual speed V_X which quite clearly increases. It can be seen that the IAS during the acceleration phase below 30 kt is inaccurate, but on reaching the CDP agrees with the real speed.

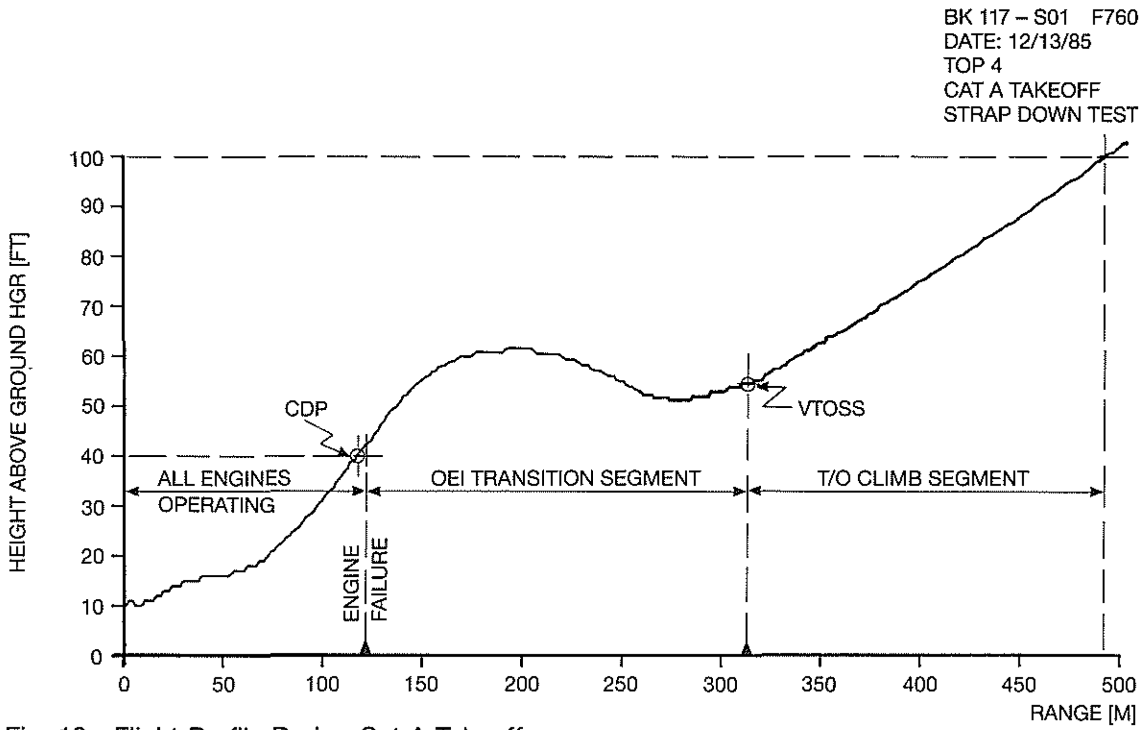

Fig. 13 Flight Profile During Cat A Takeoff

Fig. 13: Cat A takeoff, 1 engine failure after the critical decision point, followed by acceleration to V_{TOSS} and continued climb with one engine.

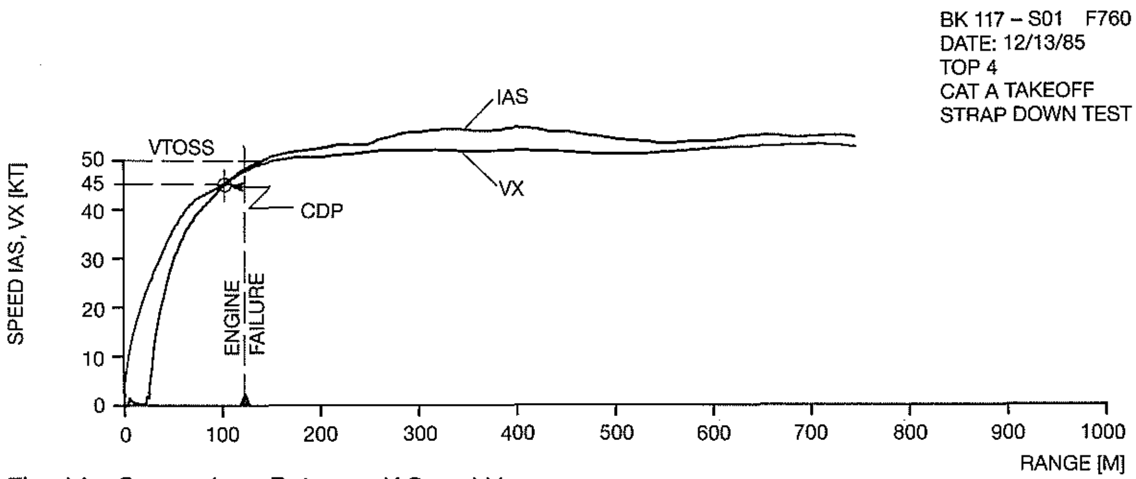

Fig. 14 Comparison Between IAS and V_X

Fig. 14: The same test as shown in Fig. 13 with time history of speed from IAS and V_X. It can be seen here, that in steady state climb of 50–60 kt the IAS, derived from the P_{TOTAL} and P_{STATIC} sensors, deviates very little from V_X.

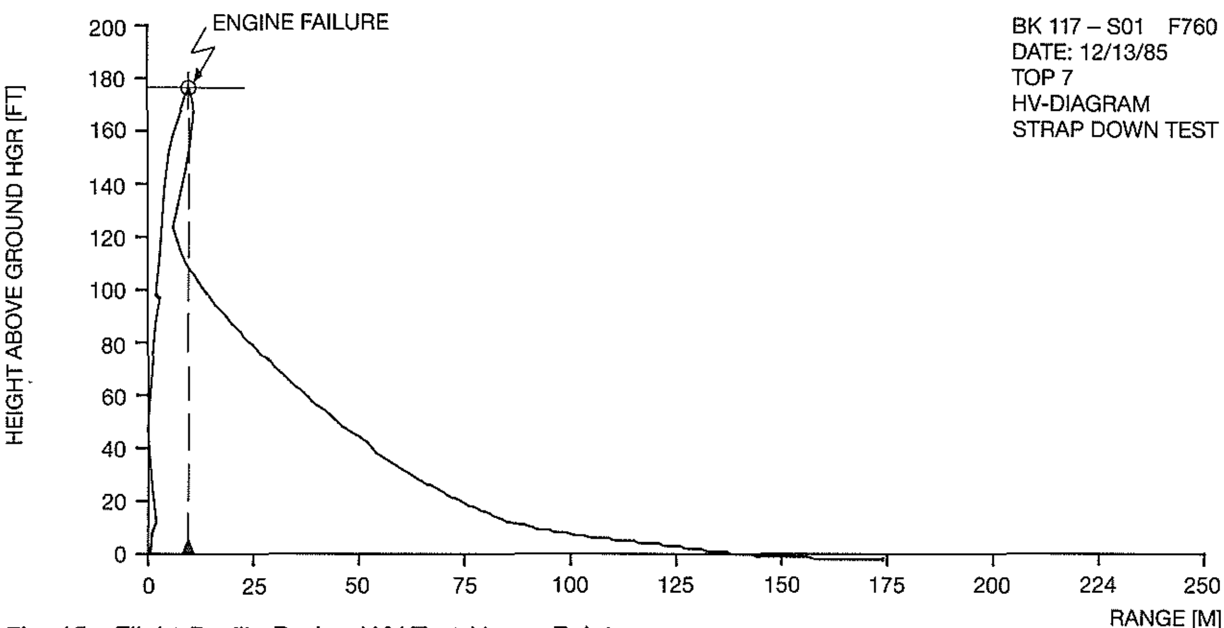

Fig. 15 Flight Profile During H/V-Test Upper Point

Fig. 15: A height velocity diagram test from the upper high hover point of 180 ft, simulated engine failure and subsequent landing. For this condition, the certification regulations require the demonstration of a one second pilot delay time between engine failure and pilot recovery.
Hence, the helicopter descends vertically before the pilot accelerates forwards and makes an appropriate landing.

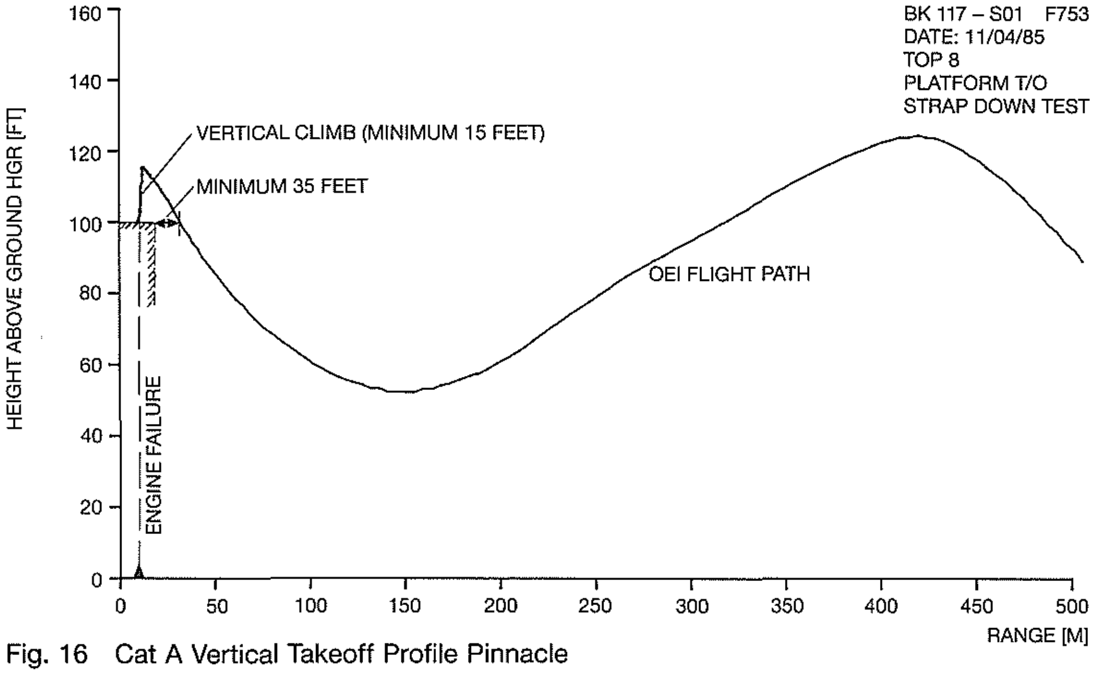

Fig. 16 Cat A Vertical Takeoff Profile Pinnacle

Fig. 16: This last diagram shows a takeoff profile after a simulated platform takeoff at 100 ft and with an engine failure at the critical point >15 ft above the platform.
The object of this test is to demonstrate that sufficient safety margin exists between the flight profile and the edge of the platform (min. 35 ft = 10 m) and how far the minimum point lies below the takeoff position before the helicopter is able to climb with the remaining engine.

4. Conclusions

- Flight path measurements with a helicopter in the low speed region are possible with a STRAP-DOWN platform under certain conditions.
- High accuracy sensors are essential in the equipment.
- A computer is necessary to analyse and display the measured data.
- Each complete test should not take longer than 2 minutes; unnecessary flight maneuvers should be avoided.

  With these restrictions a STRAP-DOWN system has the following advantages.

- The equipment can be used without additional measurement installations, for example antenna, and can be used in both, test- and production helicopters with a minimum of prior preparation.
- No additional ground installations, such as radar or theodolites are required.
- The test site can be chosen according to the required atmospheric conditions or according to the certification requirements without being dependend on a particular test site.
- After each test point the measurement accuracy can be immediately checked by the crew.
- Our experience with this STRAP-DOWN concept has been so encouraging that we intend using the equipment for all future certification testing of this type.

As previously stated, we will in addition use the equipment combined with appropriate actuators for flight path stabilization and for exactly defined control inputs, which are repeatable for comparative tests, and for the resulting flight path measurements. This topic will maybe provide adequate material for a subsequent lecture.