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Analysis of Application of INS (Inertial Navigation System) in Evaluation of Helicopter Flying Qualities

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Abstract

The objective of the research was to validate the possibility of application of modern avionic systems in evaluation of helicopter flight qualities. Two kinds of navigation systems were considered: INS and GPS, which may be integrated to obtain the more reliable results. In this paper mainly application of the INS is discussed.

The criteria of flying qualities and the MTE described in ADS-33 were analysed to identify quantities to be measured and to define the accuracy of the measurements. This formed the background for selecting the quality of sensors used in measuring equipment.

The INS unit, designed and built in Warsaw University of Technology, was used in ground experiments. The improved version of the measurement unit is now under laboratory tests.

1. Introduction

Aircraft flying qualities are the main factor which determine ability of helicopter safe and efficient flight in varying environmental conditions.

Evaluation of the helicopter flying qualities is performed in some phases of aircraft life [1]. During design and development of a prototype commercial [2] or in-house developed simulation tools are extensively used for evaluating flight dynamics and control. The results of computer simulations are validated by flight tests.

The ADS-33 [3] defines parameters describing flying qualities, criteria and methods of their evaluation. Subjective and objective criteria of flying qualities evaluation are given there. The objective criteria are defined as parameters of helicopter response; such quantities as *bandwidth, phase delay, quickness, agility factor, control power and dynamic stability* are used. Also mission task elements are described for standardisation of flying tests procedures.

To calculate the parameters of flying qualities the motion of helicopter is identified in terms of measurable quantities such as translation, attitude, velocity, rate and acceleration. Some of these quantities are measured by helicopter standard on-board avionic instruments, but in flight tests special equipment such as on-ground telemetry may be applied.

The long term goal of this research is to develop methodology of using only on board equipment during flight tests. In the first part of the research the review of regulations concerning the mandatory, required by regulations, helicopter equipment was done [4]. The conclusion is that standard on-board instruments usually does not provide all data needed in flight tests described in ADS, so additional measurement equipment need to be mounted on the aircraft.

In modern avionics IRU (Inertial Reference Unit) or INS (Inertial Navigation Systems) provide data of aircraft attitude, velocities, rates and accelerations. Integrating INS with receiver of GPS (Global Positioning System) may improve performance of the integrated systems [5]. The completeness of the data provided by INS, accuracy of these data and the fact that all sensor and processing equipment is placed on board of a helicopter makes them good candidates for more wide applications in flight tests.

In this paper an analysis of requirements for INS unit for applications in helicopter flight test is considered. The INS unit developed in Warsaw University of Technology is presented and the first results of experimental validation of INS behaviour is given. GPS/INS integrated system are considered for next phase of this research.

2. Overview of flying qualities evaluation

In ADS-33 the requirements for flying / handling qualities evaluation by flight tests are based on performing mission task elements (MTE) for which the well defined parameters of flying qualities are calculated. These parameters in great extent are related to control theory and are briefly summarised below, based on [1,3].

Bandwidth parameter, derived from the gain and phase of the frequency response of helicopter attitude to pilot's cyclic control, it is defined (Fig 1) as the lesser of two frequencies, the *phase-limited* (given by the frequency at which the phase is 135^0, behind the control) or *gain-limited* bandwidth (given by the frequency, at which the gain function has increased by 6 dB relative to the gain when the phase is 180^0). The bandwidth criteria apply to both types of response rate and attitude but for attitude response-types, only the phase bandwidth applies.

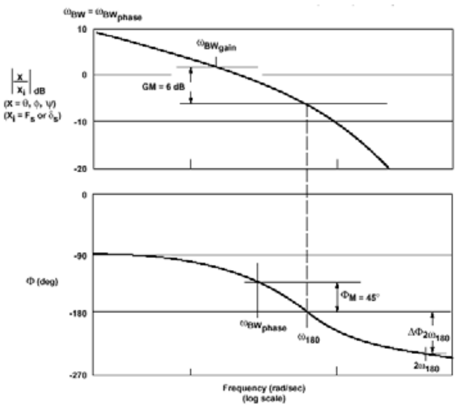


Fig.1. Bandwidth criteria (ADS 33E)

Phase delay reflects the lag of helicopter response to applied control and is defined as

(1) $$\tau_p = \frac{\Delta\Phi_{2\omega_{180}}}{57.3 \times 2\omega_{180}}$$

The quickness of response q is the maximum achievable ratio of value of the rate peak p_{pk} to a given attitude change $\Delta\phi$ (Fig. 2).

(2) $$q = \frac{p_{pk}}{\Delta\phi}$$

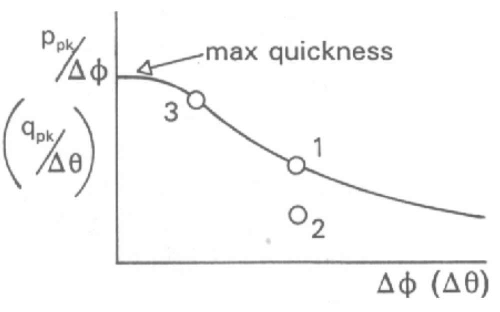


Fig.2. Quickness parameter

The quickness is a measure of frequency. For small amplitudes it represents the maximum "closed-loop" frequency achievable from the aircraft, therefore it is a measure of the manoeuvre performance (or agility) of the aircraft and/or a parameter of handling qualities.

Agility factor - this the ratio of the theoretically ideal task time with the achieved time.

(3) $$A_f = \frac{T_i}{T_a} = \frac{\omega_{BW}\Delta t}{\omega_{BW}\Delta t - \ln(0.05)}$$

where:

T – ideal task time, T_a – the time to reduce the bank angle to within 5% of the peak, ω_{BW} – bandwidth, Δt – the control pulse duration .

The ideal time is computed based on the assumption that the time to maximum helicopter acceleration is zero.

Ag*ility factor* describes the ability of the aircraft "to adopt and respond rapidly and precisely with "safety and with poise", to maximize mission effectiveness.

The other parameters: *control power* and *dynamic stability* have the "classical meanings" and are not directly translated into measured parameters of aircraft motion.

The requirements described in ADS concern for instance small or moderate changes of attitude (pitch and roll angles), heading and yaw response (for target acquisition and tracking), limits on pitch (roll) oscillation. It stems from the contents of ADS, that during flight tests it would be useful to measure all components of attitude angles and rates, as well as translations and velocities (relative to the ground) and measuring accelerations would also help to correlate pilots work-load with flight conditions.

In Table I the ranges of values of these parameters which may be encountered during flight tests are given as concluded from ADS-33. The prospective accuracy of measurement is also given as selected fraction of the range. Assuming 3% accuracy of the measuring equipment the accuracy of the total measuring system (sensors resolutions) was calculated. Such evaluations may be done separately for each MTEs given in ADS 33. In Table II the limits of manoeuvre performance is summarised.

3. Helicopter instrument requirements

Minimal standard avionic for helicopter is defined in FAA (JAA) regulations for two categories of rotorcraft.

Table I Flight test parameters of aircraft motion encountered in the ADS flight tests.

Measured parameters	Sym	Unit	Value range		Accuracy (proposed)
			min	max	
Fuselage pitch angle	θ	deg	- 60	+ 60	± 0,3
Fuselage roll angle	γ	deg	- 80	+ 80	± 0,3
Fuselage yaw angle	ψ	deg	- 200	+ 200	± 0,3
Slip angle	β	deg	- 30	+ 30	± 0,5
Fuselage roll rate	ω_x	deg/s	- 90	+ 90	3,5 deg/hr
Fuselage yaw rate	ω_y	deg/s	- 30	+ 30	3,5 deg/hr
Fuselage pitch rate	ω_z	deg/s	- 60	+ 60	3,5 deg/hr
Flight velocity (instrumental)	V_{IAS}	km/h	0	250	± 3 (do 20) ± 5 (20÷250)
Radio altitude	H_R	m	0	150	± 1
Baro altitude	H_B	m	0	500	± 15
Overload (in the C.G. of fuselage)		g	- 5	+ 5	0,001
Helicopter position		m	0	1000	0,5

Table II. The limits of helicopter motion during flight tests.

Description	ADS-33D	
	Required	Adequate
Translation during manoeuvres: longitudinal and lateral	±2 m	±3.5 m
Altitude hold during hover	±1m	±2 m
Min velocity during acceleration	93 km/h	93 km/h
Altitude variations during manoeuvres	≤15 m	∠60 m
Min pitch angle during deceleration	30^0	10^0
Min bank angle during acceleration	25^0	25^0
Roll angle hold during manoeuvres	$\pm10^0$	$\pm15^0$
Yaw angle hold during manoeuvres	$\pm5^0$	$\pm10^0$
Azimuth accuracy during 180^0 turn	equipment requirements	$\pm3^0$
Mac vertical load during deceleration	1.4g	1.4g
Vertical load	3g	2.4g

An example of avionics mounted on medium size helicopter is given in Fig.3., the equipment measuring data for flight tests are in bold - italics.

The following are the required flight and navigation instruments according to Far 27.1303:

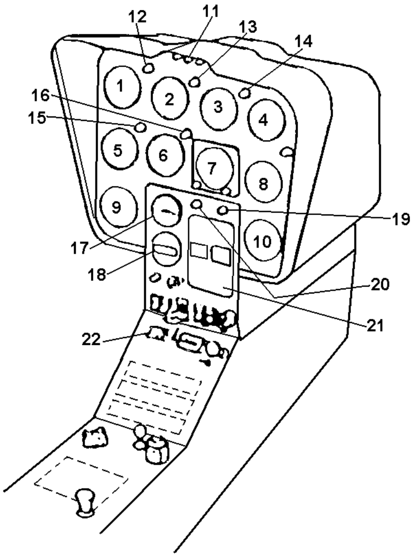
- *altimeter* - using the same pressure system as airspeed indicator
- *airspeed indicator* - calibrated to indicate true airspeed (at sea level with a standard atmosphere) with a minimum practicable instrument calibration error calibrated in flight at forward speeds of 20 knots and over, at each forward speed above 80 percent of the climb-out speed, the airspeed indicator must indicate true airspeed, at sea level with a standard atmosphere, to within an allowable installation error of not more than the greater of +/-3 % of the calibrated airspeed; or five knots,
- *magnetic direction indicator* - installed so that its accuracy is not excessively affected by the rotorcraft's vibration or magnetic fields; and may not have a deviation, in level flight, greater than 10 degrees on any heading.

According to JAR 29.1303 required flight and navigation instruments (usable for motion measurements) are:

- *airspeed indicator*,
- *sensitive altimeter*,

- *rate-of-climb (vertical speed) indicator*,
- *magnetic direction indicator*,
- *clock* displaying hours, minutes, and seconds with a sweep-second pointer or digital presentation,
- *gyroscopic bank and pitch indicator* (non-tumbling),
- *gyroscopic rate-of-turn indicator* combined with an integral slip-skid indicator (turn-and-bank indicator) except that only a slip-skid indicator is required on rotorcraft with a third altitude instrument system that is useable through flight altitudes of +/- 80 degrees of pitch and +/- 120 degrees of
- *roll gyroscopic direction indicator*.

In the Table III These requirements are summarised with data.



1. Rotor and engine tachometer;
2. ***Airspeed indicator;***
3. ***Attitude indicator;***
4. ***Coding Altimeter;***
5. Manifold pressure indicator;
6. ***Turn and slip;***
7. ***Horizontal situation indicator;***
8. ***Vertical speed indicator;***
9. ***Radiocompass;***
10. DME indicator;
11. Marker caution device;
12. Unsafe oil temperature in main rotor drive gearbox;
13. Ferromagnetic particles detection in tail rotor gearbox warning device;
14. Ferromagnetic particles detection in main rotor gearbox warning device;
15. Low r.p.m. warning device;
16. Low full warning device;
17. Air temperature in carburettor indicator;
18. ***Clock;***
19. Low oil pressure warning device; Low generator voltage warning device;
20. Engine instrument;
21. Free-air temperature indicator;

Fig.3. Avionics mounted on medium size helicopter

Table III Requirements for standard instruments.

	Instrument	Accuracy required
	airspeed indicator	± 1 km/h
	altimeter	± 1 m
	magnetic direction indicator	± 3^0
	sensitive altimeter	± 1m

Description given in regulations (FAR, JAR) does not provide information of errors, so the accuracy of instruments mounted on helicopter may be not adequate for flight tests. The instruments required by regulations mainly aid pilot to handle aircraft. Usually data presented by these instruments are utilized in flight tests, and special arrangements for signal recording are made.

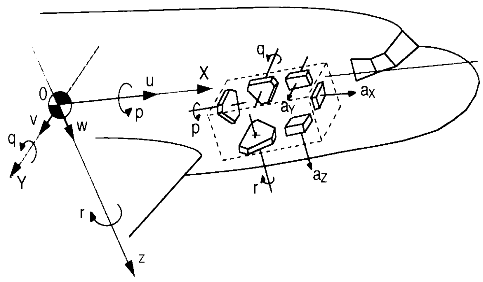
Inertial Navigation System technology.

In modern avionics attitude and rates of aircraft are measured and processed in the systems of orientation and navigation. These data are presented in indicators aiding a pilot to fly. The first concept evaluated in this study is to use "standard" avionic systems mounted on the aircraft to measure translations and rates of helicopter. These instruments are to be supported by integrated navigation system.

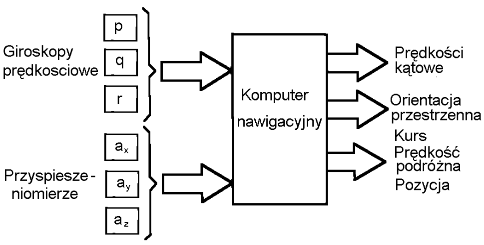
There are two candidates in modern avionics which may be applied in measurements during flight test: Global Positioning System and Inertial Navigation systems. INS measuring unit of a strap down inertial navigation system consists of a triad of accelerometers and a triad of gyroscopes fixed to the aircraft [6]. The sensed quantities are accelerations and angular rates(Fig. 4).

The output signals are: angular rates measured in aircraft coordinate system, attitude of aircraft in (described as Euler angles), position of aircraft (altitude, latitude and longitude in navigation system of coordinates), velocity relative to the ground and heading. These quantities are obtained after processing of sensor data. The data flow for INS system is given in Fig. 5 [6]

The main disadvantage, inherent to INS principle of operation is that the error of the position measurements grows with time (as t^2). To obtain adequate accuracy, good quality (and rather expensive) sensors should be applied. The other difficulty in INS application, especially in helicopter, is the level of vibrations, which corrupts the measurements of accelerations and rates.



a) Strap-down navigation system fixed to airframe



b) Input / output signals in strap-down INS

Fig.4. INS principle of operation

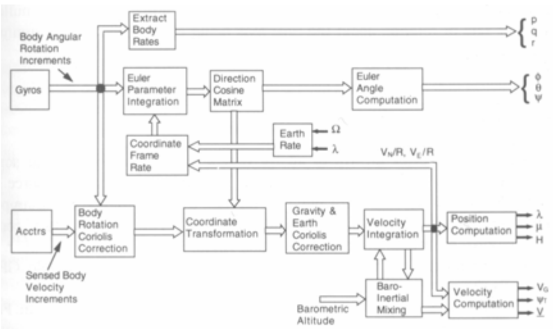
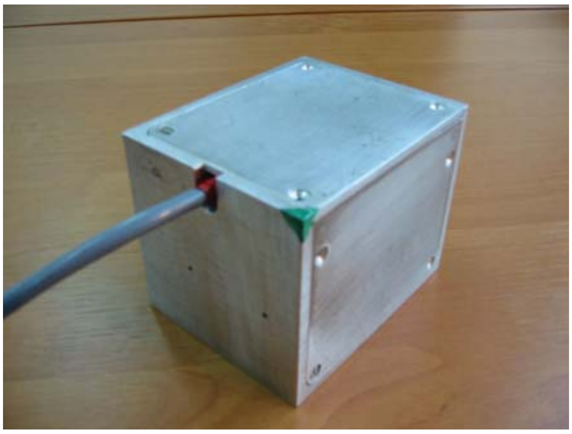


Fig.5. Data flow in strap-down navigation system

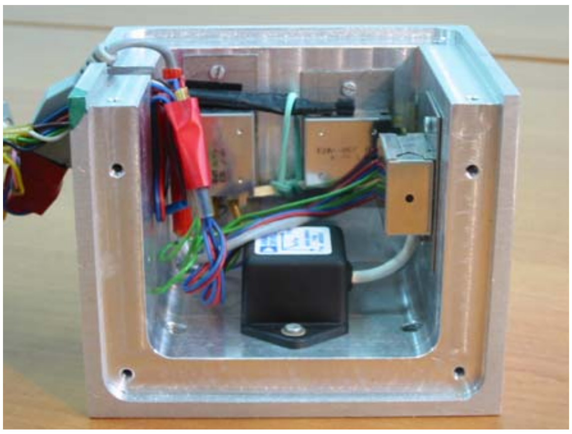
The objective of the research undertaken in Warsaw University of Technology is to develop the INS unit composed of standard, non-expensive off-the-shelf accelerometers and gyroscopes mounted to the aircraft during the fight tests to measure attitude, translations and rates of helicopter.

During the flight tests time duration of performing MTEs is usually not very long, so it may be expected that the fast growing acceleration error may be compensated either by proper signal filtering or integrating INS with GPS receiver.

In Fig 6 the INS unit developed in Warsaw University of Technology is shown. It is composed of three ENV-05F-03 Murrata piezoelectric gyroscopes and one, three component accelerometer ADXL150EM manufactured by Analog Devices. The electronic temperature measuring device is also mounted inside for prospective temperature compensation. The technical data of the sensors are given in the web pages of the manufacturer. This is the second version of the INS unit developed at WUT, which is now under laboratory tests for determination of errors of sensor axis alignment and temperature compensation.



a) Operation mode



b) inside view

Fig.6. INS unit developed in Warsaw University of Technology.

To reject the noise inherent to acceleration and rate signals the Kalman filter has been developed and validated on the first version of measuring unit. This instrument was tested in land vehicle.

In Fig. 7 two examples of noise filtering for accelerometers and gyroscopes is given as measured in on-ground tests.

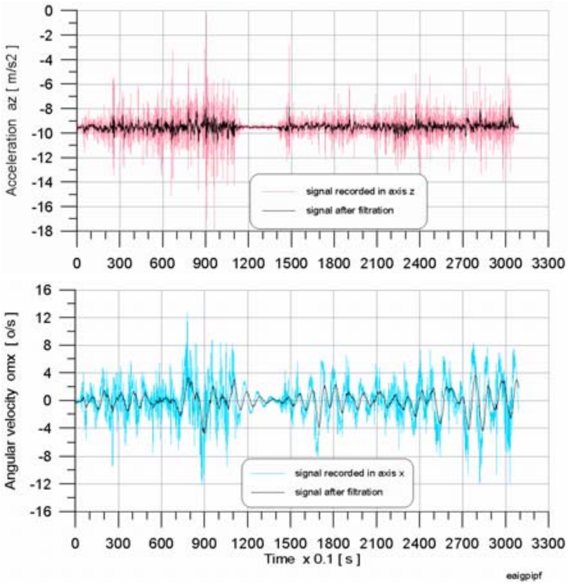


Fig.7. Filtering of acceleration (a) and rate (b) signals during on-ground tests.

INS/GPS integration

Due to switching of the S/A the accuracy of position determined by GPS receivers in C/A code raised substantially, so application of GPS receivers in flight tests becomes more attractive. Now, standard GPS receiver provides position with accuracy about 30 m, but the *relative* position is measured much more accurate. Using standard GPS receiver, with proper antenna placement (four satellites must be visible, providing continuous signal acquisition) the translations and velocities of the aircraft may be measured.

To obtain the attitude angles the Carrier Phase (CP) GPS technique may be used (Fig.8) which allows the same data from GPS as from INS, but such equipment is rather very expensive. (Fig.8).

Fig.8. Four antenna CP GPS receiver for attitude measurements (Tansvector – *Trimble)*

The GPS/INS sensors integration based on Kalman filtering is now also under development in WUT.

Conclusions

The main objective of the research undertaken at Warsaw University of Technology is to validate the possibility of utilisation of modern avionic systems in flight tests of helicopter flight qualities. The analysis of ADS and FAA requirements gave the indications to the accuracy of instruments to be used in flight tests. Modern INS and GPS sensors provide all data needed in flight tests. The measuring INS unit composed of standard off-the-shelf accelerometers and gyroscopes was developed at Warsaw University of Technology and successfully tested on the ground. The next steps will be integration with GPS and in – flight trials.

Acknowledgments

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