FREQUENCY DOMAIN IDENTIFICATION OF KA-50 HELICOPTER DYNAMICS FROM FLIGHT TEST DATA

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Abstract

An approach to identification of helicopter flight dynamics in frequency domain with application of spectral analysis techniques is developed. The basis for spectral analysis is the finite Fourier transform allowing to transform initial data into frequency domain. The Ka-50 helicopter handling qualities are determined using frequency criteria of Aeronautical Design Standard, ADS-33C(D), Handling Qualities Requirements for Military Rotorcraft, drawn up in the USA. The helicopter handling qualities are defined without conducting a helicopter system identification that allows to use developed technique directly in flight tests. The technique is demonstrated using flight test data from a lateral manoeuvre of the Ka-50 helicopter.

1. Introduction

Recently a number of papers [1-6] have appeared which discuss the application of Aeronautical Design Standard ADS-33C [7] to helicopter handling qualities evaluation. However, to substantiate compliance with the requirements of ADS-33C, simulation results are more often used than flight test data. The helicopter system identification is especially difficult because of the high degree of inter-axis coupling and the high order of the helicopter dynamical system. The developed technique allows to determine handling qualities without conducting a helicopter system identification. The results determined with use of this technique are more reliable because the flight test data are used as initial data.

The main purpose of this work was to investigate the suitability of the ADS-33C for coaxial combat helicopters. The Ka-50 helicopter handling qualities levels were determined in two ways: using a mathematical model and using flight test data. A comparison was made between these results and handling qualities ratings given the helicopter by Kamov test pilots.

2. Description of the Ka-50 Helicopter

Fig. 1. Ka-50 Black Shark helicopter

Ka-50 Black Shark (Fig. 1) is a single-seat attack helicopter for destroying armoured vehicles, slow-speed air targets and manpower on the battlefield.

Coaxial Ka-50 helicopter has two three-blade rotors of 14.5-m diameter each. The polymeric composite blade is attached to the hub by a torsion bar. The airframe features perfect aerodynamic outlines, mid-set stub wing, retractable three-leg landing gear and empennage of a fixed-wing aircraft type.

A coaxial rotor helicopter has the next features: higher power-to-weight ratio due to the absence of power losses for a tail rotor; 1.5...2 times lower inertia moments of the helicopter; ability to perform a pedal (flat) turn within the full flight speed range; the best vertical rate of climb and hovering ceiling.

3. Theoretical Development

Finite Fourier Transform

The Fourier transform of a continuous scalar time function $x(t)$ on a finite time interval $0 \le t \le T$ is called the finite Fourier transform [8, 9], and is defined by

$$X(i\omega) = \frac{1}{\sqrt{2\pi}} \int_0^T x(t) e^{-i\omega t} dt \qquad (1)$$

To define frequency responses of a helicopter, a finite Fourier transform calculation algorithm was developed. Efficiency of five different techniques of Fourier integral numeric calculation was evaluated. It was found that the most efficient method for processing the flight test data by is that of Simpson [10, 11].

Definition of Spectral Density Functions using Finite Fourier Transform

Consider a pair of realisations $x_k(t)$ and $y_k(t)$ of steady random processes $\{x_k(t)\}$ and $\{y_k(t)\}$. Let us define on finite time interval $0 \le t \le T$ the following function

$$S_{xy}(f,T,k) = \frac{1}{T} X_k^*(f,T) Y_k(f,T) \qquad (2)$$

where:

$$f = \frac{\omega}{2\pi}$$

$$X_k(f,T) = \int_0^T x_k(t) e^{-j2\pi f t} dt \qquad (3)$$

$$Y_k(f,T) = \int_0^T y_k(t) e^{-j2\pi f t} dt \qquad (4)$$

Values $X_k(f,T)$ and $Y_k(f,T)$ are finite Fourier transforms of $x_k(t)$ and $y_k(t)$ realisations correspondingly.

Cross-spectral density $S_{xy}(f)$ is defined by

$$S_{xy}(f) = \lim_{T\to\infty} M\left[S_{xy}(f,T,k)\right] \qquad (5)$$

where $M\left[S_{xy}(f,T,k)\right]$ is mathematical expectation taken by *k* index range. Autospectral densities $S_{xx}(f)$ and $S_{yy}(f)$ are simply special cases of formula (5). One-sided cross-spectral density $G_{xy}(f)$ is defined by

$$\begin{cases} G_{xy}(f) = 2S_{xy}(f), & f \ge 0, \\ G_{xy}(f) = 0, & f < 0 \end{cases} \qquad (6)$$

Substitution of $S(f)$ with the corresponding $G(f)$ brings us to the following formulas:

$$G_{xy}(f) = 2 \lim_{T\to\infty} \frac{1}{T} \times \\ \times M\left[X_k^*(f,T) Y_k(f,T)\right] \qquad (7)$$

$$G_{xx}(f) = 2 \lim_{T\to\infty} \frac{1}{T} M\left[\left|X_k(f,T)\right|^2\right] \qquad (8)$$

$$G_{yy}(f) = 2 \lim_{T\to\infty} \frac{1}{T} M\left[\left|Y_k(f,T)\right|^2\right] \qquad (9)$$

The length of realisation *T* is practically always finite so the passage to the limit $T \to \infty$ is realisable only theoretically. Mathematical expectation *M* is also always defined only by finite length since it is impossible to obtain an infinite collection of real data [9].

Definition of Single-Input-Single-Output Linear System Characteristics by Spectral Analysis Methods

A single-input-single-output (SISO) linear system is examined (fig. 2). It is assumed that realisations of steady random process with zero average are input into the system and the system is linear and has constant parameters.

Let the SISO linear system be defined by a frequency characteristic $W(f)$. Let us assume that influence of one specific input signal $x(t)$ upon the system causes one specific output signal $y(t)$ (fig. 2). The input and output signals are realisations of steady random processes $\{x(t)\}$ and $\{y(t)\}$ correspondingly [9].

Fig. 2. Single-input-single-output linear system

It can be shown that physically measurable one-sided spectral densities $G_{xx}(f)$, $G_{yy}(f)$ and $G_{xy}(f)$ are defined by

$$G_{yy}(f) = |W(f)|^2 G_{xx}(f), \quad (10)$$

$$G_{xy}(f) = W(f) G_{xx}(f) \quad (11)$$

The phase characteristic is computed from

$$\frac{G_{xy}(f)}{G_{yx}(f)} = \frac{W(f)}{W^*(f)} = e^{-j2\theta(f)} \quad (12)$$

4. Results

The Ka-50 helicopter handling qualities levels were determined in two ways: using a mathematical model and using flight test data. Bandwidth ω_{BW} and phase delay τ_P parameters were determined according to the definitions in the ADS-33C. The results are plotted in Fig. 3 using the ADS-33C small amplitude roll criteria for hover and low speed flight.

As can be seen from Fig. 3, the mathematical model still ensures a better result. This is explained by the fact that, naturally, the mathematical model accounts not for all non-linearities and inter-axis couplings.

The results plotted in Fig.3 predict Level 1 handling qualities both for a mathematical model and for the flight test data. This is substantiated by pilot ratings that characterise the helicopter as highly manoeuvrable combat helicopter distinguished by its outstanding power characteristics, efficiency and handling qualities as compared with the majority of the same class helicopters.

Marks corresponding to other helicopters - UH-60A Black Hawk, AH-64A Apache, OH-58 Bell-206, Tiger and Bell-214ST - obtained from [6, 12] are also marked in Fig. 3. All these helicopters are combat manoeuvrable helicopters and that is demonstrated by positions of their handling qualities points - not below Level 2, nearer to Level 1.

Fig. 3 also shows the handling qualities boundaries of a further development of the same standard (ADS-33D) [13]. They are more rigid than those of ADS-33C. Nevertheless, even by these criteria the Ka-50 practically retains its Level 1handling qualities.

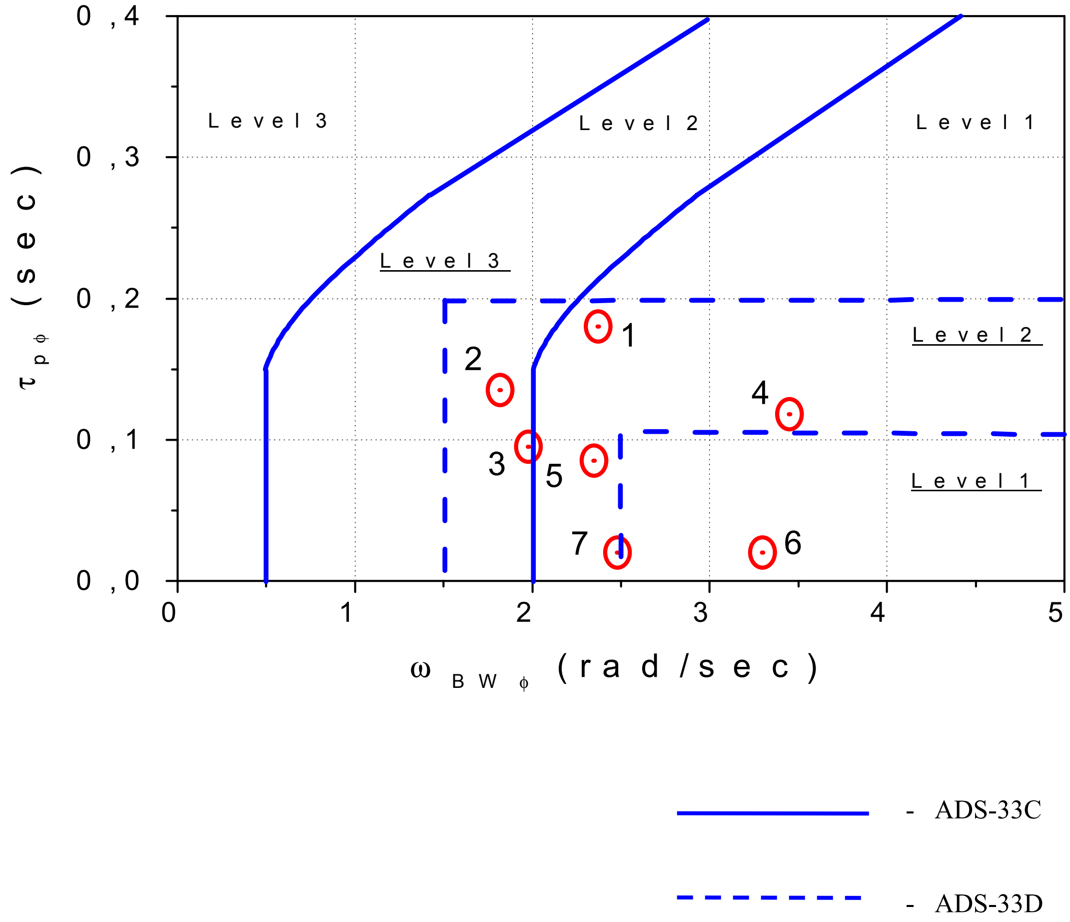

Fig. 3. Small amplitude roll criteria for hover and low speed flight

Helicopters:

1 - UH-60A Black Hawk

2 - AH-64A Apache

3 – Tiger

4 - OH-58 Bell-206

5 - Bell-214ST

6 – Ka-50 (using mathematical model)

7 – Ka-50 (using flight tests data)

5. Conclusions

1. Methodology of evaluating helicopter handling qualities using Aeronautical Design Standard ADS-33C(D) has been developed.
2. The predicted Levels of the Ka-50 helicopter handling qualities correlate well with handling qualities ratings given the helicopter by Kamov test pilots.

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