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Handling Qualities Evaluation of an Autogiro Against the Existing Rotorcraft Criteria

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Despite having first been developed in the 1920s, the autogiro has never been subject to handling qualities requirements. This paper presents a first logical step in developing handling qualities criteria for the autogiro, and that is to assess autogiro handling qualities against existing rotorcraft criteria. It is demonstrated that the autogiro's objective handling qualities can be estimated using frequency domain criteria from the ADS-33E-PRF, AGARD-R-577-70, and MIL-HDBK-1797 documents. The assessment is based on flight test data for longitudinal and lateral–directional stick-fixed oscillations and frequency sweeps collected from flight trials of a Glasgow University research autogiro.

I. Introduction

THE autogiro, as a flying vehicle, has a long and diverse history [1]. Having played a test-bed role for solving challenging problems at early stages of the rotary-wing development (for example, an introduction of flap hinges to make possible a stable and controllable vertical flight), the autogiro did not enjoy the extensive research and development efforts expended on the helicopter. Recently, however, the interest in autogiros has grown considerably, mainly due to the new technologies and low production cost. In 1993 the U.K. Civil Aviation Authority issued an airworthiness standard for light autogiros: "British Civil Airworthiness Requirements, Section T, Light Gyroplane Design Requirements" [2], and later its superseding, "British Civil Airworthiness Requirements, Section T, Light Gyroplanes" [3,4]. The University of Glasgow has contributed for development of these requirements by conducting research on autogiro aerodynamics and flight mechanics [5–11]. Notwithstanding that this airworthiness standard provides simple requirements for dynamic stability mainly due to the nature of the autogiro community (homebuilt aircraft), it does not specify any direct handling qualities criteria. It is worth noting that even those requirements for dynamic stability are primarily based on those from airworthiness requirements for small light airplanes, British Civil Airworthiness Requirements Section S [12] and aviation regulations for small rotorcraft, JAR/FAR-27 [13,14].

It is well known that aircraft handling qualities strongly affect mission effectiveness and pilot workload, and thereby flight safety. Taking into account alarming statistical results for autogiro accidents in the U.K. [15], there is an obvious need to improve autogiro safety. Research at Glasgow over the past 10 years has focused on airworthiness problems caused by dynamic instability [16–19]. The assumption was that improving airworthiness would improve handling qualities but as, to the authors' best knowledge, there are currently no criteria by which autogiro handling qualities can be systematically measured, it has not been possible so far to quantify exactly what improvement has been achieved. It is clear that as the popularity of the autogiro configuration grows, there will be a need to make formal assessments of handling qualities. The research reported in this paper represents a first logical step in developing handling qualities criteria for the autogiro, and that is to apply existing criteria for other vehicles [helicopters, fixed wing aircraft, and vertical/short takeoff and landing (V/STOL) aircraft] and assess whether they can be used in their existing form, or in a modified form. Given the resources available, it was, of course, not possible in this study to develop a full set of criteria for all aspects of the autogiro's handling qualities. Instead, the focus was on the dynamic stability and bandwidth characteristics. The objective of the research is to provide initial guidance to others researching this field and to regulatory bodies considering implementing handling qualities requirements for autogiros.

The objective assessment of handling qualities, which does not depend on a pilot's qualitative opinion, can be obtained from quantitative criteria, which are specified in various standards and specifications. The aim of this paper is to demonstrate that the autogiro's objective handling qualities can be estimated using criteria from the ADS-33E-PRF [20], AGARD-R-577-70 [21], and MIL-HDBK-1797 [22] documents. First, autogiro dynamic stability characteristics will be introduced, which are compared with other types of aircraft. The quantitative metrics of handling qualities are based primarily on stability and controllability characteristics of the aircraft. Because the short period mode and the Dutch roll mode are considered as the most influential in determining the handling qualities of an aircraft, only these two modes will be discussed. The second part of the paper will provide results of assessment of autogiro handling qualities levels against ADS-33E-PRF, AGARD-R-577-70, and MIL-HDBK-1797 criteria. It should be noted though that only objective handling qualities will be considered throughout the paper.

II. Dynamic Stability Characteristics

The research autogiro (registration G-UNIV) was manufactured by Jim Montgomerie Gyrocopters and is owned by the Department of Aerospace Engineering, University of Glasgow, for study and flight test purposes. In fact, the aircraft (Fig. 1) is a converted original two-seat Montgomerie–Parsons autogiro. The second seat was removed and the space designed for the rear pilot's cockpit was used to house test instrumentation equipment. It has a teetering rotor with two blades attached to a hub without flap or lag hinges. The aircraft is powered by a two-cylinder/two-stroke ROTAX TYPE 618 engine, driving a 62-in. diam, three-bladed fixed pitch IVOPROP propeller. Its physical characteristics are presented in Table 1. G-UNIV is equipped with a range of sensors and a main instrumentation pallet, which was used to house a PC and signal conditioning units. The digital on-board recording system includes National Instruments 12-bit DAQ card and Labview software. The recording system acquired data from a number of channels and various types of transducers during the flight tests with the sampling frequency of 50 Hz (Table 2).

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Fig. 1 Glasgow University research autogiro (registration G-UNIV).

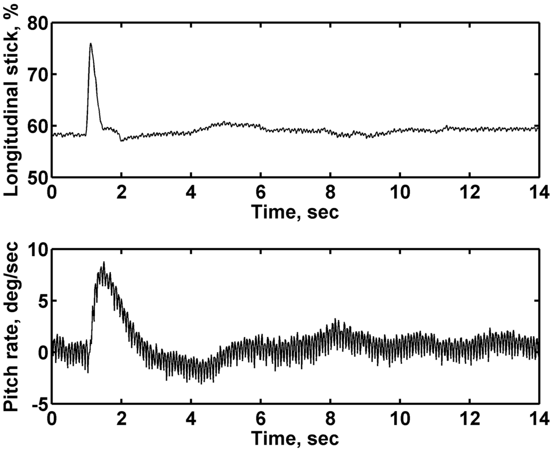

Fig. 2 Pitch rate response of the G-UNIV autogiro to a pulse input.

All the channels were filtered with fourth order Butterworth low pass antialiasing filters.

The short period mode of the G-UNIV autogiro was tested using longitudinal control pulses to induce pitch oscillations. Figure 2 shows an indicative example of the pitch rate response to longitudinal impulse disturbance input initiated from a steady level flight at 40 mph. The response characteristics, obtained directly from the test data for two pulse trials at 40 mph, are presented in Table 3, where ζ_{sp} is the short period damping ratio, and ω_{sp} is the short period undamped natural frequency. It should be stated that the pitch rate data were used to obtain these dynamic response metrics. It is clear from Table 3 that the values of the G-UNIV autogiro's short period damping are low, and most likely will not meet requirements for satisfactory, or level 1, handling qualities. The low short period damping can also be identified from Fig. 3, where the short period mode of the G-UNIV autogiro is depicted in the s plane in comparison with the VPM M16 autogiro [6] (Fig. 4, Table 4) and a Puma helicopter [23]. It is obvious from Fig. 3, that the G-UNIV autogiro's short period damping ratio is the lowest. Based on the results of the VPM M16 autogiro for 30 and 70 mph, it can be predicted that the damping ratios of the G-UNIV autogiro at higher speeds will most likely be even lower. The existence of the short period mode for the Puma helicopter is due to its articulated rotor (most hingeless rotor helicopters have pitch subsidence mode). The VPM aircraft has a substantially larger horizontal tailplane than the Montgomerie aircraft, G-UNIV (0.9 m^2 as opposed to 0.356 m^2), and is over 0.5 m further aft of the c.g. and hence it has significantly more damping in the short period mode. This is unusually large for an autogiro and has given the VPM short period characteristics which are as akin to the Puma as they are to the G-UNIV (a more conventional light autogiro configuration).

The second dynamic mode of interest in this paper is the Dutch roll mode, which represents a short period oscillation involving yaw, roll, and sideslip. The Dutch roll lateral–directional mode was tested using a yaw doublet (one right and left rudder cycle). Figure 5 shows one of the selected responses of the test autogiro to a doublet input initiated by the pedals at the airspeed of 40 mph. The three most successful doublet trials at the airspeed of 40 mph were selected for consideration and are presented in Table 5, where ζ_d is the Dutch roll damping ratio, and ω_d is the Dutch roll undamped natural frequency. Figure 6 presents characteristics of the Dutch roll mode of the G-UNIV research autogiro depicted in the s plane in comparison with those of Bo 105, Lynx, and Puma helicopters [23]. At low speed all three helicopter types have similar Dutch roll characteristics; however, as speed increases the Puma's Dutch roll becomes unstable whereas those of the Bo 105 and Lynx remain stable. Again it is the nature of the rotor design which determines the stability characteristics: both the Lynx and Bo 105 have rotors which are rigid in flap; that is, they rely on the structural stiffness of the blade

Table 1 Physical characteristics of the G-UNIV autogiro

General	Gross mass	355 kg
	Power (ROTAX TYPE 618)	55 kW (73.8 hp)
	Moments of inertia:	
	Roll	72.96 $kg \cdot m^2$
	Pitch	297.21 $kg \cdot m^2$
	Yaw	224.25 $kg \cdot m^2$
Main rotor	No. of blades	2
	Blade radius	3.81 m
	Blade chord	0.197 m
	Blade mass	17.255 kg
	Blade twist	0 deg
	Flapping inertia	83.492 $kg \cdot m^2$
	Lift curve slope	5.75 rad^{-1}
	Airfoil section	NACA 8-H-12
	Rotor direction	Anticlockwise
Propeller	Propeller blade radius	0.787 m
	Propeller blade chord	0.09 m
	Blade twist	0 deg
	Orientation of thrust line	1 deg

Table 2 Measured parameters and corresponding measurement devices

Measured parameter	Units	Measurement device
Longitudinal acceleration	m/s^2	Accelerometer
Lateral acceleration	m/s^2	Accelerometer
Normal acceleration	m/s^2	Accelerometer
Roll rate	deg /s	Angular rate sensor
Pitch rate	deg /s	Angular rate sensor
Yaw rate	deg /s	Angular rate sensor
Roll attitude	deg	Angle sensor
Pitch attitude	deg	Angle sensor
Yaw attitude	deg	Angle sensor
Indicated airspeed	mph	Air data probe
Altitude	m	Air data probe
Angle of attack	deg	Air data probe
Sideslip angle	deg	Air data probe
Longitudinal stick position	%	Position transducer
Lateral stick position	%	Position transducer
Pedal position	%	Position transducer
Throttle position	%	Position transducer
Propeller speed	rpm	Electro-optical sensor
Rotor speed	rpm	Electro-optical sensor

Table 3 Short period response characteristics

Trial no.	ζ_{sp}	ω_{sp}, rad/s	$-\zeta_{sp}\omega_{sp}$, rad/s
1	0.256	1.087	−0.278
2	0.275	1.026	−0.282

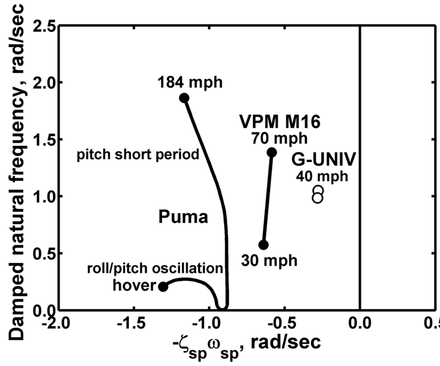

Fig. 3 Short period mode of the research autogiro in the *s* plane in comparison with the VPM M16 autogiro and a Puma helicopter.

Fig. 4 VPM M16 autogiro.

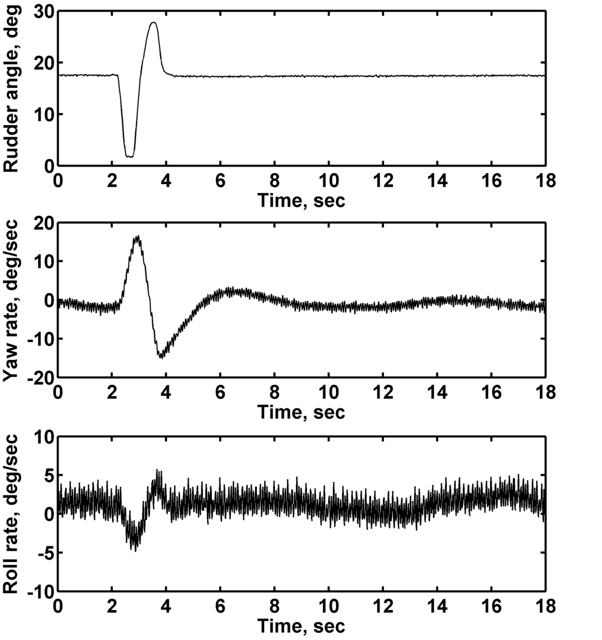

Fig. 5 Yaw and roll rate response of the G-UNIV autogiro to a rudder doublet.

root element to allow blade flapping to occur, while the Puma has an articulated rotor with flapping facilitated by a hinge. Autogiros such as G-UNIV have teetering rotors (essentially both blades are connected together and can flap, or teeter, about a central hinge) which again can provide different stability characteristics. It is clear from Fig. 6, however, that all three rotor types have broadly similar characteristics at low speed (where the autogiro operates).

III. Predicted Levels of Autogiro Handling Qualities

The handling qualities specifications for rotorcraft, such as MIL-H-8501A [24] and DEF STAN 00-970 Rotorcraft [25], were based on time-domain dynamic stability criteria. The modern U.S. handling qualities standard for military rotorcraft, ADS-33E-PRF [20], includes a new response-type mission-oriented concept based on extensive frequency-domain criteria. Mitchell et al. [26] called the appearance of this standard "a second revolution in handling qualities." What was started as the U.S. Army research program for a new experimental helicopter, LHX, in the early 1980s, became the most comprehensive handling qualities standard for military rotorcraft.

The ADS-33E-PRF standard uses two distinct methods of establishing levels of handling qualities, objective and subjective, or predicted levels and assigned levels. Predicted levels are obtained from quantitative criteria, assigned levels are obtained from test pilots using the Cooper–Harper handling qualities ratings scale to estimate the workload and task performance required to perform designated mission task elements (MTEs). There are some innovations in this standard, which are of interest in this paper. For example, the standard does not provide any categorization according to rotorcraft size. This makes this document universal and gives the possibility of developing future autogiro handling qualities requirements in a similar way, but with appropriate MTEs and response types. It should be noted that this is not the first time that handling qualities requirements for military rotorcraft have been adapted to different types of rotorcraft. There are examples of designing handling qualities requirements for civil tilt rotors [27–30] based on military standards for airplanes and rotorcraft. Some other attempts to adapt the handling qualities criteria of the ADS-33 standards for maritime [31–33], civil [34], and cargo helicopters [35] were also carried out.

The ADS-33E-PRF standard limits pitch and roll oscillations by terms of undamped natural frequency and damping ratio in the same manner as, for example, AGARD-R-577-70 [21] and MIL-F-83300 [36]. Figure 7 shows results of the *short period pitch oscillation* assessment for hover and low speed based on the data from Table 3. It can be seen that ADS-33E-PRF attains level 2 handling qualities for

Table 4 Physical characteristics of the VPM M16 autogiro

General	Gross mass	450 kg
	Power (ARROW)	89.5 kW (120 hp)
	Moments of inertia:	
	Roll	$195\ \mathrm{kg \cdot m^2}$
	Pitch	$637\ \mathrm{kg \cdot m^2}$
	Yaw	$442\ \mathrm{kg \cdot m^2}$
Main rotor	No. of blades	2
	Blade radius	4.267 m
	Blade chord	0.22 m
	Blade mass	8.5 kg
	Blade twist	0 deg
	Flapping inertia	$51.6\ \mathrm{kg \cdot m^2}$
	Lift curve slope	$5.7\ \mathrm{rad^{-1}}$
	Airfoil section	NACA 8-H-12
	Rotor direction	Anticlockwise
Propeller	Propeller blade radius	0.86 m
	Propeller blade chord	0.1 m
	Blade twist	0 deg
	Orientation of thrust line	2 deg

Table 5 Dutch roll response characteristics

Trial no.	ζ_d	ω_d, rad/s	$-\zeta_d\omega_d$, rad/s
1	0.341	0.827	−0.282
2	0.321	0.972	−0.312
3	0.272	0.880	−0.239

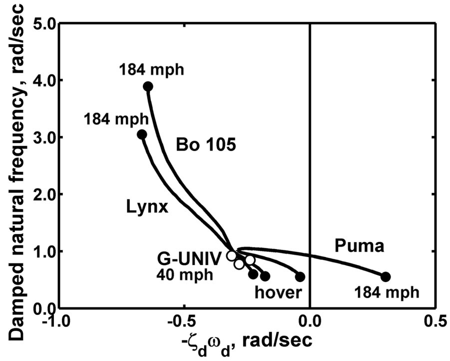

Fig. 6 Dutch roll mode of the research autogiro in the *s* plane in comparison with the Bo 105, Lynx, and Puma helicopters.

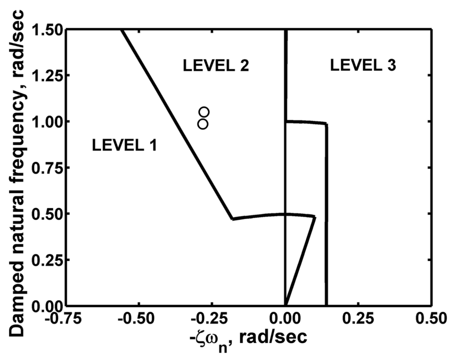

Fig. 7 Compliance with ADS-33E-PRF requirements on pitch oscillations (hover and low speed).

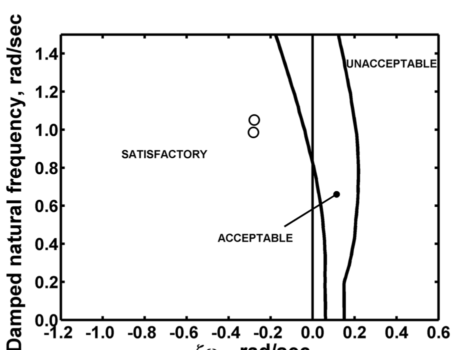

Fig. 8 Compliance with AGARD-R-577-70 longitudinal dynamic stability criteria.

the research autogiro, G-UNIV. It is clear that this criterion does not predict level 1 handling qualities because of the low damping ratios.

Further, Fig. 8 shows the compliance of G-UNIV with the V/STOL requirements of *longitudinal dynamic stability criteria* from AGARD-R-577-70, the aircraft attaining a satisfactory level of handling qualities. The satisfactory level defined by AGARD-R-577-70 can be compared to the level 1 handling qualities of the ADS-33E-PRF standard. In addition, AGARD-R-577-70 specification limits short period damping ratio; it should be at least 0.3. Because the average damping ratio of autogiro short period oscillation is approximately 0.266 (Table 3), the AGARD-R-577-70 requirement for short period damping is not satisfied.

Results of ADS-33E-PRF *lateral–directional oscillation assessments* for hover and low speed are shown in Fig. 9. It can be seen that the G-UNIV autogiro achieved level 2 handling qualities. As in the example depicted in Fig. 7, it is obvious that these criteria do not predict level 1 handling qualities because of the low values of

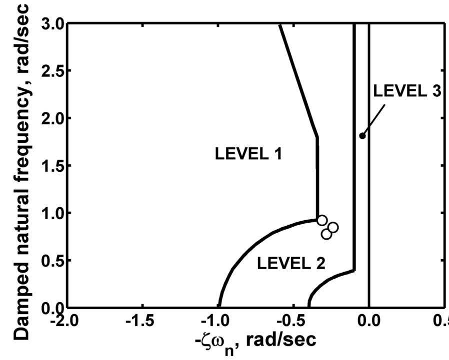

Fig. 9 Compliance with ADS-33E-PRF lateral–directional oscillatory requirements.

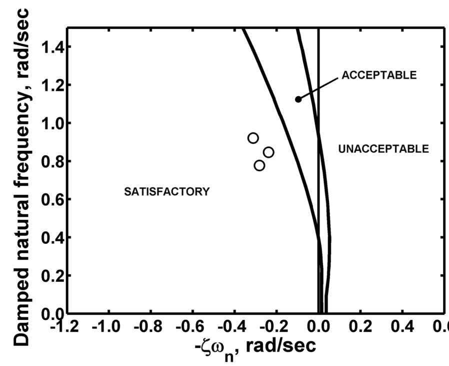

Fig. 10 Compliance with AGARD-R-577-70 lateral–directional dynamic stability criteria.

undamped natural frequency of lateral–directional oscillation. The AGARD-R-557-70 *lateral–directional dynamic stability* criteria predict a satisfactory level of handling qualities for the research autogiro (Fig. 10).

Other innovation of the ADS-33E-PRF standard that may be applied to a light autogiro is a concept of short-term bandwidth and time delay criteria, which form the basis for requirements for a small-amplitude range of rotorcraft maneuvers. Pausder and Blanken [37,38] gave background information and detailed explanation of these criteria. In general, an aircraft must have a high bandwidth to transmit the control input. Such an aircraft can be described as sharp, quick, or agile, whereas an aircraft with low bandwidth is sluggish, with a smooth response [39]. Research has shown that pilot handling qualities ratings strongly depend on the shape of the phase plot at frequencies beyond the neutral stability frequency. This led to a definition of the phase-delay parameter. A large phase delay can be caused by onboard flight control software, or delays of flight control hydraulic actuators. In addition, an aircraft with large phase-delay values can be prone to pilot induced oscillations. Because light autogiros usually do not use any stability augmentation, the phase-delay parameter is likely to be ineffective in application to light autogiros, whereas the requirements on a bandwidth are essential.

To apply the bandwidth and phase-delay criteria to the G-UNIV test autogiro, the frequency-domain attitude responses to pilot inputs are needed. The most appropriate approach to obtain frequency-domain responses is to excite the frequency range of the aircraft response by inducing control input oscillations with various frequencies. A series of frequency sweeps were conducted at airspeeds of 30, 50, and 60 mph during flight test trials of the research autogiro in February 2001. Thomson and Houston [11] used these frequency sweeps in a frequency-domain parameter estimation of the G-UNIV autogiro; earlier this approach was used by Houston [7] to identify VPM M16 autogiro's stability and control derivatives. The G-UNIV autogiro's frequency sweeps were initiated by small-amplitude inputs, which had varying frequencies of approximately 0.25 Hz at the beginning and between 2 and 3 Hz at the peak of each

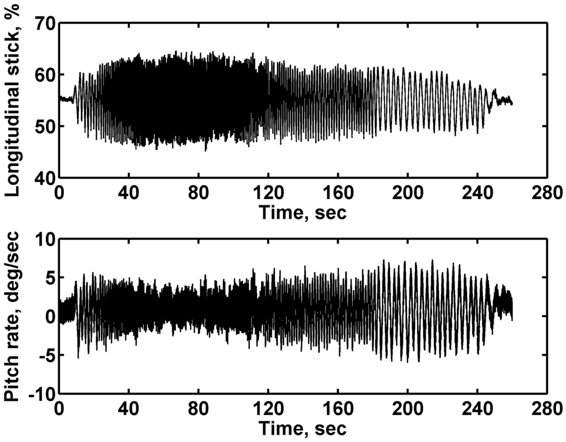

Fig. 11 Longitudinal frequency sweeps at 50 mph.

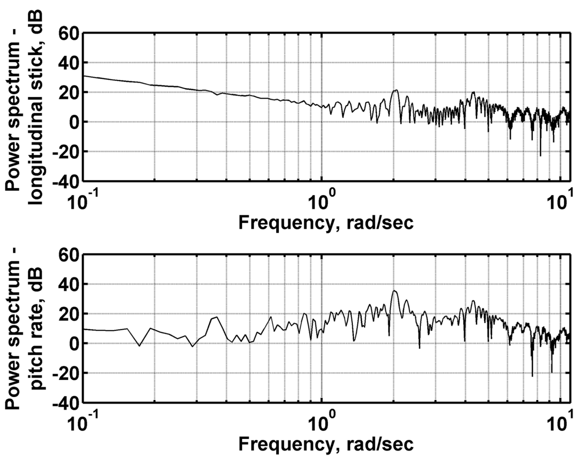

Fig. 12 Longitudinal sweep power spectrums.

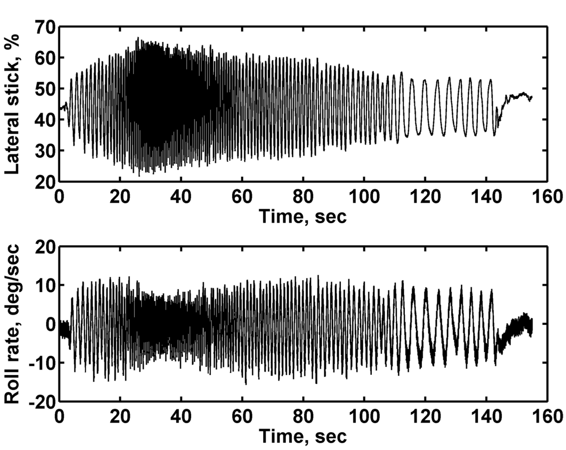

Fig. 13 Lateral frequency sweeps at 50 mph.

trial. The indicative results for the 50-mph pitch rate response to longitudinal sweeps are shown in Fig. 11 and the power spectral density plots for this response (longitudinal stick and pitch rate) are depicted in Fig. 12. The indicative results for the 50-mph roll rate response to lateral sweeps are shown in Fig. 13 and the pilot lateral stick and roll rate power spectral density plots are depicted in Fig. 14. It can be seen that in both examples the input and output power spectrums show significant energy up to 10 rad/s.

The pitch and roll bandwidth/phase-delay values were obtained from the 10 most successful longitudinal and lateral frequency sweeps using a technique defined in the ADS-33E-PRF standard.

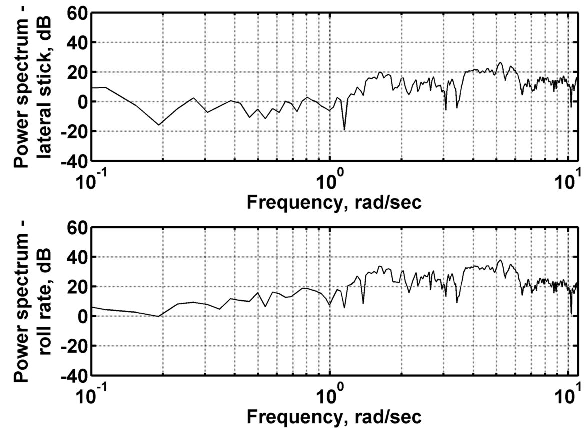

Fig. 14 Lateral sweep power spectrums.

These parameters were calculated from the spectral analysis of the pitch and roll rate response to pilot control inputs. The coherence functions for the frequency range up to 10 rad/s was very nearly one, showing good enough correlation to use the test data for a frequency-domain analysis. The required pitch and roll attitude frequency responses were determined by integrating the pitch and roll rate results. The bandwidth and phase-delay results for different airspeeds are summarized in Tables 6 and 7. It should be noted at this point that the ADS-33 standard was designed for military rotorcraft with advanced control systems, but, because current light autogiros have simple direct mechanical controls, an attitude-command/attitude-hold response-type approach was adapted in this preliminary study for demonstration purposes.

The ADS-33E-PRF standard defines pitch attitude bandwidth/phase-delay criteria for two speed ranges: 1) hover and low speed (up to 45 kt), and 2) forward flight (greater than 45 kt). Thus, the results for 30 mph (26.07 kt) and 50 mph (43.45 kt) trials should be assessed against hover and low speed requirements, and the results for 60 mph (52.14 kt) trials should be estimated against forward flight requirements. However, requirements for small-amplitude pitch attitude changes—hover and low speed [all other MTEs, UCE = 1 (usable cue environment), fully attended operations] completely coincide with those for forward flight [all other MTEs, visual meteorological conditions (VMC), fully attended operations]. As a result, the *small-amplitude pitch attitude* criteria predict level 1 handling qualities for the G-UNIV research autogiro (Fig. 15). The obtained results show that by an increase in the airspeed, the

Table 6 Longitudinal frequency sweeps characteristics

Trial no.	Airspeed, mph	Neutral stability frequency, rad/s	Phase bandwidth, rad/s	Phase delay, s
1	30	3.9	2.68	0.0494
2	50	5.0	2.25	0.0407
3	50	4.45	2.15	0.0429
4	60	4.3	1.54	0.0489
5	60	4.5	1.6	0.0458

Table 7 Lateral frequency sweeps characteristics

Trial no.	Airspeed, mph	Neutral stability frequency, rad/s	Phase bandwidth, rad/s	Phase delay, s
1	50	5.51	2.21	0.0551
2	50	5.53	2.43	0.0646
3	50	5.56	2.52	0.0672
4	60	5.35	2.35	0.0593
5	60	5.6	2.43	0.0591

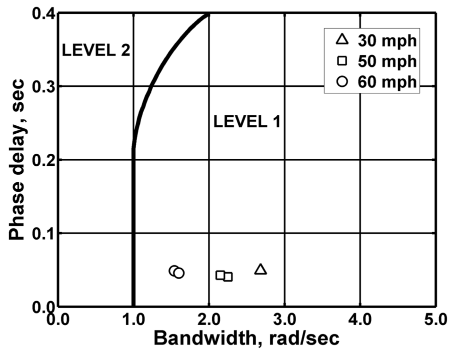

Fig. 15 Compliance with ADS-33E-PRF requirements for small-amplitude pitch attitude changes.

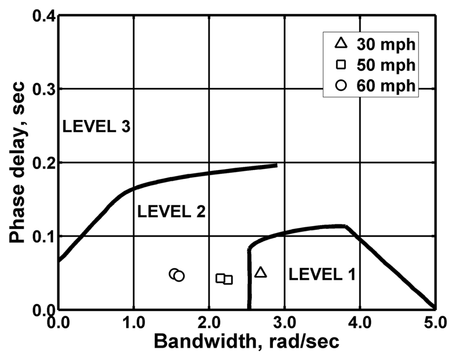

Fig. 16 Compliance with MIL-HDBK-1797 bandwidth requirements.

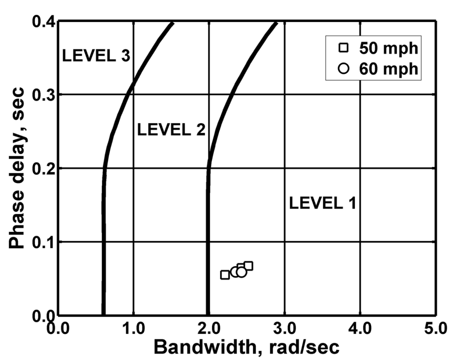

Fig. 17 Compliance with ADS-33E-PRF requirements for small-amplitude roll attitude changes.

bandwidth parameter is decreasing, indicating that the autogiro becomes less agile, or less sharp.

The MIL-HDBK-1797 document [22] also suggests using bandwidth and phase-delay criteria in a longitudinal channel. It can be seen from Fig. 16 that the MIL-HDBK-1797 criteria predict level 1 (1 point, 30 mph) and level 2 (4 points, 50 and 60 mph) handling qualities for the research autogiro. A comparison between levels defined by ADS-33E-PRF and MIL-HDBK-1797 shows that the latter standard is more stringent. However, it should be kept in mind that the adapted MIL-HDBK-1797 criteria are defined for category C flight phases, which "are normally accomplished using gradual maneuvers and usually require accurate flight-path control" [22].

The requirements for *small-amplitude roll attitude changes*—forward flight (all other MTEs, UCE = 1, fully attended operations) fully coincide with those for forward flight (all other MTEs, VMC, fully attended operations). Thus, the small-amplitude roll attitude criteria predict level 1 handling qualities for the G-UNIV research autogiro (Fig. 17). However, Pausder and Blanken [37,38] suggested

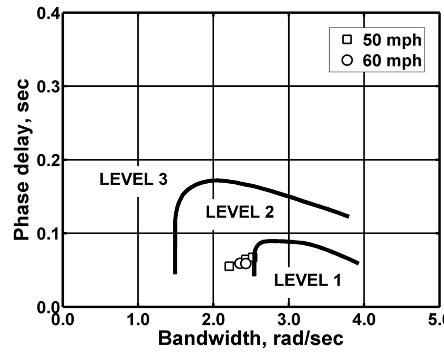

Fig. 18 Compliance with DLR bandwidth requirements.

different level boundaries for the roll axis criteria (Fig. 18), which do not agree with those of ADS-33E-PRF standard. The suggestion is based on flight test results of DLR's variable-stability Bo 105 advanced technology testing helicopter system. Four experienced test pilots with different backgrounds conducted a high bandwidth slalom tracking task and assigned Cooper–Harper handling qualities ratings. The level 1 of the DLR criteria requires not less than 2.5 rad/s for the bandwidth, and defines the phase delay to be lower than approximately 0.09 s. Requirements for level 2 are not less than 1.5 rad/s for the bandwidth, and not greater than 0.17 s for the phase delay. It is clear that both boundaries are more stringent than those of ADS-33E-PRF. Therefore, the G-UNIV autogiro meets only level 2 handling qualities of the DLR criteria (Fig. 18).

As can be seen from the results of Tables 6 and 7, the autogiro phase-delay parameter was no more than 0.07 s in all trials. It can be explained by the fact that the autogiro has a simple mechanical control system in contrast to highly augmented modern rotorcraft, where, for example, delays in the automatic flight control system or delays caused by actuator lag can influence the phase-delay parameter. This led to the conclusion that there is no reason to specify this parameter for the light autogiros, whereas bandwidth metrics should be considered.

IV. Conclusions

It has been demonstrated that the autogiro handling qualities can be estimated using the approach from the ADS-33E-PRF, AGARD-R-577-70, and MIL-HDBK-1797 documents, and, in addition, that autogiro's own criteria can be designed in the same manner as the criteria from these documents. Because the handling qualities were estimated against criteria, which were designed for military aircraft and rotorcraft and, moreover, that all the results are based only on limited flight test data, the obtained handling qualities levels of the research autogiro should be considered as a preliminary estimation. Extensive flight tests and computer simulations are therefore essential to form a database of objective and subjective assessments of handling qualities of light autogiros with the aim of developing new autogiro requirements and criteria in the future.

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