DESIGN TRENDS FOR ROTARY-WING UNMANNED AIR VEHICLES

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Abstract

The paper presents results of design trends analysis for Rotary-Wing Unmanned Air Vehicles (RWUAVs), which is founded on a unique database that consists of more than 250 full-scale helicopters and rotary-wing UAVs. The database has been created using data from a vast range of open sources, and includes geometry parameters, weight of components, preliminary power and flight performance estimation and potential applications. The statistical analysis has been carried out using advanced computerized correlation technique that exploits multiple regression analysis and may incorporate a large number of independent unknowns.

As opposed to first order and relatively simple analysis which are typically used in the first preliminary stages, the results presented in this paper include correlations and design trends of existing flying configurations, and therefore contains many design constrains that emerge only during the advance stages of the design process.

1 Introduction

1.1 UAV Classification

Different approaches to the classification of unmanned air vehicles (UAVs) which are founded on design and operational parameters were proposed. Newcome [1], reviews UAV history, and presents chronology of robotic aircraft.

The NASA Wallops Flight Facility site [2] presents the following categories of vehicles for surveillance UAVs: *Close* Range (within 50 km), *Short* Range (within 200 km), and *Endurance* (anything beyond). The *Close* and *Short* categories, Maritime Vertical Take-Off and Landing (VTOL) UAV, Tilt-Rotor and Vertical Launch and Recovery are all incorporated as *Tactical* UAV (TUAV). The *Endurance* category includes MALE (Medium Altitude Long Endurance) and HALE (High Altitude Long Endurance) vehicles.

The UAV Roadmap [3] for developing and operating UAVs over the 25 years period (2000 to 2025) describes the "theater warfighters" to which UAVs could be applied. It classifies existing and future UAVs by ten Autonomous Control Levels from "Remotely Guided" to "Fully Autonomous Swarms".

In the study on integration of UAVs into future Air Traffic Management (ATM) [4], it is indicated that classifications based on the type of mission, like TUAV, combat UAV, etc., or based on altitude and endurance, like MALE or HALE, which are often used by military customers are less relevant for ATM. The study proposes a classification which is based on the Maximum Take-Off Weight (MTOW), similar to manned aircraft. It was indicated that these weight categories correlate very well with other classification criteria like range, mission radius and maximum flight altitude.

1.2 RWUAV Classification

Previous study for preliminary design of helicopters [5] has shown that MTOW is a key parameters for the full-scale rotary-wing vehicles sizing.

The table (adopted from [4]) presents UAV classification by MTOW while Fig. 1 illustrate RWUAVs gross weight based classification.

Class	MTOW, kg	Range Category	Task Radius, km	Max Altitude, km
0	< 25	Close	< 19	0.30
1	25-500	Short	19-185	4.6
2	500-2000	Medium	185-925	9.1
3	> 2000	Long	> 925	> 9.1

Table. Classification of UAV by MTOW.

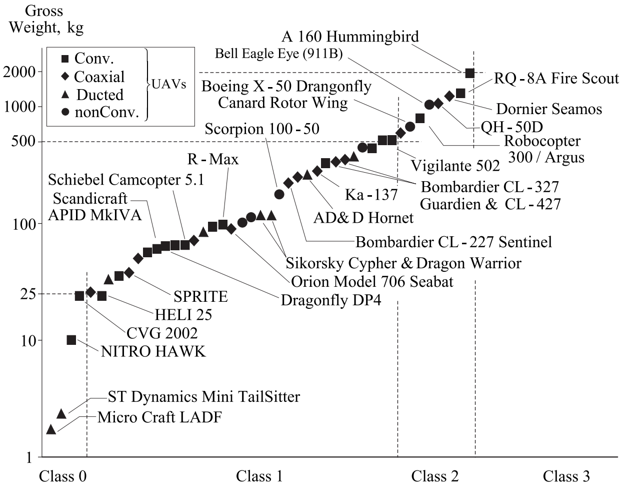

Fig. 1. RWUAVs Gross Weight Based Classification

As show, gross weight distribution of the existing (and under development) RWUAVs covers classes from 0 to 2, but most of the RWUAV configurations belong to Class 1 (25-500 kg).

Similar to the common UAV gross weight based classification [4], the RWUAVs classes demonstrate well correlation with mission radius and service ceiling (see Fig. 2, 3).

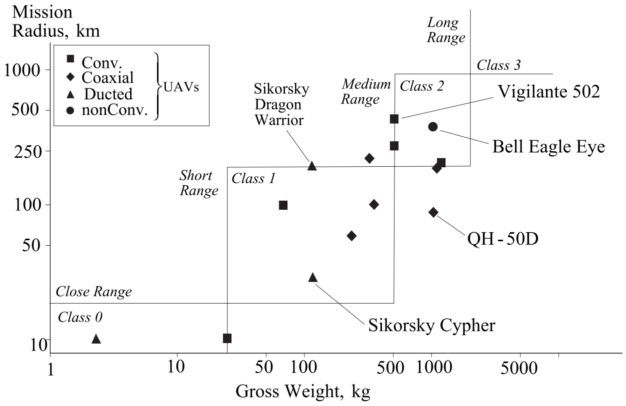

Fig. 2. Correlation of RWUAVs Classes with Mission Radius.

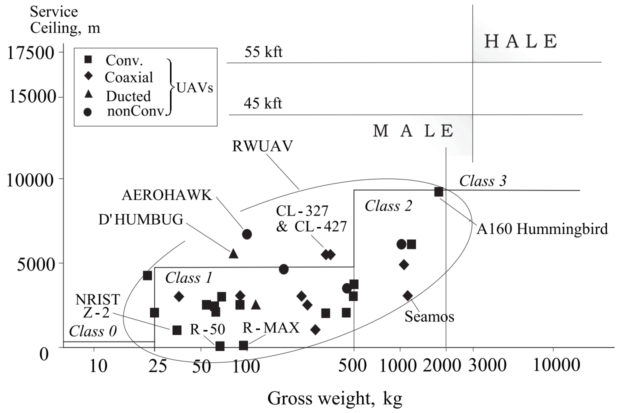

Fig. 3. Correlation of RWUAVs Classes with Service Ceiling.

Fig. 3 shows that all RWUAVs configurations are bounded within the MALE range of gross weight and altitude as also indicated in [6].

Figs. 2,3 show that there is no correlation between RWUAVs type, mission radius and service ceiling.

1.3 Potential RWUAV Applications

Analysis of RWUAVs potential use shows the following applications:

- Surveillance & Intelligence.
- Reconnaissance.
- Electronic Warfare (EW); Electronic counter measures; Electronic jamming; Communications (& data) relay; Decoy
- Targeting (over the horizon, support); Target ID / acquisition / designation.

- Surveys; Environmental monitoring; observation.
- Law enforcement & policy patrol; pipeline, border patrol; forest fire detection & fisheries patrol; day-night traffic; power line inspection; perimeter defense; civil use.
- Aerial photo and cinematography; movie & media, media support .
- Tactical support; helicopter escort; naval gunfire support; precision delivery & minefield and surface ordnance survey; real-time imagery.
- Maritime operations; anti-submarine weapon system.
- Others (military training; paramilitary operations; re-supply etc.).
- Battle Damage Assessment (BDA); tactical assessment.
- Agricultural.
- Search and Rescue (SAR); situational awareness.
- Nuclear, biological, chemical (NBC) detection & survey.

Figure 4 presents the percentage of RWAVs that are dedicated to teach one of the above applications.

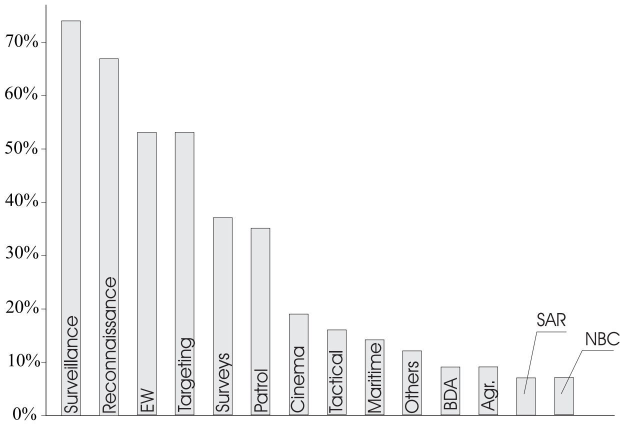

Fig. 4. Potential Applications for RWUAVs (in Percentage of Existing Configurations).

As show, the sum of the above percentages exceeds 100%, as expected from the fact that many of the RWUAVs are multi-missions vehicles. It should be noted that all weight classes are incorporated in Fig. 4. For example, the group "Surveillance & Intelligence" includes ducted Micro Craft LADF, (MTOW which is of 1.8 kg), and conventional A160 Hummingbird, (MTOW which is of 1814 kg).

2 Conceptual and Preliminary Design

Within the conceptual design stage, the basic questions regarding the configuration are examined against the mission requirements. This design stage is characterized by a wide spectrum of types of configuration where the designer specifies the advantage and disadvantage of each one of them.

The output of this stage may be illustrated as a matrix of various types of missions vs. various types of configurations. Within the arena of RWUAVs, it is clear that a configuration which is supposed to spend most of its operation time in hover, will be totally different from a RWUAV configuration that should be carry a mission at a remote area, in which case most of its operation time will be devoted to high speed forward flight, while the mission itself will occupy only small fraction of the entire mission time.

The conceptual design stage should be based on "previous experience". The common way to make this previous experience useful and educating is based on the examination of statistical trends. These are statistical rules that were derived by collecting of information about existing configurations that were proved as "successful" and passed all challenges posed by the performance requirements, the manufacturing processes, and the overall cost-effectiveness of the configuration.

Depending on the requirements, the above discussed output of the conceptual design stage may also include more than one configuration to be analyzed within the preliminary design stage. This may be a "master-configuration" with several variances, "modular-configuration" which may be adapted for various missions, or in rare cases, different configurations that will adequately cover all requirements.

It should be noted that for RWUAV, the above described stage of conceptual design is much more complicated than a similar one in the fixed-wing arena. This is due to the fact that there are much more basic configurations to be examined, where for each such configuration, many variants may be considered. This includes:

(a) Conventional helicopter configurations (Conv) - which is based on standard main and tail rotors.

(b) Coaxial configurations (Coaxial) - which consist on two counter-rotating rotors and eliminate the need for anti-torque device. Variants of this configuration are the multi-rotor systems.

(c) Ducted-Fan configurations (Ducted) - which may be based on either coaxial rotor system or single rotor.

(d) Titled Rotor/Wing/Body (nonConv) - and other nonstandard configurations.

3 Design Trend Analysis

3.1 The Analysis Methodology

This section demonstrates the advanced computers technologies for the rotary-wing vehicles conceptual/preliminary design stages.

The results presented in what follows are founded on a vast full-scale helicopter and RWUAVs database that has been collected for the conceptual-design/sizing design stages. The database includes geometry parameters, weight of components and preliminary power and flight performance estimation. The analysis has been carried out using advanced computerized correlation technique which is based on multiple regression analysis that may incorporate large number of independent unknowns.

The database which consists of more than 180 configurations has been created using data from a vast range of open sources (for example, [7]), and is focused on conventional single rotor helicopter configurations. As opposed to first order and relatively simple analysis which are typically used in the first preliminary stages, the results presented in what follows include correlations and design trends of existing flying configurations, and therefore contains many design constrains that emerge only in late stages of the design process. The results of this research for full-scale helicopter sizing were presented by the authors in [5].

Collected from different open sources (e.g. [8]), data for more then 70 RWUAVs configurations will be presented in the following correlations along with the full-scale data. In general, it will be shown that so far, designers have not abandoned the design rules of full scale helicopters, and that the statistical design trends for full-scale configurations are still valid.

3.2 Disc and Power Loading

Figure 5 presents the disc loading of conventional helicopter and RWUAVs as a function of the gross weight and in comparison with fixed-wing configurations. As shown, similar to the fixed-wing case, the variation grows with gross weight, W_0, while the general trend of dependency on $W_0^{1/3}$ remains valid.

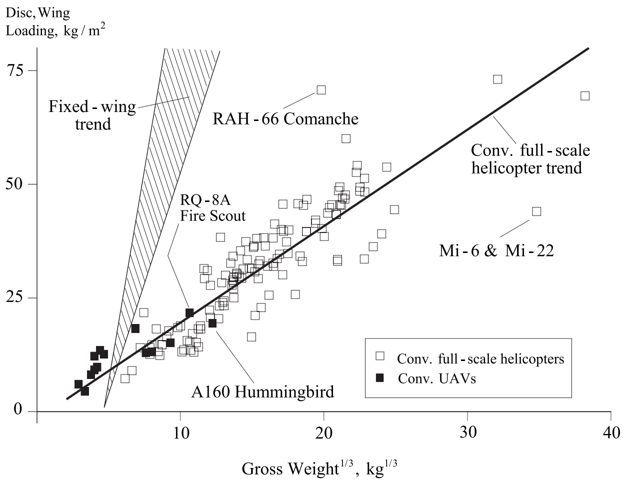

Fig. 5. Disc And Wing Loading vs. Gross Weight.

As far as the actual prediction of the disc loading is concerned, [9] suggests for fixed wing configuration two upper $\left(w_L^U\right)$ and lower $\left(w_L^L\right)$ bounds for the wing loading given by

$$\left[w_L^U, w_L^L\right] \cong [18.67, 9.78]\left(W_0^{\frac{1}{3}} - 4.61\right) \qquad (1)$$

where w_L^U, w_L^L are in $\left[kg/m^2\right]$ and W_0 in $\left[kg\right]$. According to [5], when disc loading is correlated with $W_0^{1/3}$, the following parameters are identified

$$D_L \cong 2.12\left(W_0^{\frac{1}{3}} - 0.57\right), \qquad (2)$$

where D_L are in $\left[kg/m^2\right]$ and W_0 in $\left[kg\right]$. The above trends lines are presented in Fig. 5. As shown, disc loading trends are similar for full-scale and small rotary-wing conventional configurations.

Figure 6 presents power loading versus disc loading along with lines of constant Figure of Merit (*FM*). Again, it is shown that the RWUAVs exhibit similar behavior while efficiency deteriorate (low *FM*) for relatively low gross weight. Note the for full-scale helicopter, take-off transmission power, T_{TO}, is accounted for while for RWUAVs the take-off engine power, P_{TO}, is used. Practically, $P_{TO}/T_{TO} \cong 1.0...1.4$ for the entire present database of full-scale helicopters. Also, note that the *FM* is calculated for the entire configurations and not just for the rotor itself.

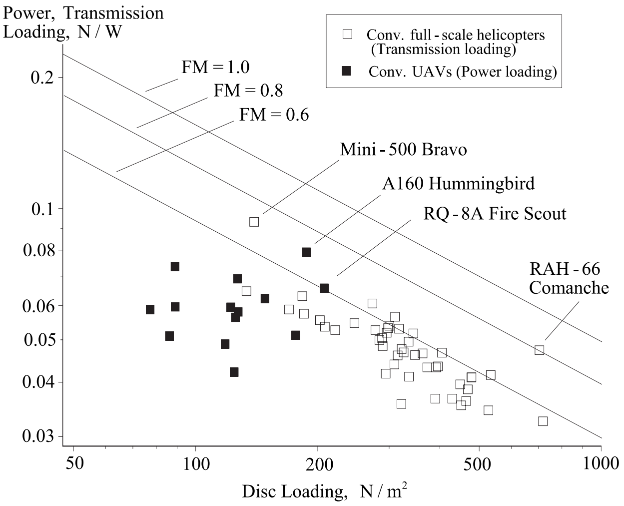

Fig. 6. Power Loading vs. Disc Loading.

The above simple linear relation shown by the constant *FM* lines in Fig. 6 may be obtained by the power global momentum estimation in hover

$$P = \frac{1}{FM}\frac{T^{3/2}}{\sqrt{2\rho A}}, \qquad (3)$$

where P is the power required, T is the thrust, ρ is the air density and A is the disc area. The above may be written as

$$\log\left(\frac{T}{P}\right) = \log\left(FM\sqrt{2\rho}\right) - \frac{1}{2}\log\left(\frac{T}{A}\right), \qquad (4)$$

where $\frac{T}{P}$ is the power loading and $\frac{T}{A}$ is the disc loading. Hence, in log-log chart, lines of different *FM* are parallel with a slope of $-\frac{1}{2}$.

Figure 7 presents the total power versus gross weight. As shown, the design trends are similar. For conventional helicopters, take-off total power was found to be correlated well with gross weight as

$$P_{TO}^{Helicopter} \cong 0.0764 \cdot W_0^{1.1455}, \qquad (5)$$

while for conventional UAV, the following trend has been found

$$P_{TO}^{Conv.\ UAV} \cong 0.2928 \cdot W_0^{0.9043}, \qquad (6)$$

where P_{TO} is in *[kW]*, and W_0 is in *[kg]*.

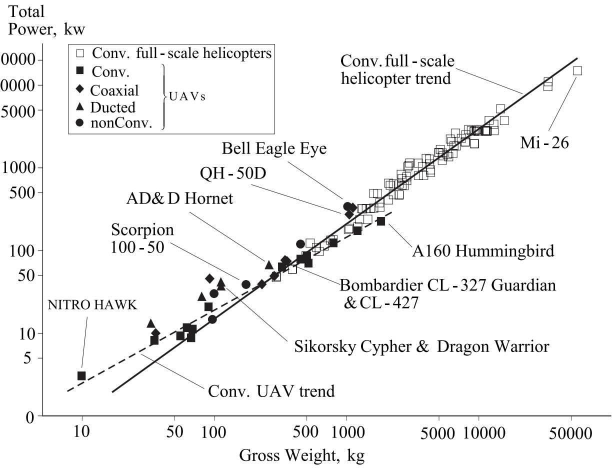

Fig. 7. Total Power vs. Gross Weight.

As show, for small gross weight, the total power required for conventional RWUAVs is larger than the one required for conventional full-scale helicopters. This is probably the result of considerations that accompanied the power plant selection, and the increasing in required power owing to the typical operation of the RWUAVs rotors in relatively low Reynolds numbers.

3.3 RWUAV Rotor Diameter

Figure 8 presents the main rotor diameter versus gross weight. This is an important issue in the conceptual design stage when the designer wishes to specify the overall dimensions of the vehicle for a given gross weight. As shown, the trend identified for full scale configurations is kept with a minor variation for RWUAVs. Figure 8 supplies a very important information for two reasons: First, it leads the designer to a working point which has been well checked and proved to be valid by analyses of many and different designers, and therefore saves many "design loops". In addition, it includes many other aspects that are not taken into account at the early conceptual / preliminary design stages (such as efficiency, cost, etc.). The fact that Fig. 8 presents existing configurations that survived all design and production obstacles gives an extra weight to its validity.

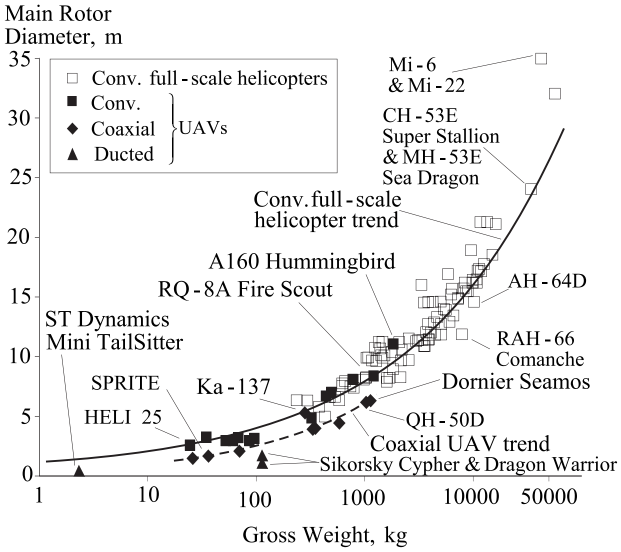

Fig. 8. Main Rotor Diameter vs. Gross Weight.

Main rotor diameter of the conventional full-scale helicopters may be determined as in [5]:

$$D^{Helicopter} \cong 0.977 \cdot W_0^{0.308}, \qquad (7)$$

where, D is the rotor diameter in *[m]*, and W_0 is in *[kg]*. The trend for conventional UAVs is practically identical. For Coaxial RWUAVs it was found that

$$D^{Coaxial} \cong 0.4331 \cdot W_0^{0.385}. \qquad (8)$$

Hence, for the same gross weight one may write

$$D^{Ducted} < D^{Coaxial} < D^{Conv}. \qquad (9)$$

In early research [5], the authors presented the statistical trend for conventional full-scale helicopters (non-Fenestron) tail rotor diameter versus gross weight

$$D_{TR}^{Helicopter} \cong 0.0886 \cdot W_0^{0.393}, \qquad (10)$$

where D_{TR} is in *[m]*, and W_0 is in *[kg]*.

The current analysis showed that trends for tail rotor diameter of the conventional RWUAVs and full-scale conventional helicopters are similar. Yet, for gross weight less 100 kg, RWUAVs tail rotor diameter is larger than the one obtained from full-scale helicopter trend estimation (which also may be a result of the relatively low Reynolds numbers which these tail rotors are encountering).

3.4 Airframe

Similarly to conventional full-scale helicopters, conventional RWUAVs parameters, such as fuselage length, L_F, and airframe over-all length (rotors turning), L_{RT}, are well determined by the main rotor diameter, D. For full-scale helicopters, see [5]

$$L_F \cong 0.824 \cdot D^{1.056}, \qquad (11)$$

$$L_{RT} \cong 1.09 \cdot D^{1.03}, \qquad (12)$$

Where lengths and diameters are all in *[m]*.

Trend analysis has shown the same trends for conventional RWUAVs fuselage length and airframe over-all length (rotors turning).

3.5 Weight Components of RWUAVs

For manned air vehicles the gross weight includes the empty weight W_E and useful load W_U, while

$$W_U = W_{PL} + W_F + W_C, \qquad (13)$$

where, W_{PL} is payload, W_F is weight of the fuel and others fluids, and W_C is the crew weight (vanishes for UAVs). Also, the following dependencies for weight fractions of the conventional full-scale helicopters were reported in [5]:

$$W_E^{Helicopter} \cong 0.4854 \cdot W_0^{1.015} \cong 0.56 \cdot W_0, \qquad (14)$$

$$W_U^{Helicopter} \cong 0.4709 \cdot W_0^{0.99} \cong 0.44 \cdot W_0, \qquad (15)$$

$$W_{PL}^{Helicopter} \cong 0.509 \cdot W_0^{0.959} \cong 0.36 \cdot W_0. \qquad (16)$$

Figures 9-10 present empty weight and payload trends for different RWUAV types in comparison with same full-scale helicopters trends.

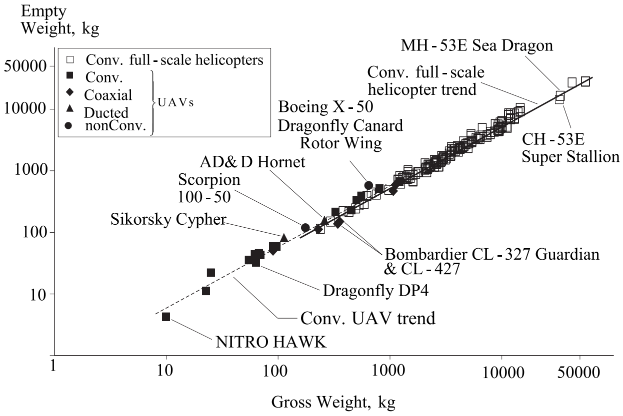

Fig. 9. Empty Weight vs. Gross Weight.

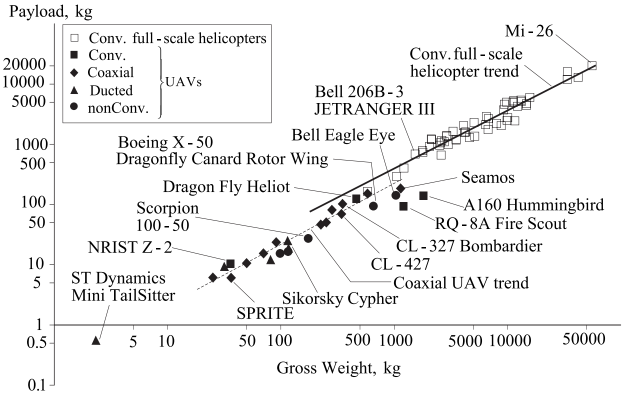

Fig. 10. Payload vs. Gross Weight.

For RWUAVs, the following relations were found:

$$W_E^{Conv\ UAV} \cong 0.59 \cdot W_0, \qquad (17)$$

$$W_{PL}^{Conv\ UAV} \cong 0.31 \cdot W_0, \qquad (18)$$

$$W_{PL}^{Coaxial\ UAV} \cong 0.22 \cdot W_0. \qquad (19)$$

As show, RWUAVs empty weight and, consequently, useful load estimations are similar to the corresponding full-scale helicopters trends.

At same time, the payload fraction decreases. Possible explanations for this may be: (a) the absence of clear definition of payload and UAV equipment, which are included in empty weight data; (b) long endurance requirements to surveillance RWUAVs, what leads to increasing of fuel fraction.

3.6 RWUAVs Performance

3.6.1 Mission Radius

Figure 11 presents the mission radius (defined as half of the range with standard fuel at sea level) versus gross weight for full scale helicopters and RWUAVs.

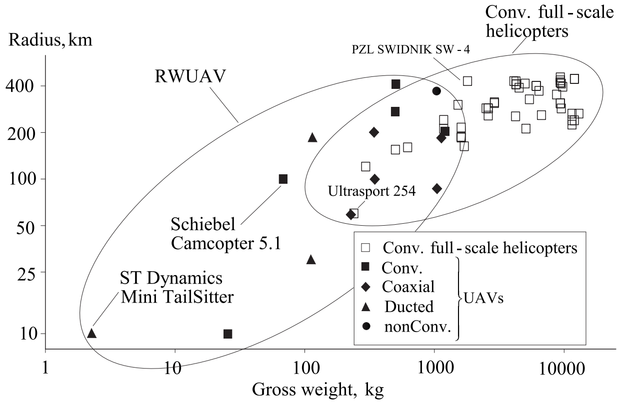

Fig. 11. Mission Radius vs. gross weight.

As show, the maximum mission radius of conventional full-scale helicopters is comparable with that of RWUAVs. Yet, it should be noted that RWUAVs have a wider range of effective applications, and mission radius range of less than 100 km is confined to RWUAVs.

3.6.2 Maximum Speed

Figure 12 presents the maximum speed at sea level versus gross weight. The design trends were found as

$$V_{\max}^{Helicopters} \cong 78.5 \cdot W_0^{0.137}, \qquad (20)$$

$$V_{\max}^{Conv\ UAV} \cong 39.8 \cdot W_0^{0.242}, \qquad (21)$$

$$V_{\max}^{nonConv\ UAV} \cong 90.9 \cdot W_0^{0.199}, \qquad (22)$$

where, $V_{\max}$ is the maximum speed in *[km/h]*, W_0 is the gross weight in *[kg]*.

As show, both conventional and non-conventional RWUAVs and full-scale helicopters demonstrate common tendency – increasing speed with increasing gross weight.

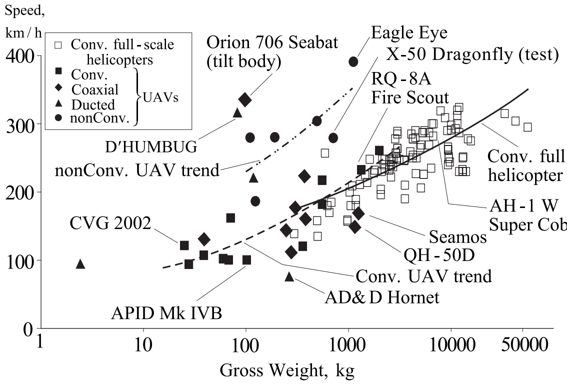

Fig. 12. Maximum Speed vs. Gross Weight.

For relatively small gross weight, the RWUAV speed estimation is lower than velocity estimation for full-scale helicopters. This phenomenon may be related to the excessive power required by RWUAVs as shown in see Fig. 7.

The trend shown in Fig. 12 for non-conventional RWUAVs coincides well with the recommendation discussed in Ref. 3, regarding the combination of hover and high forward flight speed expected from such configurations.

3.6.3 Rate of Climb

Figure 13 presents the rate of climb at Sea level versus gross weight. The design trends were found as

$$V_C^{Helicopters} \cong 142 \cdot W_0^{0.157}, \qquad (23)$$

$$V_C^{Coaxial\ UAV} \cong 99.5 \cdot W_0^{0.268}, \qquad (24)$$

where, V_C is the rate of climb at Sea level in *[m/min]*, and W_0 is the gross weight in *[kg]*.

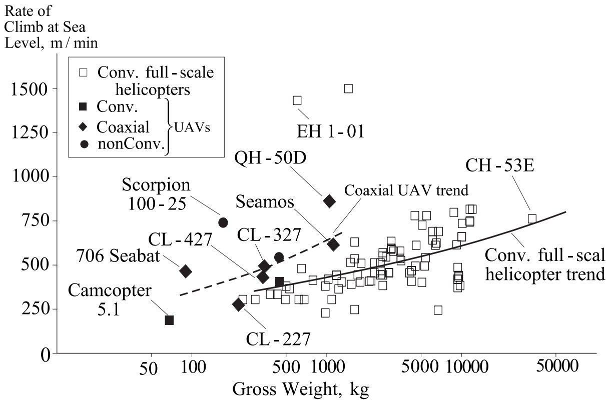

Fig. 13. Rate of Climb vs. Gross Weight.

As show, common tendency, i.e. increasing rate of climb with increasing gross weight is observed for both coaxial UAV and full-scale helicopters. For coaxial vehicles, no power is devoted for the counter-rotating system, which may be the source for the higher rate of climb shown for coaxial RWUAVs.

3.6.4 Service Ceiling

Service ceiling for full-scale helicopters and RWUAVs as function of gross weight is presented in Fig. 14. As show, the service ceiling of full-scale helicopters is around 3000 -

6000 meters. Evidently, the maximum service ceiling for full-scale helicopters is limit for non-pressured cabins in addition to power plant altitude characteristics.

For RWUAVs, the service ceiling range is wider and clearly depends on the specific mission of each configuration.

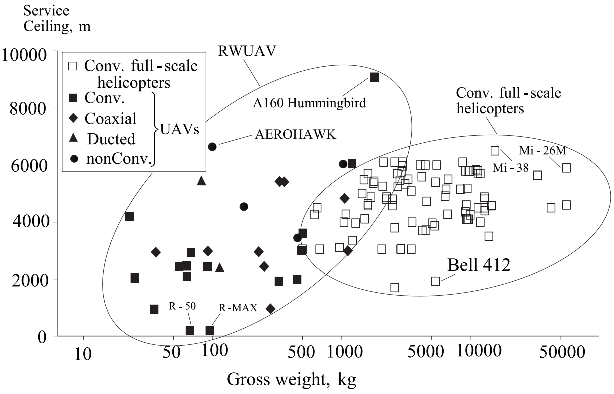

Fig. 14. Service Ceiling vs. Gross Weight.

For some special missions of UAV the ceiling may be up to 20000 and above meters (including fixed-wing UAV, see Fig. 14-15).

Note that according to Fig. 14, for RWUAVs there is a clear correlation between gross-weight and serving ceiling.

3.6.5 Productivity

The aerospace dictionary [10] define productivity as, generically, "the effectiveness with which labor, materials and equipment are used in a production operation". In our case, the equipment is the RWUAV, and the production operation is its mission.

As show in Fig. 4, most of the RWUAVs usage is in the area of surveillance & intelligence, reconnaissance, electronic warfare and targeting (50-75% for each). Hence, the traditional definitions of the air vehicle's productivity, like "payload×velocity", is not relevant to RWUAV. In [11] for the chart "UAV Productivity Improvement Trend" was presented dependency of the ceiling versus "mission payload × endurance". Similar comparison for productivity for the rotary-, fixed-wing UAV and full-scale helicopters is offered in Fig. 15.

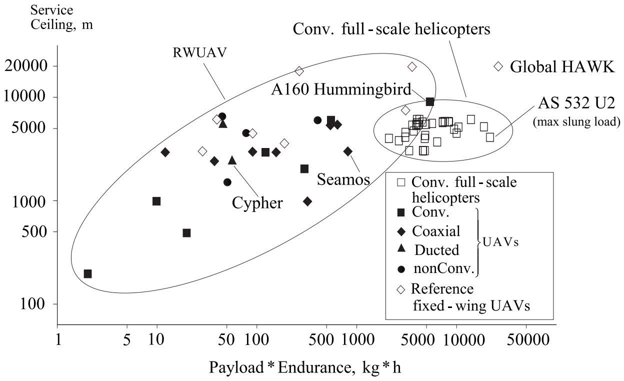

Fig. 15. RWUAVs productivity (reference fixed-wing UAV data from source [2]).

As show, the given RWUAVs characteristics are varied in a wider range compared with full-scale helicopters. It again confirms the higher dependency of the configuration on the specific mission in the case of RWUAV.

4 Conclusions

A study of RWUAV design trends has been presented. The analysis is expected to give designers basic estimation of the vehicle characteristics which is based on a vast range of RWUAVs configurations. Comparison with full-scale rotary-wing vehicles has shown both similarities with full-scale helicopter design trends, and characteristics that are unique for small RWUAVs.

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