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Unmanned Aircraft Systems in the Civil Airworthiness Regulatory Frame: A Case Study

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The last few years have witnessed a number of worldwide initiatives devoted to assess the safety levels of unmanned aircraft. These initiatives are very heterogeneous; some of them are centered in airworthiness aspects, while others focus on operations. From the point of view of a potential unmanned aircraft system manufacturer, the actual situation is full of uncertainties related to the regulations that should be applied to certify the design, manufacturing, and maintenance, and from the point of view of the potential operator, the situation is analogous with respect to operational procedures. The objective of this work is to clarify the present regulatory scene of civil airworthiness from the manufacturer's viewpoint, by summarizing all regulatory efforts up to date and analyzing them contrastively, also including the manned regulations. The most representative state-of-the-art unmanned aircraft systems are examined regarding the existing and future regulatory framework. The main aspects to be considered refer to airworthiness certification (e.g., performances, structural design, etc.). Finally, a quantitative assessment is established to clarify how the new regulatory framework, mainly based on the conventional aircraft certification codes, will affect future unmanned aircraft system, as compared with the existing regulations.

Nomenclature

A_{exp} = ground area in which people are exposed to potential harm due to a ground impact
a = slope of the aircraft normal force coefficient curve
E_{imp} = kinetic energy at impact
f_F = fatality rate (h^{-1})
$f_{GI,max}$ = ground-impact accident frequency
K_g = gust alleviation factor
n_g = gust load factor
n_m = maneuver limit load factor
P = fatality probability, given the exposure
p_s = sheltering parameter
S_w = wing area
$T_{GI,min}$ = minimum required time between impacts
W_{str} = structural weight
α = impact energy threshold required for a probability of 50% with $p_s = 0.5$
β = impact energy threshold required to cause a fatality as p_s goes to zero
ρ = population density
ρ_0 = air density at sea level

I. Introduction

The so-called unmanned aircraft systems (UASs) are complete systems designed for flying without a human pilot onboard and include, following the European Aviation Safety Agency (EASA) [1,2], not only the unmanned aircraft vehicle (UAV), but also the systems that allow the proper operation, such as the control station, the communications link, and the launch and recovery systems.

Since 1917, when the first controlled flight of an unmanned aircraft (Curtiss N-9, U.S. Navy) took place [3], the development of the UAS has been remarkable, especially in the military field and during recent war periods. This great evolution of the UAS has caused an important diffusion of these systems nowadays, making it necessary to establish an adequate regulatory frame to allow the safe operation of these aircraft in military, civil, or commercial missions. The problem is partially solved nowadays, due to the general solution to require operating the UAS outside of the nonsegregated airspace or to sometimes book time fractions inside it in such a way that the UAS could be safely operated.

A relevant milestone was the accident of a Predator B UAS [maximum takeoff weight (MTOW) of 4763 kg] in Sierra Vista, Arizona, on 25 April 2006. This fact highlighted the necessity of facing the regulation of the operations. The aircraft was performing surveillance tasks in the border between the United States and Mexico when the blockage of one of the consoles of the ground control station stopped the communications link with the vehicle and the control was lost. A chain of failures in the troubleshooting procedure led to the unexpected closure of the fuel valve. From that moment the aircraft began losing height and went out of the sight line of the control station, making the control of the vehicle irrecoverable. Although there were no human damages, the National Transport Safety Board investigated this accident thoroughly and subsequently issued several recommendations related to the design, operation, and safety, addressed to organizations that operate UASs [4,5].

Many regulatory initiatives have emerged, trying to organize the UAS operations in the nonsegregated airspace [EUROCONTROL, Joint Aviation Authorities (JAA)/EUROCONTROL UAV Task Force, European Organization for Civil Aviation Equipment (EUROCAE) Working Group 73 (WG-73), European Defence Agency, U.S. Department of Defense, Federal Aviation Administration (FAA), Radio Technical Commission for Aeronautics, NATO, and EASA]. So far, none of them have led to a firm regulation that could unify the requirements for UAS operation, exhibiting an equivalent level of safety (ELOS) to that of the manned aircraft (conventional). The absence of such a set of unified regulations would prevent the UAS industry from growing [1], which would raise difficulties for industry and market development.

Obviously, UASs will use the airspace to perform their missions, civil or military. Such airspace has a structure, management, and control designed to be exploited by manned aircraft, which are required to have a very high level of safety. For conventional aircraft, this level depends on their intrinsic characteristics, the maintenance

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technicians and operating personnel. Additionally, it is affected by the qualities of the navigation aids and the air traffic control and management that supervise and organize the missions. So it would be reasonable to expect that UAS missions would be influenced by the same requirements.

To date, the operations with unmanned aircraft vehicles have been restricted to the segregated airspace; that is, to previously announced airspace regions kept for special traffic but where conventional aircraft also fly. The question that now arises is how the operation of UASs could be allowed in the nonsegregated airspace, coexisting with the conventional aircraft, helping UASs to develop all their potential. To this end, it is necessary to convince the airworthiness and operations authorities that the unmanned aircraft are able to develop the same level of safety as the manned ones. So the UASs are not a hazard for the other traffic and for the persons and goods on the ground.

To reach such a scenario, the first step is to solve the lack of regulations as well as the development of high reliable technologies that allow UASs to operate at equivalent levels of safety as the manned aircraft. Keeping in mind the options stated by several regulators [1,6–8], it is possible to enumerate the premises that all integration regulation initiatives should consider:

1) UASs should reach equivalent levels of safety as conventional manned aircraft.

2) UAS operations should not increase the risks for the users of the nonsegregated airspace or third parties.

3) UASs should use the same air traffic management (ATM) procedures and the same flight rules as the other users of the airspace.

4) The air traffic services given to the UAS should be transparent to the other users and the air traffic controllers.

These integration premises can be condensed as four problems to be solved: airworthiness certification, interaction with ATM, interaction with other aircraft and flight crew certification. The present paper addresses the first problem, since it is previous to any other. A preliminary version of this work was presented elsewhere [9]. In the first part, the existing airworthiness certification initiatives will be summarized. Then, the recent EASA Policy will be analyzed. This analysis will be extended, in the third section, to a case study in which 23 real UASs will be assessed from the point of view of the future regulatory framework and the existing certification codes for manned aircraft, trying to quantify the impact of the application of these regulations to a relevant design aspect, such as the structural weight.

II. Current State of the Airworthiness Certification Initiatives

To guarantee equivalent levels of safety as the conventional aircraft, it will be necessary to provide internationally accepted standard and recommended practices to assess the safety of the vehicle and its operations. They should include the safety evaluation of all systems onboard and their integration characteristics required to develop their design missions. In this way it would be possible to certify the intrinsic or potential airworthiness of the UAS [10]. It will also be necessary to certify the real airworthiness: that is, the ability of the UAS of continuously being airworthy through a proper operation and maintenance so that the UAS permanently keeps its intrinsic airworthiness (the continued airworthiness process). This means that it will be important to foresee the qualifications for the maintenance and operations personnel, in a way similar as the conventional aviation. Therefore it will be necessary to develop certification codes for the licenses of maintenance technicians and operations personnel, such as ground pilots, specifically aimed at UASs. From the point of view of the airworthiness certification of the vehicle, there is no civil code of regulations yet, although there are several military codes and several civil regulation initiatives. A summary of the actual situation is presented afterwards and shows that, as far as civil initiatives are concerned, the situation in the United States is rather different from that of Europe.

In the United States, the FAA has established the Unmanned Aircraft Program Office (UAPO), who is in charge of the UAS integration process into the U.S. National Airspace. For the moment, until a new Federal Aviation Regulation (FAR) for UASs appears (expected by the end of 2011), UAPO has developed a set of certifications and authorizations for UASs. In the case of civil operations, it will be necessary to ask for a special airworthiness certification in the experimental category. As the experimental category is very wide and comprises a great variety of aircraft, the case of UASs is especially considered in FAA Order 8130.34 [11]. It should be pointed out that FAR part 21 [12] prevents the use of the UASs in commercial missions. Finally, it is important to note that FAA Order 8130.34 [11] is not a detailed airworthiness code, but a set of operational limitations.

In the case of public operations, the FAA will issue a certificate of authorization (COA) or waiver that represents a temporary procedural interim mechanism authorizing UAS flight for a special purpose and into a limited area. The objective of the FAA, together with the public organization operating the UAS, is to obtain the same ELOS with the COA as with the manned aircraft. Finally, for the issue of the COA, the FAA has published some recommendations [13], in which the military code MIL-HDBK-516-B [14] is strongly recommended as a guidance code.

On the other hand, model aircraft are regulated on a voluntary basis by means of the FAA's Advisory Circular AC 91-57 [15]. To clarify the applicability of this Advisory Circular for the operation of UASs, the FAA has published its opinion [16] and has created the Aviation Rulemaking Committee (ARC) for Small UAS (sUAS) [17], who has regulated the commercial applications of small UASs for which the AC 91-57 [15] is not applicable. The recommendations of the sUAS ARC for creating a new regulatory framework for these aircraft have been published elsewhere [18] and look like a sFAR (special FAR) code. In principle, the philosophy followed by the sUAS ARC was similar to the criteria for the light-sport aircraft category: the manufacturer had to show compliance with some identified consensus standards to obtain the airworthiness certificate. Nevertheless, the sUAS ARC states that all UASs should comply with the essential requirements published in Appendix B of [18].

In the field of military initiatives, and between the United States and Europe, the NATO Standardization Agreement STANAG 4671 [19], ratified in 2007, deserves special mention. This document contains a set of airworthiness regulations addressed to certify military fixed-wing UASs with a MTOW from 150–20,000 kg, which will operate in the nonsegregated airspace. The purpose of this code is to obtain ELOS for the affected UASs, similar to the fixed-wing aircraft certified with FAR part 23 [20] and EASA's CS-23 (Certification Specification 23) [21] codes (from which it is derived). At the same time, it includes some special features of the UAS that are recognized through new subparts. So subparts A to G come from CS-23, and H and I are new parts devoted to communications, command, and control data link and ground control station; all of them are specific UAS topics.

There are two codes within the European military field: the British Defence Standard DEF STAN 00-979 part 9 [22] and the French UAV System Airworthiness Requirements (USAR) [23]. The former, devoted to UAV systems, is the ninth volume of a collection that compiles airworthiness and design requirements for aircraft under the responsibility of the Defense Ministry of the United Kingdom. Part 9 [22] includes certification requirements for UASs, including design, development and testing topics, directed to the operation of such UASs in any class of airspace. This code has been used to complement Joint Aviation Requirement JAR/CS-23 [21] codes in the codification of NATO STANAG 4671 [19]. The latter code (USAR), has been developed by the Délégation Générale pour l'Armament (French Defence Ministry) and it is compulsory for all military French UASs. It is based on EASA's CS-23 [21] code, tailored to fixed-wing UASs [tactical; medium-altitude, long-endurance (MALE); high-altitude, long-endurance (HALE); and unmanned combat aerial vehicle (UCAV)]. It is the basis for the previously considered NATO STANAG 4671 [19].

From a civil perspective, the regulatory competence in Europe for unmanned aircraft with an operative mass over 150 kg relies on EASA, as established in its basic regulation [24], article 4, section 4.

For that reason, in 2005, the agency began the rule-making process, issuing an Advance Notice of Proposed Amendment (A-NPA 16-2005 [1]) centered on the establishment of a policy (and later on a certification specification code) on UAS certification.

Before 2005 and almost by the advent of the older basic regulation [25] which created EASA, a common Joint Aviation Authorities (JAA)/EUROCONTROL initiative appeared: The JAA/EUROCONTROL Initiative on UAVs—UAV Task Force. That project aimed at the development of a model for regulating UASs. The initiative was fruitful and its final report [8] appeared in May 2004, which is essential to understand the actual point of view of EASA on UAS integration. This report presents a deep multidisciplinary analysis on the future establishment of a regulatory frame for UASs, including safety/security, airworthiness, operational approvals, maintenance, and licenses, but not ATM. It is composed of a central body, two annexes, and five attachments. The conclusions of this work have been capital to form EASA's view, so the approach followed by the agency in its A-NPA 16/2005 [1] is based on the scheme marked by the JAA/EUROCONTROL Task Force.

EASA's A-NPA 16/2005 [1] is the basis for the future European regulation on UASs, with a MTOW greater than 150 kg and not explicitly excluded by the basic regulation [24]. The philosophy of the document follows the conclusions of the JAA/EUROCONTROL Task Force, with two possible approaches for the new regulation:

1) The conventional approach requires adaptation of the existing code for manned aircraft to UASs in specified conditions.

2) With the approach based on safety objectives, it is necessary to create completely new regulations based on complying with total safety objectives and centered on the most relevant hazards.

Among these alternatives, the first one was selected for the new regulation but the second one would be used when necessary (for instance, through the issue of restricted airworthiness certificates), as established in the JAA/EUROCONTROL Task Force final report [8].

A-NPA 16/2005 [1] presents two alternatives for selecting the appropriate manned airworthiness certification specification for UAVs that will be reduced to one in future regulations:

1) Alternative 1 is the impact energy method. The method compares the hazard presented by a UAV with that of existing conventional aircraft to obtain an indication of the appropriate level of requirements which should be applied. The most significant feature of this proposal is that it relies on a comparison with existing conventional aircraft design requirements that contribute to a currently accepted level of safety, and it avoids controversial assumptions about future contributions to that level of safety from operational, environmental, or design factors. The comparison criterion is based on the fact that the capability of a vehicle to harm any third parties is broadly proportional to its kinetic energy on impact. For the purposes of the comparison method it is assumed that there are only two kinds of impact: either the impact arises as a result of an attempted emergency landing under control (unpremeditated descent scenario), or it results from complete loss of control (loss of control scenario). Once the kinetic energy for each scenario is computed it is possible to determine the appropriate certification specification to be applied. Then it would be necessary to construct a certification basis which addresses the same aspects of the design as the existing codes, and to the level indicated by the kinetic energy comparison. Special conditions would be required for any novel features of the design that are not addressed by the existing codes.

2) Alternative 2 is the method based on UAV safety objectives. Safety objectives have been used as a means to define and justify the civil aircraft characteristics. These safety objectives are oriented to onboard people protection and are defined by the FAR/CS-25 [26] and CS-23 [21] regulations. As there are no people onboard a UAV, safety objectives criteria for UAVs must be redefined and oriented to on the ground people protection. By comparing today aircraft safety objectives (as they are defined in the regulations) to the UAV proposed safety objective, a correspondence between CS-23 [21], CS-25 [26], and UAV categories is established. Three main parameters have been considered: statistical aircraft fatal losses, technical aircraft losses defined in the regulations and catastrophic failures.

Following its rule-making procedure, EASA published A-NPA 16/2005 [1] as a policy document in order to raise proposals from other institutions and to complete the regulation before arriving at a consolidated version. During this process, the agency and interested parties (national authorities, manufacturers, etc.) interacted, and the results were compiled in the Comment Response Document (CRD) 16/2005 [2]. This document was issued in December 2007 and was open for comments until February 2008. It compiled 320 comments from 45 different sources. These comments or suggestions, after being studied by EASA, can be identified as accepted, partially accepted, considered (accepted, but no changes in the text), or rejected. The main topics affected have been development of a global new regulatory mainframe for UASs (A-NPA 16/2005 [1] is only a first step) and regulation for UASs with MTOW < 150 kg (out of EASA's scope). The EASA response is that the agency is not competent in this area, as stated in the basic regulation [24,25], but the member states are.

However, the agency agrees in the high interest of having a harmonized opinion and also in the collaboration of the EUROCAE WG-73 as a developer of a set of certification guidelines. Nowadays, the Joint Authorities for Rulemaking on Unmanned Systems is in charge of harmonizing and developing the draft versions on a new European rule for this light-UAS category, based on the CS-VLA (Certification Specifications for Very Light Airplanes) [27] and CS-VLR (Certification Specification for Very Light Rotorcraft) [28] airworthiness European rules. The next paragraphs represent a summary of the aforementioned comments:

1) Coordination with military working groups is considered. There are comments that suggest using the USAR code for military UASs.

2) In the conventional vs safety-target approach, the comments related with retaining the conventional approach based on the existing certification specifications have been accepted.

3) In the total system approach, the agency answers that the European Single Sky initiative is the final aim, but it is far from the current objectives.

4) For regulation of the sense-and-avoid systems, there were many comments related to the necessity of regulation for these systems. EASA maintains the opinion that sense-and-avoid systems should be regulated by the organization responsible of ATM.

5) Security is considered. EASA will have to toughen its rule in order to improve the protection against intruders.

6) Design organization approvals (DOA) for UAS manufacturers is partially accepted.

7) For airworthiness certificate and control stations, accepted comments related the request of one airworthiness certificate for each UAV control station.

8) Environmental protection and noise are considered. The rules related to noise emissions and environmental protection should be the same as for existing manned codes, but the possibility of amending them is open, if necessary.

III. Recent Advances: EASA Policy Statement

Following a public discussion in the European Union after the A-NPA 16/2005 [1] and CRD publications, the agency finally stepped forward in the rule-making procedure for UASs and issued a new policy statement document [29] in September 2009. This policy establishes general principles for type certification (including environmental protection) of a UAS. The policy complies with the current provisions of the basic regulation [24], regulation (European Communities, EC) 1702/2003 [30], and all management board decisions relating to product certification. This policy shall be used by the agency's staff when certificating UASs. The policy represents a first step in the development of comprehensive civil UAS regulation and may be regarded as providing guidance to part 21 subpart B of Regulation (EC) no. 1702/2003: type certificates and restricted type certificates; operational regulations pertaining to UASs are not addressed within this document. This policy statement is therefore an interim solution to aid acceptance and standardization of UAS certification procedures and will be replaced in due course by acceptable

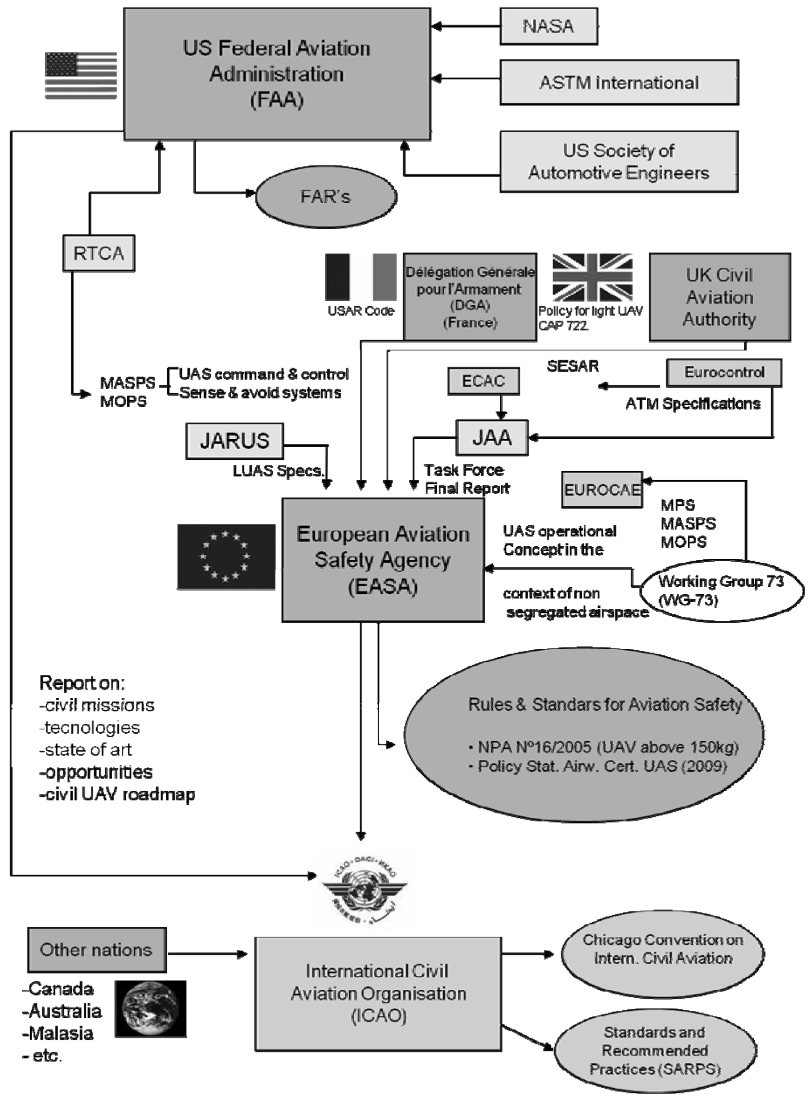

Fig. 1 Actual regulatory international playing field for UASs.

Table 1 Main characteristics of the selected state-of-the-art UASs

UAS	Type[a]	Range, km	Endurance	Altitude, m	MTOW, kg
Aladin	Micro	15	> 1 h	150	3
Manta	Mini	37	6–8 h	4870	27.7
Fulmar	Mini	800	8 h	2000	20
Furos	CR	20	6 h	3000	11
Taridan Mastiff	CR	30.5	7 h, 30 min	4480	138
Lipan M3	SR	40	5 h	2000	60
Rheinmetall KZO	SR	100	3 h, 30 min	2000	161
Outrider tactical UAV	MR	>200	4.9 h	4570	174.73
RQ-2 Pioneer	MR	185	5 h	4600	204.12
T-16 Arcturus	LALE	37	12–24 h	3657.6	37
Apoena 3000	LALE	3000	24 h	3000	82
RQ-1 Predator	MALE	726	24 h	7620	855
MQ 9 Reaper	MALE	5926	14–28 h	7500	4760
RQ-4 Global Hawk	HALE	25,928	24–48 h	20,000	11,600
nEUROn	HALE	100	100 min	14,000	6500
EADS Barracuda	UCAV	High range	Long endurance	6096	3250
X-45 A	UCAV	920	Long endurance	10670	5528
IAI Searcher	LADP	250–300	18 h	6096	426
RQ 5 Hunter	LADP	150	8–10 h	4876.8	726
Mantarraya	DEC	100	4 h	3000	60
Radio plane OQ 2	DEC	——	1 h	2440	47
Trek Aerospace Dragonfly	MRE (rotary)	925	3 h	3900	485
CL-327 Guardian	MRE (rotary)	200	6.25 h	5500	350

[a]CR (close range), SR (short range), MR (medium range), LALE (low-altitude, low-endurance), MALE (medium-altitude, low-endurance), HALE (high-altitude, low-endurance), UCAV (unmanned combat aerial vehicle), LADP (low-altitude, deep-penetration), DEC (decoy), MRE (multirole endurance).

means of compliance (AMC) and guidance material to part 21 when more experience has been gained.

The main topics covered by the policy statement are the following:

1) In the routine case, the issue by the agency of a type certificate will be based upon the applicant demonstrating compliance with a defined type certification basis and a certificate of airworthiness is granted to an individual UAS when compliance with the approved type design has been shown. Any applicant applying for a UAS type certificate is required to demonstrate their capability by holding a DOA issued in accordance with part 21 subpart J [30].

2) In the alternate approach (within the scope of part 21 [30]), to facilitate an early introduction of civil UAS operations, it will be possible to apply for an airworthiness approval. This approach recognizes that some UASs may benefit from a stepwise approach in conjunction with the issue of a restricted type certificate and/or restricted certificate of airworthiness. This alternative may be based on the safety-target approach, using an overall target level of safety defined by the agency, in lieu of a specified airworthiness code.

3) UAS control stations and other remote equipment perform functions that can prejudice takeoff, continued flight, landing, or environmental protection shall be considered as part of the aircraft and included in the type certification basis.

4) The applicable airworthiness code or codes to be used as reference for establishing the type certification basis will be proposed by the applicant using a methodology for selecting the applicable manned aircraft code defined in A-NPA 16/2005 [1]. A tailoring of the code should be proposed by the applicant, in a justified manner.

5) The agency acknowledges that USAR [23] developed by the French military authorities, and later updated by the NATO Flight in Non-Segregated Airspace group to STANAG 4671 [19], has been developed using a methodology closely related to the one described in EASA's policy. At an applicant's request, the agency may accept USAR version 3, STANAG 4671 [19], or later updates, as the reference airworthiness code used in setting the type certification basis provided that the code identified by the methodology of the policy does not indicate that safety standards in excess of CS-23 [21]

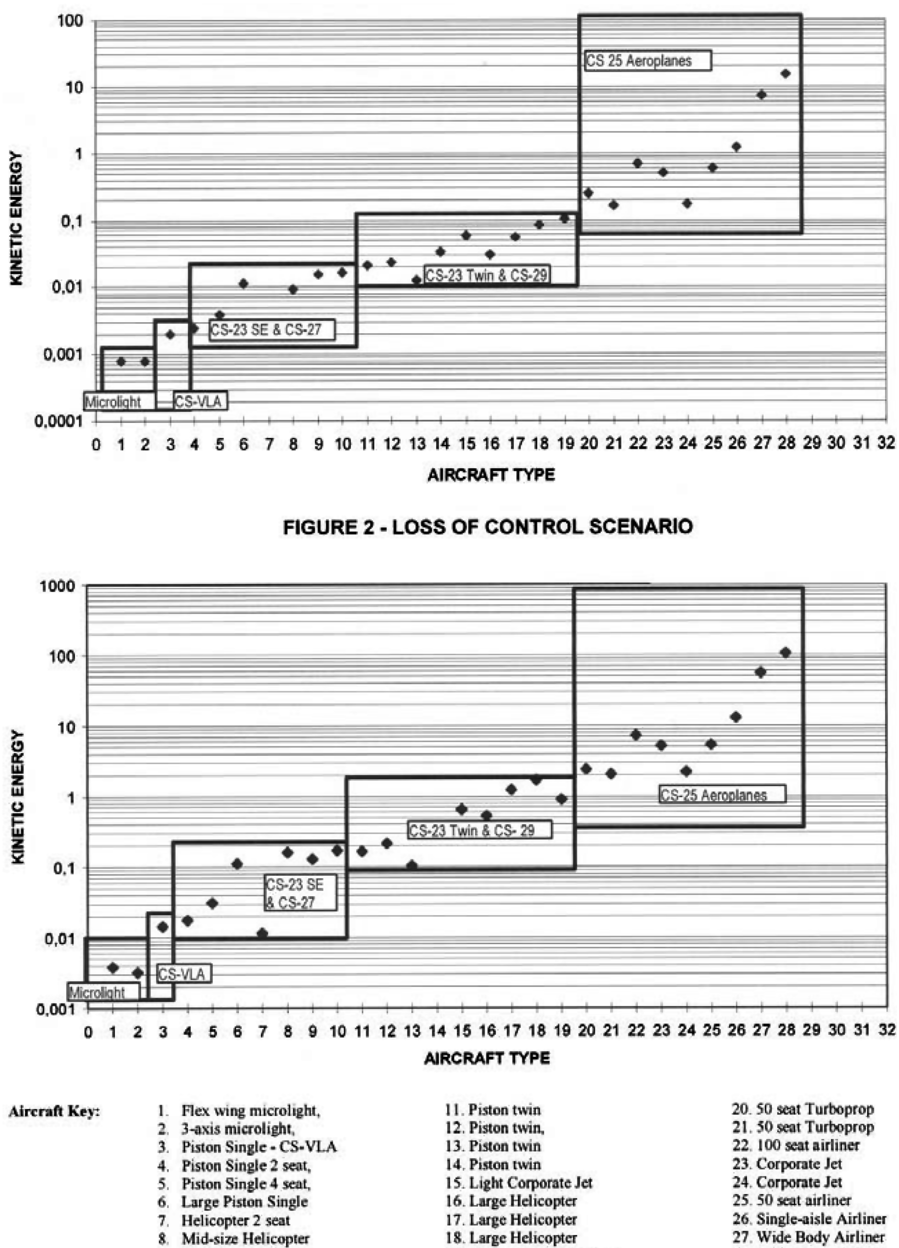

Fig. 2 Unpremeditated descent scenario (top) and loss of control scenario (bottom), corresponding to the impact energy methodology EASA A-NPA No. 16/2005 ([1], Appendix 1) and depicted in the EASA policy statement [25]. $E = (M \times V^2)/10^9$, where E is the kinetic energy as plotted, M is mass in kilograms, and V is velocity in knots.

are required, and the safety targets included in the system safety assessment reflect values resulting from the application of this policy.

6) There are several special conditions covered in the policy, for which the agency includes some guidance. These conditions are the following: emergency recovery capability, command and control link, level of autonomy, human machine interface, control station, types of operation and system safety assessment.

7) Other issues considered are the application of part 21 subpart I for noise certificates, and Annex I of part M of Regulation (EC) No. 2042/2003 [31] for the continuing airworthiness, and the agency's point of view on the certification of detect and avoid systems.

Finally, it will be necessary to wait until all these aforementioned initiatives culminate in a specific airworthiness code for UAS, although the main bases have been already established. Figure 1 summarizes the actual UAS regulatory scene, and the relationship among all actors in the international playing field.

IV. Case Study: Application of the ESA Policy Statement to Existing UASs

As was summarized before, there are a number of initiatives worldwide devoted to establishing requirements that allow the integration of UAS in the nonsegregated airspace, maintaining the same ELOS as for the manned aircraft. These initiatives are very heterogeneous; some of them are centered in airworthiness aspects while other do the same in relation to operations. From the point of view of a potential UAS manufacturer's position, the actual situation is plenty of uncertainties concerning with the regulations to be applied for certifying the design, manufacturing, and maintenance; and from the point of view of the potential operator the situation is analogous in relation to operational procedures.

The objective of this section is to present a case study in which representative state-of-the-art UASs will be analyzed from the point of view of the existing and foreseen regulatory frameworks. EASA's policy statement is the regulatory initiative selected for the study; so the UAS will be analyzed following the methodology presented in the policy. The output of this exercise will be the manned aircraft code or codes associated to each UAS studied. Then a quantitative analysis, centered in structural aspects, will be performed on the UAS to draw general conclusions about the procedures proposed by some authorities, that could affect future UAS designs.

Table 1 summarizes the main data of 23 state-of-the-art UASs. Their sizes and missions are representative of the actual market, with the MTOW ranging between 3 and 11,600 kg. First, the methodology for selecting the applicable airworthiness code(s) complied in Appendix A of EASA's policy statement is applied to the selected UAS. This methodology comes from the Alternative 1 published in EASA A-NPA 16/2005 [1]. As explained in its section 3, it is necessary to calculate the kinetic energy on impact in two scenarios: unpremeditated descent and loss of control. Thus, the kinetic energy has been calculated for the 23 selected UAS for both scenarios. These values have been introduced into Figures 1 and 2 of the A-NPA Appendix A and are shown in Fig. 2. The unpremeditated descent provides an indication of the standards to be applied to any feature of the design whose failure would affect the ability to maintain safe altitude above the ground. And the loss of control scenario provides an indication of the standards to be applied to any feature of the design whose failure would affect the ability to maintain control (particularly rate of descent). Obviously the primary structure must be included in such analysis. An analogous exercise has been done for alternative 2 of A-NPA 16/2005 [1] for comparison purposes, although this alternative has not been adopted in EASA's policy statement. To consider alternative 2, it is necessary to estimate the crash energy (energy of the UAS at the crash moment and it is proportional to the kinetic energy) and the lethal crash area (it is the area in which it is expected to find victims; it is correlated from an expression that relates MTOW and wing area). Then the number of potential ground victims is estimated, based on the lethal area and on population density. The crash probability and safety objectives can thus be determined. Comparing today's manned aircraft safety objectives (as defined in the regulations) with the UAS proposed safety objectives, a correspondence between CS-23 [21]. CS-25 [26], and UAS categories is established. Through the values estimated for the lethal crash area, A-NPA 16/2005 [1] provides a first-equivalence table between the UAS and the manned aircraft airworthiness codes. A second equivalence assessment relates the UAS safety objectives, measured in terms of crash probability per flying hour, with the various CS-23 [21] categories or military category. The results obtained on applying these methods to the selected UAS are compiled in Table 2.

In parallel to the methodology developed by EASA, there are other researchers in the United States [33,34] that also work on how to select an airworthiness code for UAS among those existing for

Table 2 Applicable airworthiness codes for the selected UAS following the EASA methodology

UAS	Alternative 1	Alternative 2: Lethal-crash-area-based code	Alternative 2: Crash-probability-based code
Aladin	Microlight/CS-VLA [27]	Ultralight	Military
Manta	Microlight/CS-VLA [27]	Ultralight	Military
Fulmar	Microlight/CS-VLA [27]	Ultralight	Military
Furos	Microlight/CS-VLA [27]	Ultralight	Military
Taridan Mastiff	Microlight/CS-VLA [27]	CS-VLA [27]	Military
Lipán M3	Microlight/CS-VLA [27]	Ultralight	Military
Rheinmetall KZO	Microlight/CS-VLA [27]	Ultralight /CS-VLA [27]	Military
Outrider tactical UAV	Microlight/CS-VLA [27]	CS-VLA [27]	Military
RQ-2 Pioneer	Microlight/CS-VLA [27]	CS-VLA [27]	Military
T-16 Arcturus	Microlight/CS-VLA [27]	Ultralight	Military
Apoena 3000	Microlight/CS-VLA [27]	Ultralight	Military
RQ-1 Predator	CS-23 [21] single engine	CS-23 [21] $M < 6000$ lb reciprocating	Military
MQ 9 Reaper	CS-23 [21] twin, CS-25 [26] airplanes	CS-23 [21] commuters	CS-23 [21] $M < 6000$ lb reciprocating
RQ-4 Global Hawk	CS-25 [26] airplanes	CS-23 [21] commuters	CS-23 [21] $M < 6000$ lb reciprocating
nEUROn	——	CS-23 [21] commuters	CS-23 [21] $M < 6000$ lb reciprocating
EADS Barracuda	CS-25 [26] airplanes	CS-23 [21] $M > 6000$/commuters	CS-23 [21] $M > 6000$ lb
X-45 A	CS-25 [26] airplanes	CS-23 [21] commuters	CS-23 [21] $M < 6000$ lb reciprocating
IAI Searcher	Microlight/CS-VLA [27]	CS-VLA [27]	Military
RQ 5 Hunter	CS-23 [21] single engine	CS-23 [21] $M < 6000$ lb reciprocating	Military
Mantarraya	Microlight/CS-VLA [27]	Ultralight	Military
Radio plane OQ 2	Microlight/CS-VLA [27]	Ultralight	Military
Trek Aerospace Dragonfly	CS-27 [32]	CS-VLA [27] and CS-23 [21] $M < 600$ lb reciprocating	Military

manned aircraft. In this case study, these investigations are also taken into account for comparison purposes.

The aforementioned research work [33,34] is established under the philosophy of safety-target approach, following the orientation of the 1209 AMC section of EASA CS-25 [26] code, where a risk reference system is proposed relating the category of an event including injuries and/or fatalities with its frequency of occurrence. The problem here is to define an ELOS for UAS based in this concept. The worst scenario is the one in which there are fatalities, so the ELOS need to be defined exclusively on the fatality rate. When the ELOS has been defined, the target level of safety (TLS) can be determined as the maximum acceptable frequency of an accident, among all possible accidents. Having in mind that the scenario includes fatalities, in the particular case of UAS, the accident involving fatalities are only of two types: ground impact and midair collisions. Both of them implies a figure for the fatality rate of $f_F = 10^{-7}$ h^{-1}, or less, to be consistent with that of the manned aircraft. Nevertheless, the midair collision scenario will not be considered because it is almost impossible to be modeled due to enormous difficulties in modeling the exact UAS trajectories, the daily air traffic (only a small portion is ATM controlled), the absence of flight plan and the differences in onboard sense-and-avoid systems installed.

Although a TLS for the fatality rate cannot be directly used as a design standard, it is possible to determine the appropriate system reliability under various conditions to achieve it. A mathematical expression can be obtained for the best variable to reflect the TLS in a ground impact, which is the minimum required time between impacts, $T_{\mathrm{GI,min}}$:

$$T_{\mathrm{GI,min}} = f_{\mathrm{GI,max}}^{-1} = \frac{A_{\exp}\rho}{f_F} P \quad (1)$$

where $A_{\exp}$ is the ground area in which people are exposed to potential harm due to a ground impact, ρ is the population density, f_F is the fatality rate required, and P is the fatality probability, given the exposure. The reference data for calculating the $T_{\mathrm{GI,min}}$ have been an $A_{\exp}$ equal to the reference UAV area (wing surface) augmented by a small buffer to account for the width of an average human [33,34], a population density of 200 people per km^2 [33,34], a fatality rate f_F of 10^{-8} h^{-1} [35], and a fatality probability P equal to the following expression [33,34]:

$$P = 1\bigg/\left(1 + \sqrt{\frac{\alpha}{\beta}}\left[\frac{\beta}{E_{\mathrm{imp}}}\right]^{\frac{1}{4p_s}}\right) \quad (2)$$

where α is the impact energy threshold required for a fatality probability of 50% with $p_s = 0.5$, β is the impact energy threshold required to cause a fatality as p_s goes to zero, and p_s is a sheltering parameter $\in [0, 1]$ that determines how the population's exposure to an impact. The values of the previous parameters have been investigated by Dalamagkidis et al. [33,34], and the most appropriated ones are $\alpha = 106$ J, $\beta = 100$ J, and $p_s = 0.5$.

Using Eqs. (1) and (2), the values for $T_{\mathrm{GI,min}}$ have been estimated for the 23 selected UAS and the results have been compared with those obtained for a group of real UAVs by Dalamagkidis et al. [33,34]. The results are plotted in Fig. 3. The continuous line shows the linear correlation (in log scale) presented in [33,34] for the requirement versus the MTOW and the dotted line is a linear upper envelope, which corresponds to multiplying the former requirement by 3. The selected UAS fall within the margin between the two lines and demonstrates the existence of a linear behavior between log MTOW and log $T_{\mathrm{GI,min}}$. Using this figure Dalamagkidis et al. derived a classification of UAVs based in the order of magnitude of their MTOW (and, correspondingly, of their $T_{\mathrm{GI,min}}$), where each subsequent class will require an accident rate an order of magnitude smaller than the previous. The classification can be consulted in [33,34]. Table 3 shows the application of this classification method to the UAS considered in the present work.

Comparing Tables 1 and 2 with Table 3 the first conclusion that can be drawn is that the results are quite different. EASA's methodologies associate more complex codes to the UAS than the $T_{\mathrm{GI,min}}$ method. While EASA recommends using CS-VLA [27], the $T_{\mathrm{GI,min}}$ method indicates that the mini and small categories correspond to converted radio-controlled model aircraft whose operations are based on FAA's AC 91-57 [15], which is not applicable to UAS, according to FAA policy [16,17]. For larger UAVs, the $T_{\mathrm{GI,min}}$ method associates FAR part 103 [36] (ultralight vehicles; empty weight lower than 115 kg) and FAR part 23 [20], while EASA's method assigns CS-23 [21] and CS-25 [26]. Essentially, EASA's philosophy associates more demanding codes to the different UAVs, so the requirements to be applied to future UAVs will be tougher than today.

The impact of the associated codes to each UAS is presented hereafter. The regulatory framework for the analysis is the one selected in the EASA policy statement, so those codes are listed in the second column of Table 2. To understand the effect of applying EASA's codes to each UAS, it is important to note that a key feature of actual UASs is their low wing loading. This characteristic makes them very sensitive to gusts and, thus, the maximum limit load factor usually comes from the analysis of the gust response. Assuming that this is the case for the selected UASs, the positive gust limit load factor has been calculated for each UAS following the Pratt discrete gust criteria recommended in the CS-VLA [27], CS-23 [21], and CS-25 [26] regulations for the cruise design speed. The calculations have been made twice (i.e., by applying two scenarios). In one case, the cruise design speed has been established as the real maximum cruise velocity of each UAV, obtained from the manufacturer's data. In the

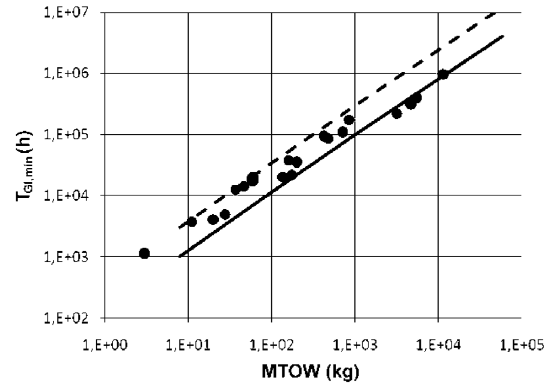

Fig. 3 Calculated $T_{\mathrm{GI,min}}$ requirement (solid line) as a function of MTOW for the selected UAS following [33,34]. The dashed line represents three times the $T_{\mathrm{GI,min}}$ requirement. Dots are the selected UAS.

Table 3 Classification of the selected UASs for certification purposes based on $T_{\mathrm{GI,min}}$ requirements [33,34]

UAS	Category ($T_{\mathrm{GI,min}}$)
Aladin	Mini (AC 91-57 [15])
Manta	Mini (AC 91-57 [15])
Fulmar	Mini (AC 91-57 [15])
Furos	Mini (AC 91-57 [15])
Taridan Mastiff	Small (AC 91-57 [15])
Lipán M3	Small (AC 91-57 [15])
Rheinmetall KZO	Small (AC 91-57 [15])
Outrider tactical UAV	Small (AC 91-57 [15])
RQ-2 Pioneer	Small (AC 91-57 [15])
T-16 Arcturus	Small (AC 91-57 [15])
RQ-1 Predator	Light (FAR 103 [36] and FAR 23 [20])
MQ 9 Reaper	Light (FAR 103 [36] and FAR 23 [20])
RQ-4 Global Hawk	Light/normal (FAR 23 [20])
EADS Barracuda	Light (FAR 103 [36] and FAR 23 [20])
X-45 A	Light (FAR 103 [36] and FAR 23 [20])
IAI Searcher	Small/light
RQ 5 Hunter	Light (FAR 103 [36] and FAR 23 [20])
Mantarraya	Small (AC 91-57 [15])
Radio plane OQ 2	Small (AC 91-57 [15])
Trek Aerospace Dragonfly	Small (AC 91-57 [15])
CL-327 Guardian	Small (AC 91-57 [15])

other case, the design cruise speed has been established following the associated EASA code (column 2, Table 2). The gust intensity is 56 fps (at sea level and decreasing linearly with altitude) and the altitude, the manufacturer's altitude for each UAS. In the majority of the UASs, the second value is substantially greater than the first one, so the positive limit gust load factor based on it is also greater. Nevertheless, it is important to keep in mind that not all the UAS investigated are expected to have a gust load factor greater than the maneuver load factor. So this fact will be considered in the following results. To clarify the aforementioned process, the calculations of the real and W_{str} for the RQ-2 Pioneer UAV is shown. The equation for the gust load factor, obtained from EASA's certification specifications, is

$$n_g = 1 + K_g \frac{\rho_0 \mathrm{UVa}}{2\mathrm{MTOW}/S_w} \tag{3}$$

where $a = 5.02\ \mathrm{rad}^{-1}$, MTOW $= 204$ kg, and $S_w = 3\ \mathrm{m}^2$ for the RQ-2 Pioneer. The gust alleviation factor K_g is also obtained for the certification specifications and its value is 0.81 for the aforementioned UAV. To estimate the regulations' gust limit load factor, the value for V is the design cruise speed estimated following the associated EASA code (CS-VLA [27]) which, for the RQ-2 Pioneer, provides 118.8 km/h EAS (equivalent airspeed). For the real gust limit load factor the value for V is the maximum cruise velocity obtained from the manufacturer (223 km/h EAS for RQ-2 Pioneer). Using such speeds, the values are regulations $n_g = 4.52$ and real $n_g = 2.88$, as depicted in Table 4. The value for n_{lim} is 3.8, as established in CS-VLA [27].

It is well known that a relationship exists between the limit load factor (the maximum of maneuver and gust load factors) and the structural weight; and there are conceptual design methods for estimating this weight with the limit load factor an explicit parameter [37–39]. To cover all possibilities the limit load factor is estimated according to three different procedures. First, the maneuver load factor is computed using the appropriate EASA manned aircraft code. Second, the gust load factor is determined with the discrete gust model [26] using the manufacturer-declared maximum cruise velocity. This gust load factor will hereinafter be called the real gust limit load factor. And last, again the discrete gust model will be used, but with the design cruise speed of the corresponding EASA code. All these results are collected in Table 4. From the point of view of the manufacturer, the limit load factor is the maximum of real n_g or n_m. But it is evident that for many UAVs the regulations n_g is greater than any of both. These UAVs will be selected for further study. Table 5 shows the results obtained for the structural weight of these recently selected UAVs after applying Roskam's method [38]: the structural weight is estimated as a fraction of the MTOW in terms of the manufacturer's limit load factor or obtained following the EASA code limit load factor.

Table 4 Real UAS gust limit load factor according to declared data, and calculated values for maneuver and gust limit load factor following selected EASA airworthiness code indicated in Table 2

UAS	Real n_g	Regulations n_m	Regulations n_g
Aladin	6.61	3.8	6.61
Manta	3.36	3.8	5.64
Fulmar	4.19	3.8	6.17
Furos	6.45	3.8	7.24
Taridan Mastiff	2.67	3.8	4.46
Lipán M3	5.25	3.8	5.98
Rheinmetall KZO	3.43	3.8	3.89
Outrider tactical UAV	2.28	3.8	3.76
RQ-2 Pioneer	2.88	3.8	4.52
T-16 Arcturus	5.34	3.8	6.43
Apoena 3000	3.43	3.8	5.19
RQ-1 Predator	2.78	3.8	4.56
MQ 9 Reaper	2.08	3.27	2.84
RQ-4 Global Hawk	1.50	2.77	2.16
nEUROn	1.66	3.08	1.91
EADS Barracuda	2.81	3.49	2.81
X-45 A	2.30	3.18	2.30
IAI Searcher	3.10	3.8	4.75
RQ 5 Hunter	2.36	3.8	4.13
Mantarraya	4.58	3.8	4.58
Radio plane OQ 2	4.67	3.8	5.75

Table 5 Structural weight estimated according to declared data and to EASA selected manned aircraft airworthiness code

UAS	Real W_{str}, kg	Regulations W_{str}, kg	Regulations W_{str}/real W_{str}, %
Aladin	0.64	0.64	0.00
Manta	5.93	7.03	18.52
Fulmar	4.28	4.86	13.48
Furos	2.35	2.44	3.77
Taridan Mastiff	29.53	34.94	18.31
Lipán M3	12.84	13.39	4.27
Rheinmetall KZO	34.45	35.88	4.14
RQ-2 Pioneer	43.68	50.66	15.98
T-16 Arcturus	7.92	8.40	6.12
Apoena 3000	17.55	20.08	14.42
RQ-1 Predator	266.76	309.64	16.08
IAI Searcher	91.16	104.83	14.99
RQ 5 Hunter	226.51	268.24	18.42
Mantarraya	12.84	12.84	0.00
Radio plane OQ 2	10.06	10.75	6.93

Results shown in Table 5 indicate that there are two different situations. In some cases (see column 3), the weight does not vary, despite the two limit load factors used to calculate the structural weight. This fact suggests that the manufacturer has considered the EASA associated code as the design standard, as can also be deduced from Table 4. In other UAVs there are remarkable changes in structural weight; up to 19% in the worst case, which corresponds to an increase in the gust load factor of 68%. Any increase in load factor leads to a certain increase in structural weight. The variation in structural weight is depicted in Fig. 4, in terms of the kinetic energy listed. The various UAVs have been grouped in different boxes, depending on the associated airworthiness code, resembling clusters in Figure 2 from EASA A-NPA 16/2005 [1] and policy statement.

The structural weight changes do not only represent a change in UAV structural design, but also mean changes in other design aspects. For instance, for those aircraft listed in Table 5 with an increase in structural weight, this is due to the fact that the manufacturer's declared maximum cruise velocity is different from the design cruise speed given in the EASA reference code. When this last speed is greater than the declared one, the loads calculated for the code design cruise speed are greater too. But this also means that the powerplant installed in the UAV may not be capable of reaching this higher speed. Therefore a stronger powerplant would be required if the manufacturer wanted to reach such speed. The installation of a new engine might introduce new modifications in the UAS design, opening the door of a major UAS redefinition.

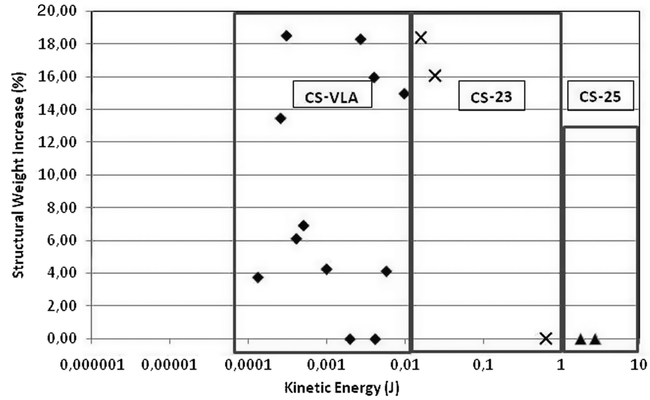

Fig. 4 Structural weight increase (%) for the selected UAS in terms of the kinetic energy.

V. Conclusions

There is a great potential for civil UAS applications, but to fully exploit such potential it will be necessary to integrate UAV operations into the same air space (nonsegregated) than the manned aircraft. To reach such scenario, a set of airworthiness codes or standards will have to be elaborated, to ensure the same safety levels than the conventional aircraft. An outlook of the regulatory framework for UAS has been presented. Although the actual initiatives are somewhat confusing and disperse, the EASA policy statement seems to be a sound basis for the new regulatory process.

The comparison of the EASA policy statement with other philosophies shows that this one is a restrictive approach, and so it is a guarantee of safety. The case study applied to 23 state-of-the-art UASs confirms this approach.

Most UAVs assessed in the present study would have difficulties in complying with the EASA codes, essentially because they would not withstand the gust loads, due to a low structural weight. In some cases the UAV actual performance would be well below the design cruise speed prescribed in the suitable airworthiness codes. Former conclusions indicate that the manufacturers of future UAS should take the EASA code (or an alternative equivalent) as certification basis, since early stages of the design, to avoid troubles in the certification process.

Thus, most existing UAVs would require some modifications if they had to comply with the corresponding airworthiness manned aircraft codes. In some cases, the performances could be deeply affected too.

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