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Review on delta wing against other wing designs for micro aerial vehicles*

by

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Abstract: Wings play a vital role in the design of micro aerial vehicles (MAV), in view of aerodynamic performance, maneuverability and hovering capabilities of the vehicles. The wings are generally classified as flapping, delta, swept, and so on. In this paper, the literature is reviewed regarding the diverse techniques utilized for the design, experimentation, analysis, simulation, and modeling of different types of wings. Among these types, this paper focuses on the design of delta wings. Accordingly, we review 60 relevant research papers and provide an analysis, based on their content. First, the paper presents the chronological review of the contributions relevant for the design of different types of wings. Subsequently, we focus on various materials such as stainless steel, aluminum, carbon fiber, etc., and on parameters such as Reynolds number, angle of attack, aspect ratio, etc., which are utilized for the design of wings. The paper also provides a detailed performance study regarding the contribution to the design of delta wing. Finally, we present various research issues, which can be useful for the researchers in accomplishing further research on the design of delta wings.

Keywords: micro aerial vehicles, wings, delta wing, materials, parameters, survey

1. Introduction

1.1. The problem considered

MAVs (see, for instance, Salichon and Tumer, 2012; Dames et al., 2016; Zollmann et al., 2014; Khan, Yanmaz and Rinner, 2015) are the small aircraft with the wingspan of about 15 cm. In comparison with Unmanned Aerial Vehicles (UAVs), the magnitude order of MAV is lower and also the actual physical size of the vehicle is mostly truly small (Guo, Li and Wu, 2012; Ryu, Chang and

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Chung, 2016). MAVs provide excellent alternatives to piloted vehicles in a variety of tasks, like reconnaissance, sensing, surveillance, search and recovery, and automated target authentication (Sybilski, Żyluk and Wróblewski, 2018; Hamizi and Khan, 2019). MAVs can perform such tasks without endangering human lives, giving an important edge to the organization that uses them (Cetin, Celik and Yavuz, 2018). Basically, the precision regarding the navigation of MAV through closed environments (Barbosa et al., 2019) is higher than that of the UAVs. Furthermore, this vehicle can be adapted to the immensely discrete service with its tiny frames and quiet operating conditions (Sivasankaran et al., 2016; Sivasankaran and Ward, 2016; Bachmann et al., 2009; Tisse, Durrant-Whyte and Hicks, 2007; Kamal, Bayoumy and Elshabka, 2016). In general, the development of the flying robot, which navigates through different areas is still a long term goal, which requires lightning-quick reflexes for control, actually higher than the ability of humans (de Croon et al., 2012; Fedele and Ramundo, 2019). Hence, quite some degree of autonomous sensory control is essential to reach this goal. This is not only used to avoid the obstacles, but also to provide a steady configuration to the aircraft. The main application of MAV includes military prospective, mainly for explorations, surveillance, targeting, and broadcast (Wang et al., 2005; Dghim et al., 2016). Moreover, it can also be utilized for observing the biochemical and hazardous materials and for implantation of sensors in the domain of civilian applications whereas the commercial applications include traffic monitoring, power line check-up, real estate observation, and surveying the wildlife.

The deficiencies in typical control surfaces make the vehicles hard to fly. The control effectors are largely utilized for achieving numerous relevant characteristics, but, of course, have a limited capacity. Hence, the controllability of the vehicles is enhanced by implementing the appropriate design of wings (Sahai, Galloway and Wood, 2013; Hsiao et al., 2012; von Ellenrieder, Parker and Soria, 2008; Tobing, Young and Lai, 2017; McIntosh, Agrawal and Khan, 2006; Rizzi, 1989; Hubner and Hicks, 2011; Song, Weng and Lebby, 2010), which further improves the vehicle performance. Besides, the flexibility of wings can reduce the power consumption of MAVs (Bry et al., 2015; Ingalagi and Katti, 2016). These small airplanes are highly receptive to wind gusts so that the stability of flights must be sustained (Au, Phan and Park, 2016; Gordnier, 2009; Faruque and Humbert, 2014; La Mantia and Dabnichki, 2011; Jongerius and Lentink, 2007; Nakata, 2009). Thus, during windy conditions, the wings get contorted due to high load by the washout effect, which diminishes the induced drag on wind tips and forms the maximum lift to drag ratio. Further, the original shape of the wing is recovered after struggling with the wind gust to make the flight stable.

The complication of MAV can be balanced by the precise design of the concerned wing type. In order to achieve the stability, the lifting wing area, the chord, and the wingspan should be approximately equal to each other. The wings of UAV are designed in such a way that the wing chord is nearly 0.0755m with 5% double camber configuration, unit aspect ratio, and low Reynolds number (Hassanalian and Abdelkefi, 2016; Wang and Schlüter, 2012). Thus, distinctive aerodynamic properties such as high stall-angles of attack and nonlinear lift versus angle of attack curves are attained with the above configurations. The appropriate design of MAV wings (Ghommem et al., 2014; Cleaver et al., 2016; Samani and Sedaghat, 2013; Ismail et al., 2014) is obtained by significant analytical and theoretical work, as well as numerical simulations.

The paper reviews the design, experimentation, analysis, simulation, and modelling of the delta wing of MAV. Altogether, this paper provides the chronological review of the contributions to the design of different types of wings. Then, it also describes the various materials utilized in all contributions and adopted parameters for designing wings. Further, this paper analyses the content of each contribution to the design of delta wings along with a performance study. With all this information, this paper concludes with specification of the essential research gaps and challenges, which have to be addressed in order to enhance MAV performance.

This paper spotlights the contribution to the design of delta wings, namely

- it reviews 60 research papers and provides a substantive analysis; the survey starts with presentation of the chronological review of the totality of contributions on the design of different types of wings;
- then, the analysis considers various materials such as stainless steel, aluminium, carbon fiber, etc., and parameters such as Reynolds number, the angle of attack, aspect ratio, etc. utilized for the design of wings;
- in addition, this paper also provides a detailed performance study regarding the contributions to the design of the delta wing;
- finally, this paper presents the various research issues, whose resolution can be useful for the researchers to accomplish further effective research on the design of delta wings.

1.2. Organization of the paper

The organization of the paper is as follows. The second section of the paper depicts the design considerations, which include the design contributions, utilized materials, and design measures of state-of-the-art. The third section describes the performance study along with the determination of methodology of each contribution on the design of delta wings. Finally, the fourth section presents the review outcome concerning the formulation of gaps and challenges regarding the research and needful future directions for effective improvement.

2. Design considerations

2.1. State-of-the-art design contributions

This section discusses the contributions associated with the different types of wings such as flapping wings, delta wings, swept wings, membrane wings, and other types of wings. The references regarding the contributions to the design of each wing type are shown in Table 1.

Considering the flapping wings, the total share of the respective contribution is nearly 28%. In 2005, Żbikowski, Galiński and Pedersen (2005) suggested the effective design, implementation, and testing of the flapping wing of MAV using a four-bar linkage mechanism, and then in 2006, Ansari, Żbikowski and Knowles (2006) modelled the effective insect-like flapping wing for MAV. On the other hand, in 2008, Chung et al. (2008) configured the piezoelectric fan of the flapping-wing with efficient transmission of energy. Later, Mueller, Bruck and Gupta (2010) implemented the Compliant Flapping Wing for MAV using a new test stand design. Then, Guo, Li and Wu (2012) designed the model of flapping wing for MAV with significant numerical modelling along with a theoretical study, whereas Orlowski and Girard (2012) performed a detailed analysis of flapping-wing regarding its dynamics, stability, and control.

Liu et al. (2013) studied the aerodynamic properties as well as the stability of the prototype bio-inspired flapping-wing, while Bos, van Oudheusden and Bijl (2013) examined the performance of the flapping-wing flight in terms of vortex dynamics as well as the associated force through simulation of three-dimensional flow over the wing. A bit later, Broering and Lian (2015) analyzed the aerodynamic properties of the tandem flapping-wing for both two and three dimensions, while Yan, Taha and Hajj (2015) analyzed the effects of aerodynamic modelling for the maximum kinematics of flapping flight for floating MAV.

Following this, Hassanalian and Abdelkefi (2016) estimated the weight of fixed and flapping-wing through dynamic modelling, and Xue et al. (2016) demonstrated the flexibility of flapping-wing of MAV in forward flight. In the same year, Zhang, Wen and Yang (2016) designed the model of the bio-inspired flapping-wing in hanging flight by optimizing the lift force, and Ryu, Chang and Chung (2016) determined the vortex structure and aerodynamic properties of the flexible hawkmoth-like flapping-wing. Moreover, Xu et al. (2016) developed the flapping wing design based on embedded boundary approach, while Moriche, Flores and Garcia-Villalba (2016) implemented the structure of the flapping-wing through three-dimensional Direct Numerical Simulation (DNS) and Floquet stability analysis. Finally, Olivier and Dumas (2016) estimated the configuration of the flapping-wing using numerical simulation.

Regarding the delta wing type, the total share of contributions, assigned to this category, is 53%. Already in 1998, Hentschel (1998) developed a self-

Table 1: Contributions on the design of different types of wings

Wing type	**Contributions**
Flapping-wing	Guo, Li & Wu (2012), Orlowski & Girard (2012), Chung et al. (2008), Ansari, Żbikowski & Knowles (2006), Liu et al. (2013), Hassanalian & Abdelkefi (2016), Mueller, Bruck & Gupta (2010), Bos, van Oudheusden & Bijl (2013), Broering & Lian (2015), Yan, Taha & Hajj (2015), Xue et al. (2016), Zhang, Wen & Yang (2016), Żbikowski, Galiński & Pedersen (2005), Ryu, Chang & Chung (2016), Xu et al. (2016), Moriche, Flores & Garcia-Villalba (2016), Olivier & Dumas (2016)
Delta wings	Gursul, Gordnier & Visbal (2005), Elsayed et al. (2011), Sohn (2010), Mystkowski (2013), Lee & Pereira (2013), Vlahostergios et al. (2013), Cai et al. (2014), Khoshvagt-Aliabadi, Sartipzadeh & Alizadeh (2015), Fritz (2013), Qin et al. (2015), Pevitt & Alam (2014), Suresh, Radhakrishnan & Shankar (2013), Huang, Mostafa & Wu (2003), Mat et al. (2014), Gordnier & Melville (2001), Eiamsa-ard, Nuntadusit & Promvonge (2013), Ul Haque, Khawar & Raza (2008), Qiana, Nadria & Dufour (2016), Wu et al. (2016), Pal et al. (2012), Chomdee & Kiatsiriroat (2007), Zhang et al. (2004), Ke et al. (2006), Wang et al. (2005), Gentry & Jacobi (2002), Mary (2003), Lee & Choi (2015), Lee (2016), Gordnier & Visbal (1998), Hentschel (1998), Ingalagi & Katti (2016), Özgören, Sahin & Rockwell (2002)
Other types	Lian et al. (2003), Hays et al. (2015), Tao & Sun (2016), Buoso & Palacios (2015), Liu & Hsiao (2014), Ananda, Sukumar & Selig (2015), Dghim et al. (2016), Wang, Xu & Yue (2016), Merrett (2016), Jain, Wong & Rival (2015)

adaptive numerical simulation model to analyze the lift by the sharp-edged delta wing and simulated the delta wing using three-dimensional Navier-Stokes equation. Then, Gentry and Jacobi (2002) modified the channel flows in the delta wing by generating the streamwise vortices for enhancing the heat transfer. Özgören, Sahin and Rockwell (2002) performed a comparison of vortex development patterns in delta wing. Following this, Mary (2003) proposed the large eddy simulation of vortex breakdown behind a delta wing, while Huang, Mostafa and Wu (2003) presented the double-delta wing in fighter trainer aircraft through conceptual design optimization. Lian et al. (2003) designed the membrane wing for MAV. Then, in 2004, Zhang et al. (2004) analyzed the influence of pitch of in-line delta winglet vortex generators by naphthalene sublimation technique through the comparison of heat and mass transfer.

Thereafter, Gursul, Gordnier and Visbal (2005) studied the structure of vortex and breakdown of delta wing. Wang et al. (2005) differentiated the vortices of delta wing in near-wake incompressible and supersonic free structures to examine this practice by comparing data from an incompressible flow experiment designed specifically to correspond to an earlier experiment in supersonic flows. Then, Ke et al. (2006) investigated the influence of the angle of attack on the performance regarding heat transfer and pressure drop in delta winglet vortex generators (VGs). Later on, Chomdee and Kiatsiriroat (2007) improved air cooling in electronics modules in effect of investigation of heat transfer control by delta winglet vortex generators, while ul-Haque, Khawar and Raza (2008) investigated the effect of turbulence modelling with combination of computational speed and accuracy for high angles of attack aerodynamic design. Following this, Sohn (2009) analyzed the sharp-edged delta wing with the help of visualization and particle image velocimetry (PIV) measurement. Then, Elsayed et al. (2011) evaluated the capabilities of differential spoiler setting (DSS) in enhancing the wingspan loading. Further, Pal et al. (2012) simulated the flow of coolant air in a heat exchanger of delta winglet type vortex generators using the common-flow-up configuration.

In terms of later research, Mystkowski (2013) utilized the piezo-stack vortex generators to determine the regulation of flow separation over solid surfaces of a delta wing. In the same year, Suresh, Radhakrishnan and Shankar (2013) established the load control process in tailless delta wing aircraft at both the subsonic and supersonic flight by systematic approach for manoeuvre load alleviation (MLA) problem with multi-objective formulation and optimisation methods, while Eiamsa-ard, Nuntadusit and Promvonge (2013) examined the influence of the thermal performance of heat exchanger tube on a delta wing. It should be noted, though, that much earlier Gordnier and Melville (2001) had adopted the Navier-Stokes equation to simulate the limit-cycle oscillation of cropped delta wing.

Then, Khoshvaght-Aliabadi, Sartipzadeh and Alizadeh (2015) investigated heat transfer enhancement in a tube using the vortex-generator insert with different arrangements of the delta-winglets, for which Qin et al. (2015) proposed the Delayed Detached Eddy Simulation of aerodynamic forces of delta wing under static ground effect. Then, Lee and Choi (2015) described the control of the delta wing vortex under various geometric configurations. Further, Qian, Nadria and Dufour (2016) designed the non-linear system of a delta wing with a case study of an unstable wing, while Wu et al. (2016) developed the interrupted delta wing through the investigation of heat transfer and thermal resistance features. In the same year, Lee (2016) analyzed the effect of Gurney flap-like strips in reverse delta wing (RDW) under various heights and geometric configuration, while Ingalagi and Katti (2016) analyzed the characteristics of airflow in the square duct using delta wing vortex generators.

Now, we turn to the other types of wings. The respective contributions account for 18% of the total number of surveyed papers.

Thus, Jain, Wong and Rival (2015) developed the vortex on span wise-flexible wing. In 2014, Liu and Hsiao (2014) carried out an experimental analysis of aerodynamic properties of wings of MAV with a low aspect ratio. Ananda, Sukumar and Selig (2015) analyzed the aerodynamic properties of ten wings at low aspect ratio and Reynolds number, while Buoso and Palacios (2015) examined the aeromechanical performance of the dynamically actuated membrane. Hays et al. (2015) determined the harmonic and transient behaviour from electric field excitation of membrane wing, while Bry et al. (2015) implemented the fixed-wing and quadrotor aircraft in an indoor environment using trajectory planning and state estimation algorithms.

In 2016, Wang, Xu and Yue (2016) designed the oblique wing aircraft through the analysis of dynamic characteristics, and Dghim et al. (2016) demonstrated the effective synthetic jet actuation by controlling a wingtip vortex. Further, Tao and Sun (2016) designed the 3D swept model with reduced airframe noise by controlling the aerodynamic performance using an artificial neural network, while Merrett (2016) predicted the time component of flutter, and provided a set of conditions for viscoelastic structural instabilities in general.

The chronological distribution of the contributions, related to different types of wings is shown in Fig. 1. Before 2007, the contributions on the design of delta-wing appear to be leading compared to other types of wings. For 2008, the contributions on the design of flapping-wings and delta wings are equal in numbers. No contributions on both wings during the year 2009 have been considered, and more contributions on delta wings for the years 2010 and 2011. Further in 2012, the number of contributions on the design of flapping-wing is higher. The delta wing -related contributions here considered are again more numerous than those for the flapping-wing between the years 2013 and 2015.

However in year 2016, the final year of this survey, the contributions on the flapping-wing is dominate over those for the other types of wings.

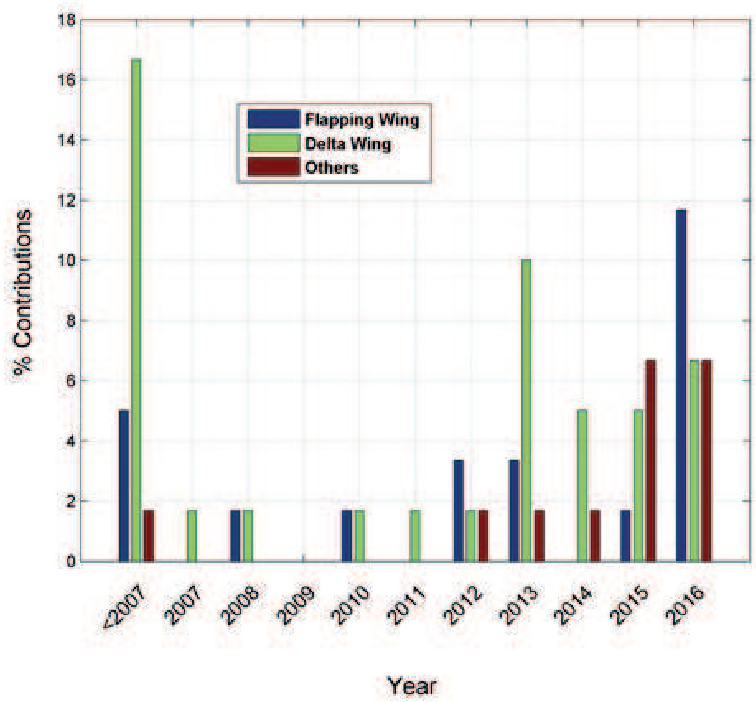

Figure 1: Chronological distribution of the considered contributions on different types of wings

2.2. Materials and design measures

The different types of materials, which are utilized in various studies, here surveyed, are shown in Table 2. The materials, utilized in these references for designing all types of wings include piezoelectric ceramics, aluminium, stainless steel, zirconate titanate (PZT), carbon fiber, prepreg laminate, polyethylene film, mylar, textiles, piezoelectric materials, aluminum, wood, glass, balsa wood, dielectric elastomers, hyper-elastic materials, reinforced plastics, ferroelectric ceramics, shape memory alloys, naphthalene, nylon, polycarbonate, and polymers. Among those materials, only single contributions mention having used the piezoelectric ceramic, zirconate titanate, aluminum, prepreg laminate, polyethylene film, mylar, textile, piezoelectric materials, wood, glass, balsa wood, dielectric elastomers, hyper-elastic materials, reinforced plastics, ferroelectric ceramics, shape memory alloys, nylon, polycarbonate, and polymers. Two of the contributions reported the use of the naphthalene material, while the use of stainless steel, aluminium, and carbon fiber was mentioned in four contributions for each of these materials. The material, which was most often utilized in the contributions surveyed was aluminium, mentioned in five of the references.

Regarding the flapping-wing studies (17 in total), single contributions employed such materials as piezoelectric ceramics, aluminum, zirconate titanate, polyethylene film, mylar, textiles, nylon, and polycarbonate. On the other hand, stainless steel was used in four of the respective studies, and two of these studies utilized carbon fiber.

The contributions related to the design of delta wings (32 in total) mentioned the use of piezoelectric materials and reinforced plastics in single cases each, aluminium in five cases, naphthalene in two cases. Then, concerning the studies, in which such materials as prepreg laminate, carbon fiber, wood, glass, balsa wood, dielectric elastomers, hyper-elastic materials, ferroelectric ceramics, shape memory alloys, and polymer were used, there were three for each of these materials.

Thus, it is quite clear that among the contributions surveyed, the most often used material for designing and elaborating the flapping-wing is stainless steel, and the least used materials are piezoelectric ceramic, aluminum, polyethylene film, nylon, and polycarbonate. On the other hand, the most frequently used material for designing and testing the delta wing is aluminum, and the least used materials are piezoelectric materials and ferroelectric ceramics.

The design, modelling and assessment parameters, assumed in the here surveyed studies on wings of MAV are shown in Table 3. Most of these parameters appear in several of the contributions here surveyed. For quite obvious reasons, related to the physical background of the research, the angle of attack and the Reynolds number appear most frequently, namely in 28 and 23 of these references, respectively, out of the total of 60 of them. Other two parameters, which appear quite frequently in the studies here reported are the following ones: the pressure distribution (15 references) and the speed (also 15 references). Then comes a group of parameters that are somewhat less, but still quite frequently utilized, namely the Euler angle, the flapping angle and the pitching angle (10 references for each of these), flight time (10 references), lift to drag ratio (9 references), followed by the skew angle, the sweep angle, the slide-slip angle and vorticity (8 references use each of these parameters). This broad group of parameters is definitely most often used by the authors of the studies surveyed and virtually covers all of these studies. Of the other ones let us mention the wing area and the aspect ratio (both appearing in 6 references), and then mean vortex and force (each of them being used in 5 studies). It appears to be quite obvious that the other parameters, shown in Table 3, are treated as having lesser importance, or being used only in special cases, or for quite definite purposes. This may apply to such ones as power efficiency (three references) and vibration amplitude (two references).

Attention ought to be paid to the fact that among those listed in Table 3 there are no parameters that would appear in just a single reference. However, a separate list is provided in Table 4, where we provide the least used parameters, a part of them having somewhat different or quite specific character, namely such ones as vortex core size, wing stiffness, geometric aerodynamic parameters; attitude and noise parameters, etc. It can be easily noticed that the content of the two tables (Table 3 and Table 4) overlaps in terms of frequency of appearance.

3. Performance study on design of delta wings

The aerodynamic characteristics of thin sharp-edge delta wings are of interest for supersonic aircraft and have been the topic of experimental as well as theoretical studies for many years in both the supersonic and subsonic speed ranges. In recent years, the importance of the vortex flows related to thin delta and delta-related wings has increased significantly due to the supersonic commercial air transport programs that are nowadays in progress.

3.1. Methodology

The methodology of each contribution, relative to design and experimentation, analysis, simulation, and modelling is shown in Table 5.

The control of vortices and the respective breakdown were mainly addressed in Gursul, Gordnier and Visbal (2005), Lee and Pereira (2013), Gentry and Jacobi (2002), Lee and Choi (2015), Özgören, Sahin and Rockwell (2002), Sohn (2010), Mary (2003), Vlahostergios et al. (2013) and Wang et al. (2005), while the aerodynamic characteristics were primarily taken into account in Huang, Mostafa and Wu (2003), Qian, Nadri and Dufour (2016), Qin et al. (2015), and Mat et al. (2014).

Then, the studies by Elsayed et al. (2011), Cai et al. (2014), Ke et al. (2006), Suresh, Radhakrishnan and Shankar (2013), Hentschel (1998) and Mystkowski (2013) considered the issues of differential spoiler settings, control efficiency, the effect of angle of attack, controlling load, steady, compressible inviscid and viscous flows and boundary layer control of delta wings.

Finally, the heat transfer enhancement was considered in such studies as those by Khoshvaght-Aliabadi, Sartipzadeh and Alizadeh (2015) and Wu et al. (2016), while air cooling was taken into account in Chomdee and Kiatsiriroat (2007), Ingalagi and Katti (2016) and in Pal et al. (2012).

Table 2: Materials utilized in various contributions

Materials	Flapping-wing	Delta wing	Other types
Piezoelectric ceramics	Guo, Li & Wu (2012)	-	-
Aluminium	Guo, Li & Wu (2012)	-	-
Stainless steel	Guo, Li & Wu (2012), Chung et al. (2008), Żbikowski, Galiński & Pedersen (2005), Olivier & Dumas (2016)	-	-
Zircornate Titanate	Chung et al. (2008)	-	-
Carbon fiber	Liu et al. (2013), Hassanalian & Abdelkefi (2016)	-	Lian et al. (2003)
Prepreg laminate	-	-	Lian et al. (2003)
Polyethylene film	Liu et al. (2013)	-	-
Mylar	Hassanalian & Abdelkefi (2016)	-	-
Textile	Hassanalian & Abdelkefi (2016)	-	-
Piezoelectric materials	-	Mystkowski (2013)	
Aluminum	-	Lee & Pereira (2013), Cai, Li & Zhang (2014), Khoshvagt-Aliabadi, Sartipzadeh & Alizadeh (2015), Eiamsa-ard, Nuntadusit & Promvonge (2013), Lee & Choi (2015)	-
Wood	-	-	Liu & Hsiao (2014)
Glass	-	-	Liu & Hsiao (2014)
Balsa wood	-	-	Liu & Hsiao (2014)
Dielectric elastomers	-	-	Buoso & Palacios (2015)
Hyper-elastic materials	-	-	Buoso & Palacios (2015)
Reinforced plastics	-	Pevitt & Alam (2014)	-
Ferroelectric ceramics	-	-	Hays et al. (2015)
Shape memory alloys	-	-	Hays et al. (2015)
Naphthalene	-	Zhang et al. (2004), Ke et al. (2006)	-
Nylon	Żbikowski, Galiński & Pedersen (2005)	-	-
Polycarbonate	Ryu, Chang & Chung (2016)	-	-
Polymer	-	-	Merrett (2016)

Table 3: Parameters used in the design of wings of MAV

References	Power efficiency	Euler, flapping and pitching angles	Frequency	Vorticity	Vibration amplitude	Pressure distribution	Sweep, skew and slide slip angle	Flight speed	Flight time	Mean vortex	Reynolds number	Wing area	Force	Angle of attack	Aspect ratio	Lift-to-drag ratio
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Guo, Li & Wu (2012)	X															
Orlowski & Girard (2012)		X														
Chung et al. (2008)					X											
Gursul, Gordnier & Visbal (2005)					X											
Lian et al. (2003						X			X	X						
Elsayed et al. (2011)									X	X						
Sohn (2010)						X										
Hassanalian & Abdelkefi (2016)											X	X				
Mueller, Bruck & Gupta (2010)													X			
Mystkowski (2013)		X						X				X		X	X	
Lee & Pereira (2013)																X
Vlahostergios et al. (2013)				X		X					X	X		X		
Bos, van Oudheusden & Bijl (2013)		X									X			X		

Table 3, continued (part 2)

References	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Liu & Hsiao (2014)											X		X	X	X	X
Cai et al. (2014)														X		
Broering & Lian (2015)		X				X						X		X		X
Ananda, Sukumar & Selig (2015)											X				X	
Yan, Taha & Hajj (2015)	X	X	X										X	X	X	
Buoso & Palacios (2015)									X					X		X
Khoshvagt-Aliabadi, Sartipzadeh & Alizadeh (2015)						X						X				
Jain, Wong & Rival (2015)			X	X				X	X				X	X		
Fritz (2013)						X					X	X		X		
Qin et al. (2015)							X		X		X	X				X
Wang, Xu & Yue (2016)							X	X						X		
Pevitt & Alam (2014)								X	X							
Dghim et al. (2016)			X			X				X	X	X				
Suresh, Radhakrishnam & Shankar (2013)		X				X						X		X		
Huang, Mostafa & Wu (2003)							X							X		
Hays et al. (2015)											X					
Xue et al. (2016)			X					X								
Zhang, Wen & Yang (2016)														X		X
Mat et al. (2014)											X			X		X

Table 3, continued (part 3)

References	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Gordnier and Melville (2001)			X										X			
Eiamsa-ard, Nuntadusit & Promvonge (2013)						X		X			X	X				
ul-Haque, Khawar & Raza (2008)						X					X			X		
Qian, Nadri & Dufour (2016)									X							
Wu et al. (2016)								X			X	X				
Pal et al. (2012)						X						X		X		
Chomdee & Kiatsiriroat (2007)						X						X				
Zhang et al. (2004)						X		X	X			X				
Ke et al. (2006)						X		X			X	X				
Wang et al. (2005)				X		X		X						X		
Gentry & Jacobi (2002)										X	X			X		
Mary (2003)							X				X			X		
Lee & Choi (2015)				X			X	X			X	X		X	X	X
Lee (2016)				X			X	X			X			X		X
Gordnier & Visbal (1998)							X			X		X		X		
Hentschel (1998)				X				X								
Żbikowski, Galiński & Pedersen (2005)		X					X							X		
Ryu, Chang & Chung (2016)				X					X							
Merrett (2016)								X	X							

Table 3, continued (part 4)

References	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Xu et al. (2016)											X					
Ingalagi & Karri (2016)		X									X				X	
Moriche, Flores & Garcia-Villalba (2016)		X	X								X					
Olivier & Dumas (2016)	X	X	X									X		X		
Özgören, Sahin & Rozkwell (2002)				X				X			X			X		
Sums of appearances	3	10	7	8	2	15	8	15	10	5	22	18	5	26	6	9

Table 4: Other parameters used for designing the wings of MAV

Parameters	References	Parameters	References
mechanical demand	Guo, Li & Wu (2012)	deflection angle	Jain, Wong & Rival (2015)
vertical take-off and landing capability	Guo, Li & Wu (2012)	sting diameter	Fritz (2013)
free tip deflection	Chung et al. (2008)	leading edge radius	Fritz (2013), Dghim et al. (2016)
vortex core size	Ansari, Żbikowski & Knowles (2006)	wing thickness	Fritz (2013), Qin et al. (2015), Ryu, Chang & Chung (2016)
wing flexibility	Gursul, Gordnier & Visbal (2005)	mesh resolution	Pevitt & Alam (2014)
pitch oscillation	Gursul, Gordnier & Visbal (2005)	jet momentum coefficient	Dghim et al. (2016)
separation bubble	Lian et al. (2003)	roll acceleration and damping	Suresh, Radhakrishnan & Shankar (2013)
wing stiffness	Liu et al. (2013), Jain, Wong & Rival (2015)	wing tip chord	Huang, Mostafa & Wu (2003)
vortex flow	Sohn (2010)	geometric and aerodynamic parameters	Tao & Sun (2016)
wing dimension	Hassanalian & Abdelkefi (2016)	correlation	Hays et al. (2015)
frictional effects	Mueller, Bruck & Gupta (2010)	wing-to-body mass ratio	Xue et al. (2016)
dynamic response	Mueller, Bruck & Gupta (2010)	attitude and noise parameters	Bry et al. (2015)
total mass	Mystkowski (2013), Vlahostergios et al. (2013)	translation motion	Zhang, Wen & Yang (2016)
altitude	Mystkowski (2013)	stroke amplitude	Zhang, Wen & Yang (2016)
inertia moments	Mystkowski (2013), Wang, Xu & Yue (2016), Merrett (2016)	leading edge bluntness	Mat et al. (2014)
taper ratio	Mystkowski (2013)	stiffness matrices	Gordnier & Melville (2001)
root chord and root-tip sweep	Mystkowski (2013)	heat of the fluid	Eiamsa-ard, Nuntadusit & Promvonge (2013)
total drag	Lee & Pereira (2013)	diameter of test tube	Eiamsa-ard, Nuntadusit & Promvonge (2013)
turbulence kinetic energy	Vlahostergios et al. (2013), Mary (2003)	volume flow rate	Eiamsa-ard, Nuntadusit & Promvonge (2013)
turbulence dissipation rate	Vlahostergios et al. (2013)	flux	ul-Haque, Khawar & Raza (2008)

Table 5: Other parameters used for designing the wings of MAV - continuation

Parameters	References	Parameters	References
deviation angle	Bos, van Oudheusden & Bijl (2013)	sensitivity	Qian, Nadri & Dufour (2016)
Rossby number	Bos, van Oudheusden & Bijl (2013)	Colburn factor	Wu et al. (216)
slope of lift curve	Liu & Hsiao (2014)	height and length of vortex generator	Chomdee & Kiatsiriroat (2007), Ingalagi & Katti (2016)
maximum lift coefficient	Liu & Hsiao (2014)	width and height of the channel	Zhang et al. (2004)
pressure drag and skin friction drag coefficient	Cai et al. (2014)	thermal diffusivity	Zhang et al. (2004)
kinematic viscosity	Broering & Lian (2015), Khoshvagt-Aliabadi, Sartipzadeh & Alizadeh (2015), Lee (2016)	hydraulic diameter	Ke et al. (2006)
fluid density	Broering & Lian (2015)	turbulence intensity	Wang et al. (2005)
plunging displacement	Broering & Lian (2015)	vortex strength	Gentry & Jacobi (2002), Gordnier & Visbal (1998)
Oswald's efficiency	Ananda, Sukumar & Selig (2015)	vortex strength	Lee & Choi (2015)
chord length	Yan, Taha & Hajj (2015), Qin et al. (2015)	geometric span	Lee (2016)
quasi-steady circulation	Yan, Taha & Hajj (2015), Qin et al. (2015)	frequency and density ratio	Xu et al. (2016)
deformation tensor and gradient	Buoso & Palacios (2015), ul-Haque, Khawar & Raza (2008), Lee & Choi (2015)	theoretical friction factor	Ingalagi & Katti (2016)
heat transfer coefficient	Khoshvagt-Aliabadi, Sartipzadeh & Alizadeh (2015), Wu et al. (2016)	normalized flexibility	Olivier & Dumas (2016)

Table 6: Description of contributions on the design of delta wing

Main research	**Details**
Design and experimentation	non-slender vortices and their breakdown (Gursul, Gordnier & Visbal, 2005), nonlinear dynamic systems (Qian, Nadri & Dufour, 2016), static-tip vortex (Lee & Pereira, 2013), differential spoiler setting (Elsayed et al., 2011), control efficiency (Cai et al., 2014), heat transfer enhancement (Khoshvaght-Aliabadi, Sartipzadeh & Alizadeh, 2015), load control process (Suresh, Radhakrishnan & Shankar, 2013), air cooling in electronics modules (Chomdee & Kiatsiriroat, 2007), influence of angle of attack on delta wing (Ke et al., 2006), generation of stream wise vortices (Gentry & Jacobi, 2002), controlling delta wing vortex (Lee & Choi, 2015), characteristics of air flow in square duct (Ingalagi & Katti, 2016), vortex development patterns (Özgören, Sahin & Rockwell, 2002)
Analysis	vortex flow characteristics (Sohn, 2010), lift to drag ratio (Huang, Mostafa & Wu, 2003), aerodynamic development (Mat et al., 2014), influence of thermal performance (Eiamsa-ard, Nuntadusit & Promvonge, 2013), effect of Gurney flap like strips (Lee, 2016)
Simulation	peculiar subsonic flow-field (Fritz, 2013), aerodynamic forces and flow physics (Qin et al., 2015), fluid dynamics (Pevitt & Alam, 2014), limit- cycle oscillation (Gordnier & Melville, 2001), heat transfer and thermal resistance characteristics of fin (Wu et al., 2016), flow of coolant air (Pal et al., 2012), vortex breakdown (Mary, 2003), delta wing roll (Gordnier & Visbal, 1998), steady, compressible inviscid and viscous flows (Hentschel, 1998)
Modelling	vortex breakdown control (Vlahostergios et al., 2013), boundary layer control (Mystkowski, 2013), separated flow over at subsonic speed (ul-Haque, Khawar & Raza, 2008), differentiation of vortices (Wang et al., 2005)

3.2. Performance study

The results, concerning performance, as expressed through the values of the parameters, used in the various studies, devoted to the design of the delta wing, as reported in the here surveyed literature, are presented in Table 6. The table shows the maximum reported values that can be attained by the respective parameters under diverse aspects.

4. Review outcome

4.1. Research gaps and challenges

The problems, which arise in the design of delta wings, have been considered here on the basis of the detailed survey of the relevant papers.

So, in particular, it can be concluded that the complexity of the vortical flow constitutes the main obstacle in designing the optimum configuration of the aircraft. Numerical examination of vortex breakdown at a constant angle of attack provides the most important attribute for the study. Accordingly, an effective numerical simulation or model is required to obtain, or approximate the solutions with respect to laminar, unsteady inviscid and turbulent conditions. The angle of attack assumes a major role in the process and consideration of vortex breakdown. It appears necessary to adopt the constant angle of attack rather than varying the angle. Further, the aerodynamic behaviour in the flight depends on both stationary and non-stationary characteristics of wings. In non-stationary conditions the complexities arising during the operation of the vehicle could not be overcome. The limitations of CPU in analysing in conditions of actual physical time lead to challenges related to the time steps. When resolved, this may lead to the ability of predicting both moments and aerodynamic forces.

In addition, the angle of attack is needed to be associated with the take-off and landing parameters of the vehicle, and it is to be ensured that the unfavorable flying characteristics of flight are avoided during the modelling of flight. Another aspect may be constituted by the focus on time-accurate simulations at high values of the angle of attack. In view of the presence of multiple time scales, the time step should be properly selected on the basis of verified knowledge. Besides, valuable knowledge regarding the physical characteristic of the delta wings like wing material and aerodynamic shape are another aspect that should be taken into account during designing the wings. Computational efficiency as well as accuracy have to be properly addressed in order to reduce the complexity of the design. Effective numerical simulations are utilized and numerous data are generated. Subsequently, handling, integrating, storing, and analyzing these data is another task that should be appropriately addressed. Since there is a need for extracting precise information from these data, novel post-processing methods are required, which would enable estimating the characteristics of flow over the delta wings.

Table 7: Measures of design parameters of delta wing

Reference	Time, *sec*	vortex-flow, m^3/s	Pressure, *Pa*	Speed, m/s	angle of attack, *rad/* ^{0}	aspect ratio, *1*	wing area, m^2	lift-to-drag ratio, *1*	Reynolds number, *1*	other parameters *various*
	1	2	3	4	5	6	7	8	9	10
Gursul, Gordnier & Visbal (2005)										vibration = 0.7 Hz, pitch oscillation = 1^0
Elsayed et al. (2011)	35* 10^{-6}									
Sohn (2010)		8.2 *10^5	24.86							
Mystkowski (2013)				15	0.08	3.981	0.32			
Lee & Pereira (2013)								±0.025		
Vlahostergios et al. (2013)				1.14	30^0				9.8 *10^3	
Cai et al. (2014)					60^0					
Khoshvaght-Aliabadi, Sartipzadeh & Alizadeh (2015)			1700							
Fritz (2013)					18^0				6 *10^6	
Qin et al. (2015)	0.108				20^0				1.5 *10^6	
Pevitt & Alam (2014)				80						

Table 7, continued

Reference	1	2	3	4	5	6	7	8	9	10
Huang, Mostafa & Wu (2003)					10^0					
Mat et al. (2014)					23^0				1.5 $*10^6$	
Eiamsa-ard, Nuntadusit & Promvonge (2013)									15 $*10^3$	
ul-Haque, Khawar & Raza (2008)			26.8 psia		13.30				6* 106	
Qian, Nadri & Dufour (2016)	1									
Wu et al. (2016)				3..					3* 10^3	
Pal et al. (2012)					170^0				1* 10^3	
Chomdee & Kiatsiriroat (2007)					20^0				9* 10^3	height and length of vortex generator = 12mm and 21mm
Zhang et al. (2004)									4,050	
Ke et al. (2006)					25^0		1*1mm^2			
Wang et al. (2005)			69	8	12^0					
Gentry & Jacobi (2002)					50^0	1.25			2270	
Mary (2003)					70^0				1.6 $*10^6$	
Lee & Choi (2015)				13.5	10^0			$\pm$0.025	2.45 $*10^5$	
Lee (2016)					20^0				3.82 $*10^5$	
Gordnier & Visbal (1998)					30^0				4 $*10^5$	
Ingalagi & Katti (2016)						1			24 $*10^3$	
Özgören, Sahin & Rockwell (2002)					30^0				9.34 $*10^4$	

4.2. Future development directions

Since the delta wing has the benefit of enhancing the speed of the vehicle from transonic to supersonic speed with adequate sweep angle, promoting high maneuverability, high stall angle with a large angle of attack, this type of wing is convenient in MAV. The other advantages of delta wings are their simple design, strength, relatively low cost, and ample interior volume for fuel or other required equipment. As a result, the delta wing finds a wide range of applications, for which MAV can be deployed. Since the needs, associated with potential use, push beyond the design limit, the scope of research on delta wing is very wide indeed. Under such circumstances, parameter optimization and modelling appear to be the current critical issues, as it is still difficult to perform an optimum design of a delta wing. In particular, the design of adequate delta wings for supersonic aircraft still remains an unsolved point.

5. Concluding remarks

This paper presents a survey of different techniques utilized for the design of wings of MAV. The main intention of this study was to consider explicitly the design, experimentation, analysis, simulation, and modelling regarding delta wings. Thus, 60 relevant papers were included in the survey, and they were assessed from selected points of view. At first, a review of all the considered contributions was presented, in the chronological order, for the different types of wings. Secondly, the different materials and design parameters, utilized by particular researchers for the design of the delta wing have been scrutinised. Finally, a performance comparison, regarding adopted methodologies and parameter measurements, based on the contributions on the design of delta wings was presented. The survey implies that more work has been done, and more researchers studied the delta wings in relation to other types of wings. Since more researchers focus on the design of delta wings for MAV, there is a hope that the development of the delta wing design for supersonic aircraft, taking into account the items here indicated as crucial in terms of gaps and challenges for the future research, will end with a success.

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