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Unmanned Aerial Vehicle (UAV) Structural and Manufacturing of Conventional and Humpback Tubercles Leading Edge (TLE) in Aeronautical Applications

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Abstract*: The paper reviews the literature on tubercles as recent advance bio-inspired wing technology in the field of aeronautics. The purpose of this paper is to conceptually identify the work on tubercles, particularly for unmanned aerial vehicle (UAV) technology and thereby provide a delineation review and in-depth technological applications of biological systems interrelation with engineering. The paper discussed the evolution of conventional UAV wing with clean airfoil in terms of designs and mechanisms, materials and manufacturing processes, whereby all researches attributed these capabilities both in simulation and experimental studies. Tubercles, commonly known as protuberancesof a Humpback whale pectoral flipper which found on the leading edge, offering performance enhancement in terms of aerodynamic perspective. Implementing tubercles design has proven its improvement on airfoil performance, effectively reduce noise and separation bubble size. Despite the present studies on aerodynamic performance, other crucial elements such as structural performance and manufacturability of the tubercles leading edge (TLE) wing should be taken into consideration for better lifting and maneuverability of UAVs. To date, there is insufficient reviews on the structural issues of TLE wing in-depth and provides comprehensive understanding regarding this topic. Hence, thepurpose of this is mainly to demonstrate lineage of the TLE wing and current researches' trend. This discussion will pave the way of state-of-the-art research area on this optimum performance of wing particularly in terms of manufacturability perspectives.

***Index Terms*: Unmanned Aerial Vehicle (UAV), conventional wing, structural analysis, Tubercles Leading Edge (TLE) wing**

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I. INTRODUCTION

An unmanned aerial vehicle (UAV)is a pilotless aircraft that can be remotely controlled from a ground control room. The interest in UAV development is growing in recent years due to its capabilities of utilizing relatively more reasonably priced airplanes without the on-board human operator when the missions involves long operational time and severe risks [1], [2]. Through evolution of UAVs technology, adapting the idea from biology, creatures in nature were viewed as engineering designs with general features has directed pool of inventions towards an increasingly enhance potential of their capabilities towards engineering capabilities, mechanisms and tools [3], [4]. In today's aeronautical applications, the advancement of modern airplanes designs especially the complexity to adapt or emulate the capability of creatures in nature for UAV is one of the great factor contributing to continuous development in UAV industry. However, the complexities in the design is not optimized in terms of robustness and reliability due to the lack of appropriate structural mechanics, or even other possible uncertainties in materials characterization and manufacturing practices [5].

In this paper, a review is carried out based on challenges on adapting the capabilities of bio-inspired mimicking nature in order to seek for a better improvement in engineering field. This literature is constructed in a way that provides the broad overview on the studies and applications related with conventional normal airfoil of UAV as well as its structural and manufacturability perspectives, followed by an in-depth discussion on the applications of humpback whale-inspired. The categories of computational and experimental studies for both conventional UAV and humpback whale-inspired were then reviewed thoroughly. Finally, structural issues to define its practicality in the manufacturing perspective was summarized, before enclosed with suggestions for future research direction.

II. ADAPTIVE BIO-INSPIRE APPLICATIONS

Prior to the development of UAV, the basic inspiration and motivation for flying has come from the capabilities of birds, insects and aquatic animals that able to generate efficient lift and thrust with same wing planform. This bio-inspirations attempts to produce engineered systems that possess characteristic in aeronautical applications has inspired human towards replicated or mimicked the features and capabilities of the biological evolution in human engineered systems. Hence, this inspiration lead to the design of new technologies and the improvement of conventional ones.

The notion of characterize animal features is far from new. Leonardo da Vinci, the first developed early blueprints for ‘flying machine’ inspired by a bird in adopting flapping mechanism to produce lift and thrust [4]. Then, the Wright Brothers succeeded in creating and flying the first airplane off the ground by adapting the ability of pigeon's wing to create lift. Throughout the biological evolution, the increasing demand integrating the structure and functions replicated the features of animal species has driven the designers towards more simple and efficient, hence significant progress has been made. Namely, one can take biologically identified anatomical structures and their functions in engineering applications, as in Table I.

Table I: Biomimetics studies in engineering applications

Type	Animal	Anatomic structures	Anatomical Advantages	Engineering application
Flying	Birds	Limbs and feathers	The forces of thrust, drag, lift and gravity affect the flight patterns of birds	Flapping UAVs [6]
	Owls	Feathers	Fly silently and helps to absorb aerodynamic sound, suppress vibrations when waves of sound come crushing over the wing	UAVs Wind turbines [6]
	Wild geese	Wings	Ascending air current with less effort	AIRBUS [7]
	Insects (dragonfly)	Multiple wings and legs	Flapping of wing creates pressure gradients for thrust, lift	small UAVs (micro aerial vehicle)[8]
	Bats	Limbs	Membrane of skin that stretches between arms and leg help to produce lift	small UAVs (micro aerial vehicle) [8], [9]
Aquatic	Whale	Flipper (Tubercles effect)	Tubercles on the leading edge produces greater lift and less drag than a smooth surface fin	small UAVs (micro aerial vehicle) [10]–[14]

These engineering applications in relation to biomimetics studies has made great progress to assess various external shapes subject parametric designs with the aid of automatic and rapid computation fluid grids. In particular, aerodynamic perspective potentially gain endurance by reducing drag. However, the structural perspective also should be taken into account as it contributed towards weight reduction of the wing which can be translated into a lighter UAV with an increased endurance and a reduced speed stall [15]. Thus, the complexity of the wing designs nowadays drawn attention from structural perspectives prior to manufacturing and testing UAVs under the real-world condition.

III. STRUCTURAL OVERVIEW OF CONVENTIONAL UAV WING

The fundamental structural design principle for the tubercles-based biomimetic reflected the structural design principles of established the conventional design of UAV wing. In most aeronautical applications, the technical requirements and guidelines in the form of specifications, standards and system engineering provide benefit for the next generation of UAV development. This information may influence the requirement and improvement of structural design criteria, thus increase the robustness and reliability of the design. In this paper, one of the main structure that contribute to provide lift of UAV is the wing section. The need for wing structural design criteria is essential and the use of this technical requirement is to explore the structural layout through the selection of structural members and mechanisms like parameterizing the geometry of aircraft, performing the optimization of size and shape [16]. Hence, in this research, the overall literature on structural overview of conventional wing is reviewed and discussed in four criteria, such as:

(1) Wing-normal configuration that describes its internal and external members of the wing

(2) Wing mechanisms based on importance and its functions

(3) Material selection subjected to its properties

(4) Manufacturing methods that contributed to build the parts of the wing

These criteria are important which will guide on how the literature and its elements are reviewed. Each of the criteria in structural of conventional UAV wing will be explained further in the next-sub-sections.

A. Wing Configurations

Wing is the major part of UAV. It provides benefit of lifting with less air drag subjected to a given weight and speed, making it more energy efficient and environmental friendly aircraft. Since the wing are often optimized to maximum lift at cruise speed, less power is utilized to offset the drag while maintaining lift.

In general, the component of UAV wing can be categorized into two, namely the external wing structure and the internal wing structure. The internal wing structure consists of ribs, stringers and spars, whereas the external wing structure consists of skin. The components of UAV wing for both internal and external wing structures is depicted in Fig. 1.

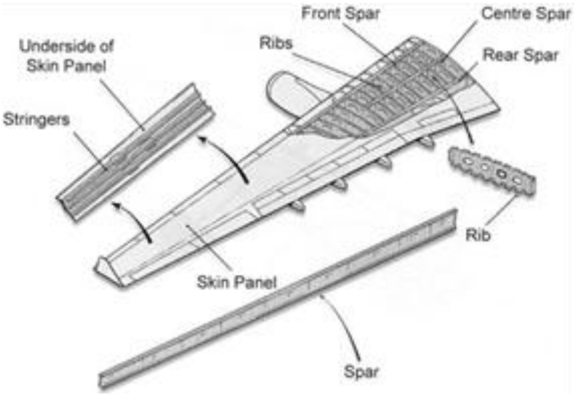

Fig. 1. Components of wing [17]

Referring to Fig.1, the internal structures of most wings such as spars and stringers operating spanwise, while ribs operating chordwise at leading edge until trailing edge. The spars plays a major role as the principle structural members of a wing. The main function of internal structures are to support the distribution load and concentrated weights such as fuselage, engines and landing gear. On the other hand, skin mainly attached to the whole wing structure externally, which also carries part of the loads force during flight. It also transmits the stresses to the wing ribs, hence the resulting stress from the ribs is passed on to the wing spars [18].

Therefore, the wings are designed according to its compromise geometry that allows the aircraft to fly at certain flight conditions. The wing design can vary to provide certain desirable flight characteristics. The variation has lead the researchers and designers towards the idea of changing the shape and size of the wing that contributed to unique design optimization. Namely, one can change the shape of the wing with the aid of mechanisms and it subjected to a given weight and speed. Hence it may sufficient to alter performance for better efficiency and improved maneuverability [19].

B. Wing mechanisms

The second criteria of UAV wing structural design is the wing mechanisms design requirements. The challenge of wing design structure is its capability of withstanding the prescribed loads and several load conditions of the changed of wing shape. In order to increase the reliability and reduce the complexity, the mechanism design and actuation system should be embedded in the structure [18][20]. For instance, the rigid wing with a standard rib and spar configuration can achieve higher degree of complexity and weight penalty by adding morphing such as hydraulic actuators, pumps and other auxiliary support systems for better efficiency. The degree of freedom of these structure can be enhanced by adding multifunctionality such as smart materials and adaptive structures to ribs and spars. Hence, the advent of actuation systems such as shape memory alloy (SMA), piezoelectric actuation (PZT), Rubber Muscle Actuators (RMA), linear actuator and pneumatic for wing designs from geometrically flexible structures can be used to activate the shape modification and maintain the shape using aero-elastic control [18], [19], [21]–[23]. These concepts of mechanisms designs of UAV wing shape-changing can change one or differentwing geometric parameters to adapt its configuration by means of various mission requirements, as depicted in Fig. 2.

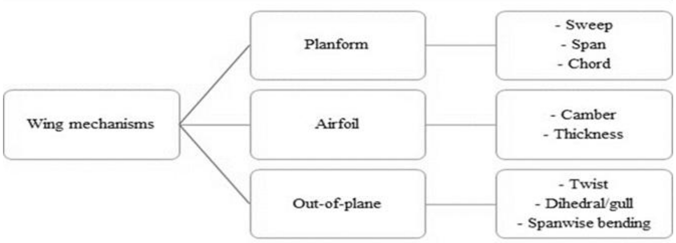

Fig.2.Classifications of UAV wing mechanisms [18], [24]

Referring to Fig. 2, the variable sweep, variable span and variable chord allow the change in wing-planform shape directly affect wing drag either in all or some based on the flight condition. As in Fig. 3, sweep change subjected to varying sweep angles influence drag to increase, while span change subjected to the spanwise alteration that possible reduce drag significant. Whereas, the changes in chord length by extending the trailing or leading flaps is related to span, which influenced the wing area [25]. Sweep and span are two parameters that affect wing aspect ratio, which the changes parameters influence lift-to-drag ratio subjected to stability and maintainability of cruise range and endurance of engines requirements [26]. The changes in wing aspect ratio may produces in lift curve slope and forces as well as change the inertia of the aircraft due to the change in wing area by means of application smart materials and actuation systems.

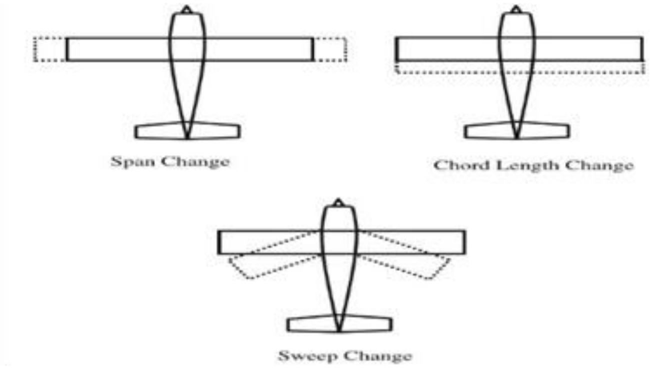

Fig. 3.Wing planform [18]

Despite that, the airfoil shape is mainly concerned with camber line curvature and maximum relative thickness which affect the characteristic of a wing, as in Fig. 4.

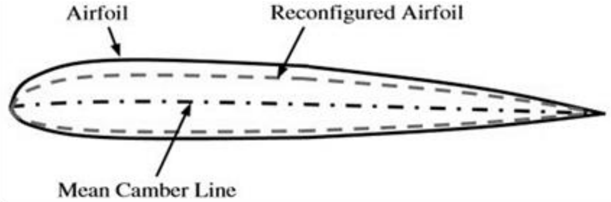

Fig. 4. Airfoil profile varied with minor changing in the mean chamber line [18]

Researches with regards to airfoil adjustment mostly concerned with camber variation and thickness change. Theoretically, the airfoil shape could be modified by contracting or expanding of the actuators inside the wing section such as leading or trailing edge without significant changes of mean chamber [24]. The need for wing curvature change is to adjust the airfoil geometry at different flight conditions, which lead to better aerodynamics of an increase of lift-to-drag ratio [25], [26]. Several methods can be carried out to effectively vary the camber such as change the camber in specific part (trailing or leading edge) or letting the entire wing act as a unique control surface. Prabhakar [27] discussed the common choice of actuators used in the changing airfoil shape such as conventional and solid state smart materials. Barbarino et al. [18] performed a comprehensive review of applications of camber control in the airfoil adjustment of fixed wing and rotary aircraft considered various actuators, skins and purposes.

In overall, the wing mechanisms are usually viewed as a design option to be incorporated in certain UAV with the aid of maturing component technologies such as actuators, skins and control theory for exploring the aerodynamic potential of aircraft wing by adapting the wing shape for various flight conditions. The compliant shape changing complexity of integrating mechanisms control onto the UAV wing is incorporated with the combination of variable designs [28]. This acknowledge the response from the wing structural performance from the resulting aerodynamic performance, hence meet the requirement of load-carrying and aeroelastic stability.

C. Material Selection

The most important aspect during creation process of new UAV wing construction is the knowledge about loads acting on designed element. In the case of aircraft structure, the factors like tail loads, side loads on the fuselage and gusts hitting the wing should be taken into consideration prior to applying the structural material that able to withstand both tension and compression. According to [29], unidirectional material are one of the superior material in regards to strength and weight structure, which is strong in tension as the materials are consist of the composition of thin, long fibers and relatively flexible. Furthermore, in order to make a very good structural material of the thin fibers by embedding with a lighter and softer resin to hold the fibers together and able to take required compression loads.

One of the material that meet the requirement of strong, light and easily available at reasonable price is Aluminum alloys. Aluminum is the unidirectional material that stronger than wood in both tension and compression, however it is three times heavier. Then, steel was considered for aircraft structure which has the same weight-to-strength ratio of wood or aluminium. Steel has high density, thus it is three times heavier and stronger than aluminium. In conjunction with the development of UAV, the use of composite materials has grown as the appropriate solution for high altitude/high aspect ratio wings by taking into account the weight and stiffness [30], [31], [32]. Composite material is a combination of two or more constituent materials with different chemical and physical properties and have the property derived from individual components [33], [34], [35], [36]. This type of materials are lighter, stronger and less expensive compared to other traditional materials [32]. Composite materials of fibers offer greater manufacturing feasibility of complex parts, special contours and appearance, which most metals not possible to fabricate without riveting or welding the separate pieces. Due to its high stiffness, low density and high strength, composite has been a key player in aircraft industry since 1950s [37], [38], [39], [40]. Table 2 illustrates the comparisons of materials which are normally adopted in aircraft industries. The materials come with engineering requirements that suits different design and manufacturing phase.

Engineering requirements	**Materials**		
	Steel	**Alloys (Aluminum)**	**Composite**
Stiffness-strength of material related to weight	Less rigid	Rigid	Most rigid
Stiffness-strength of material at the same element wall thickness	Higher	Low	High
Weight/density of material	Higher	High	Low
Machining or cutting	Require welding or riveting for joint	Require welding or riveting for joint	Less assembly and joining operations
Thermal expansion	Low	High	Lower
Heat conduction	High	Higher	Lower
Resistance to temperature	Higher	Lower	High
Long term performance	Limited life span	Shorter life span due to fatigue limit	Long service life using prepreg technology
Production implementation	Less cost-effective for small run production	Less cost-effective for small run production	Cost-effective for small run production

Table 2: Comparisons of materials [41], [42]

Therefore, the innovative technologies of UAV exhibit various type of materials in accordance with the demand for lightweight structures in accordance to weight and manufacturing standpoint. However, in the mainstream aircraft industry, composites materials seems to be the most interested material but it is more costly for the commercial applications. Metals and alloys are preferred but need to consider the weight, compared to wood with a lot of restriction like temperature and humidity [41]. Thus, the selection of materials can be solve with the aid of computer models imposing the use of new materials in the future.

D. Manufacturing of Wing

The other essential criteria pertaining to the fundamental structural design principle of building the UAV wing is the manufacturing process. This criteria is depending on the type of materials used to build the parts.

Basically, the fabrication involved the making process of each component parts from stock materials. The fabrication includes tool and jig making and conventional machining to the assembly stages [43]. Tools are made as work surfaces to construct metal parts and also, functioned as templates, while jigs are mainly be used to guide cutting, drilling and assembly [34], [44]. Three types of manufacturing process to build the physical part of the UAV wing, namely conventional machining operations, composite material fabrication processes and additive manufacturing.

The common process of conventional machining operations is Computer Numerical Control (CNC). It is the preferred fabrication process of UAV for shaping ductile metals like Aluminium, stainless steel and etc. [45], [46]. In specific, the skin is formed from metal sheet that precisely shaped, cut and chemically treated. Whereas, the spars and ribs are made by rolling or piercing using milling machine. On top of that, all the parts are assembled in a way that joining them together, either by riveting, welding or fitting between spar and rib as well as spar and skin.

Similar to conventional machining, the components of composite UAV wing are built using mould as template to construct composite parts [47]. In specific, the composite materials are laid up to build laminate thickness and reinforced with reinforcement material before the whole part being cured to form composite [48], [49]. The composite wing is manufactured in two way, namely open molding and closed molding. As stated by George [50], open molding subjected to expose the materials to atmosphere during the manufacturing, while closed molding used two-sided mould sets or vacuum bag. Aspects like production rate or speed, cost, performance, size and shape are the major concerns in selecting the appropriate manufacturing process, as summarized in Table 3 [51].

The current technique in the area of engineering designs and manufacturing technologies is additive manufacturing. It is also known with other examples like 3D Printing, Fused Deposition Modeling, Stereolithography and Selective Layer Sintering. It is the application of adaptive design technology to build a physical model, prototypes, pattern, tooling components and final production parts layer by layer through the joining of liquid, sheet or powder material from computer data or 3D scanning system [52].

In comparison to conventional manufacturing, additive manufacturing able to cope with complex geometries, reduce product' life cycle assessment by avoiding the usage of other tools or material scrap [53]–[55]. The materials used in this method is thermoplastics, photopolymers, acrylic plastics and even composites (carbon fiber, ceramic, glass) [56]. One of the prototype of wing segment of UAV is developed by applying 3D printing using photopolymers, as in Fig. 5.

In overall, the choice of manufacturing process to build the UAV subjected to the complexity design of parts and material used. Nevertheless, the product's weight and production cost also need to be taken into consideration for the optimization. The literature of manufacturing pertaining to UAV is summarized in Table 4.

Fig. 5.Physical model of UAV wing [57]

Table 3: Criteria for manufacturing composite [51]

Process`	**Production speed**	**Cost**	**Strength**	**Size**	**Shape**	**Raw Material**
Hand lay-up	Slow	High	High	Small to large	Simple to complex	Prepreg and fabric with epoxy resin
Spray lay-up	Medium to fast	Low	Low	Small to medium	Simple to complex	Short fiber with catalysed resin
Filament winding	Slow to fast	Low	High	Small to large	Cylindrical to axis symmetric	Continuous fibers with polyester resins
Vacuum bag moulding	Medium to fast	Low to medium	High	Small to large	Simple to complex	Fiberglass fabric, non-woven nylon, polyester fabric
Compress moulding	Fast	Low	Medium	Small to medium	Simple to complex	Molded compound
Pultrusion	Fast	Low to medium	High	Small to medium	Constant cross-section	Continuous fibers
Resin transfer moulding	Medium	Low to medium	Medium	Small to medium	Simple to complex	Preform and fabric with vinylester and epoxy
Reinforced reaction injection moulding	Fast	Low	Medium	Small	Complex	Pallets (short fiber with thermoplastic)

IV. STRUCTURAL ANALYSIS

In this study, the structural analysis is focused on the assessment of UAV wing structure in a comprehensive manner. It involves the fundamental analysis criteria such as computational and experimental in deriving the issue on structural optimization of UAV wing subjected to structural criteria of normal-conventional wing, which discussed earlier. The literature on structural analysis will be elaborated based on the elements of the structural overview of conventional UAV wing in terms of evolution of UAV research by means of year. Details on this structural analysis will be discussed in the subsequent sub-sections.

Table 4: Summary of UAV wing manufacturing

Ref.	Categories	Manufacturing method(s)	Wing section	Raw Materials
[30]	Manufacturing composite	Vacuum bagging	Skin	Foam core & fiberglass/epoxy prepregs
			Spar ribs, stringer	Carbon, Kevlar, fiberglass/epoxy
[2]	Manufacturing composite	Vacuum bagging	Skin	E-glass, styrofoam, carbon fabric
			Front spar	Styrofoam, carbon fabric
			Ribs	Balsa wood
[58]	Conventional machining (CNC)	Metal cutting	Spar & ribs	Aluminium
		Metal extrusion	Stringers	
[59]	Manufacturing composite	Wet lay-up	Skin	Fiber & fabric
	CNC	Extrusion	Spar	Aluminium
		CNC milling	Ribs	
[60]	Manufacturing composite	Vacuum bagging	Skin	Glass fiber with Rohacell 31A
			Main spar	Foam core & carbon fabric
			Ribs	Wood
[61]	Manufacturing composite	VARTM	Skin	Fiberglass/carbon fiber
			Spars & ribs	Foam core/balsa wood
[45]	Manufacturing composite	VARTM	Skin	Fiberglass/carbon fiber
	CNC	Metal cutting	Spar, rib	Aluminium, balsa wood
[56]	Additive manufacturing	Fused deposition modelling	Whole UAV wing	Molten thermoplastic & ABS
[57]	Additive	3D printing	wing	Photopolymers

A. Computational Structural Analysis

The computational structural analysis is the subject analysis of finite element method by taking account the structural model and loading conditions that benefits the optimization of the wing performance. In the literature of structural analysis, the computational method is discussed in terms of the software used and the outcome of such analyses conducted. The aid of software packages in conducting finite element analysis, one can predict how a product reacts to real-world physical effects under operational loads (i.e forces, vibration, heat and fluid flow) and also predict the behaviour of actual product either wear out, break or work the way it was designed. The summary of the literature works is explained in Table 5.

From the literature studies, various selection of computational finite element software are accountable for solving the structural problem through various type of structural analyses, by taking into account the wing section, material properties and wing design. The existing commercial structural analysis software using finite element method has been widely used to simulate the behaviour of the structures designed under given loading cases, hence, in some way, the gap of the studies is addressed. The use of structural analysis tools required the understanding of the anticipated structural response and engineering judgement by means of the software capabilities, hence lead to the development of high-fidelity design analysis. Most importantly, the computational methods provides useful tools to more accurately predict the fundamental physics of problem in a way that feasible, practical and affordable.

B. Experimental Structural Analysis

On the other hand, the experimental structural analysis involved the testing hypotheses to be matched on actual structural behaviour of wing structure. Commonly, the experimental data is validated and verified theoretically, making it very applicable to the hypothesis being tested. The experiment may yield quantitative data which can be analysed with more sophisticated statistical analysis, indirectly lead to the valid of theory through repetition of experiments. The literatures are reviewed in terms of the fabrication of the design and the outcome of the analyses performed. The construction of testing facilities, one can provided verification of structural modifications, uncovered errors and defects unforeseen in design and analysis.

From the literature review on experimental structural analysis, the structural testing were the best practices to find quantitative effect subjected to numbers of variables. Although it is relatively easy to replicate, it may consume more time in preparing the experimental set up and materials for wing. This including the limitation cost to manufacture and test the wing and its structure parts. Therefore, wing structural analysis consists of optimizing several parts of wings such as skin, spar, ribs and stringer, including the connecting mechanisms which lead to the time and costly for conducting the experiments. The literature of structural analysis associated to both computational and experimental methods is summarized in Table 5.

V. TUBERCLES EFFECT ON HUMPBACK WHALE

The previous discussion is mainly focused on the construction of conventional design of the existing UAV wing; particularly the normal airfoil design at the leading edge of wing. In contrast, adapting the anatomical features of a whale that change the geometry of airfoil at the leading edge also has gain significant insight from aerodynamic perspective.

Megapteranovaeangliae are the baleen whale species with massive size of 40 tons and 15 metres in length, as in Fig. 6. The highly articulated pectoral fins with characteristic tubercles on the leading edge provide great maneuverability forhunting krill, plankton and small shoals of fish [62].

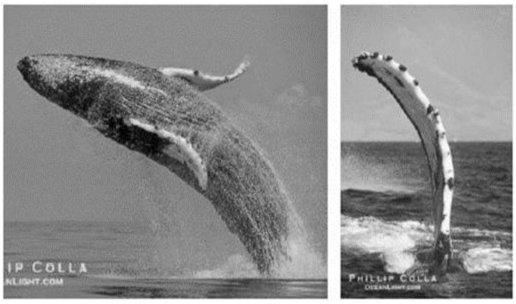

Fig. 6. Tubercles on the leading edge of Humpback whale

Table 5. Summary of UAV structural analysis

Software	Wing Type/airfoil	Analysis	Wing section	Material properties	Method	References	Gap
ANSYS	Light UAV/NACA0009	• Static	Skin	Vulcanized rubber	*Computational*	[63]	The material used is rubber and the authors neglected the deformation of internal components of the wing
	Light UAV/NACA0009	• Static	Rib	Aluminium	*Computational*	[64]	The internal components of the wing mostly made by aluminium, the skin still use rubber. Yet the rubber material is stiff, hence affect the wing to easily twist. The span expansion mechanism failed to keep the ribs equally spaced along the span.
			Spar	Steel			
			Actuation plate	Aluminium			
			Actuation nut	Aluminium			
			Block	Acrylic			
			Beams	Aluminium			
			Connecting pins	Aluminium			
	NACA4318	• Static linear	Skin	Vectran (urethane-coated)	*Computational/ Experiment*	[65]	The structure of skin is inflatable, and the analyses does not consider the internal components as it may affect the deformation of the wing
		• Static nonlinear	Skin	Vectran (hyperelastic material)			
	Light UAV/NACA0009	• Static	Skin	Shape memory polymer	*Computational*	[19]	The optimal wing shape changing not achieve optimal mechanisms due to stiffer materials. The changing shape lead to geometric constraint and weight increase.
			Connectors	Rubber			
	UAV	• Static linear, static nonlinear	Skin	Aluminium Alloy 2024, Glass fiber, carbon fiber reinforces plastic composite	*Computational*	[66]	The study focused on combination of composite materials with metals for the wing skin. The complex technique of artificial neural network was used to examine the pressure for the wing structure, but the optimized skin thickness was not concluded.
		• Dynamic	Skin	Glass fiber, carbon fiber reinforce plastic composite			
	NACA 64A215	• Static and Dynamic (fatigue crack growth)	Skin, ribs and spars	Aluminium Alloy 2024-T351	*Computational*	[67]	The wing is taper wing and the material used is only aluminium alloy. The fatigue analysis is to predict the structural life of wing structure.
	NACA0012 (taper) and	• Static	Skin	Graphite/ epoxy	*Computational*	[68]	The wing skin used composite material but

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	NACA2412 (rectangular)	(Orientation and material composition)	Spar, ribs, flanges and stringer	Aluminium 7075-T6			the other wing components used aluminium. The best composition resulted in less deformation but high in weight.
	UAV	• Static linear, Dynamic, Buckling static	Skin with/without spar and rib	S Glass, Kevlar, Boron Fiber	*Computational*	[69]	The analysis only for the wing skin and the load is only air pressure, need to consider loads act on spar
	UAV/Jedelsky profile	• Static and Dynamic	Skin	Glass fiber, foam core and	*Computational/ Experimental*	[70]	No spars or ribs, the skin is only thin curved plate attached with actuators.
			Actuator	Micro fiber			
	UAV/Selig 1210	• Static and buckling	Spars	Aluminium alloys	*Computational*	[71]	The joint between spars and ribs may affect the actual product as the spacing of the ribs mostly near the wing root, this may lead to buckle at the wing tip.
			Ribs	Balsawood			
PATRAN/ NASTRAN	UAV Meridian	• Buckling static	Skin	Carbon epoxy composite	*Computational*	[46]	The materials of the skin are the combination of carbon/epoxy and aluminum alloy only on the upper skin, thus caused the weight of aircraft heavier.
			Ribs	Aluminium 2024-T3			
			Spar	Aluminium 2024-T3			
			Stringers	Carbon epoxy composite			
	Tactical UAV/NACA4412	• Static linear	Spar webs, spar flanges	Aluminium 7075-T652	*Computational*	[47]	The material used are only aluminium alloys.
			Ribs & control surfaces	Aluminium 2024-T3			
		• Dynamic	Ribs	Aluminium 2024-T3			
	GA (W)-2(modified)	• Static linear	Inter spar ribs	Carbon/ epoxy composite	*Computational*	[72]	The analysis of crushing load on spar due to wing bending is only acted on spar or ribs, not the whole wing
	NACA4412	• Dynamic and static	Ribs and spars	Aluminium 2024-T3 and Aluminium 7075-T652	*Computational*	[59]	The analysis considered both skin and internal structures, however, the materials are the combinations of composite and metal alloys.
		• Buckling static	Skin	Glass fiber			
	NASA/LANGLEY LS (1) (GA (W)-1)	• Static	Skin	Carbon fiber reinforce plastic	*Computational*	[73]	The maximum stress only observed at root of the wing not the entire wing

	Typical UAV	• Static and Dynamic	Skin, spar, stringer	Aluminium	*Computational*	[74]	Lack of information on loading condition for the simulation. Need to redesign spar and ribs
	UAV	• Static linear and Static linear various orientation	Spars	Aluminium 7075-T651	*Computational*	[75]	The structural optimization of the wing only assumed the loads acted on the wing to be 500N.
			Ribs and fittings	Aluminium 2024-T3			
			Skin	Graphite/ epoxy			
	NACA64A215/64A210	• Static and Dynamic	Ribs and spars	Aluminium 2024-T351	*Computational*	[76]	The whole wing structure used aluminium alloys, which will makes the UAV heavier.
	Long endurance UAV/ NLF0416	• Static	Skin	Aluminium	*Computational*	[77]	The analyses only for isotropic materials, which subjected to heavy in terms of weight compared to the use of other lighter materials
			Ribs and spars				
ABAQUS	Bendable UAV (swept and straight wings)	• Buckling static	Skin	Carbon/ epoxy	*Computational*	[78]	The design of the UAV wing is bendable for buckling analysis, but only on the skin.
	Ultralight UAV	• Static nonlinear	Skin	Foam core	*Computational/ Experiment*	[79]	Significant deviation on the stacking ply sequence of composite skin due to adhesive thickness of resin and placement of strain gauge
			Spars,Ribs, Spars interconnectors	Carbon fiber/ epoxy			
	NACA4415	• Static	Skin	Carbon fibre fabric, Kevlar veil and honeycomb cores	*Computational/ Experiment*	[80]	The analyses are in good agreement for composites materials on the whole wing design. The materials can be used as referenced for further studies on composite
			Spar	Carbon fibre fabric and unidirectional carbon fibre			
			Rib	Carbon unitape and Kevlar veil			
Pro-Engineer	NACA2415	• Static	Skin	Carbon with fiberglass	*Computational/ Experiment*	[81]	No specific load and no stresses on the skin and rib are observed for the simulation due to simulation inadequacies
			Ribs and Spars	Fiberglass			
CATIA Generative Structural Analysis	Long Endurance Electric UAV	• Static linear	Spars and ribs	Balsa wood	*Computational/ Experiment*	[82]	The analyses found that 12% difference between experiment and computational analyses, thus caused that a huge difference for the study of the wing
			Spar and ribs reinforcement	Fiberglass composite			
			Boom	Pultruded carbon tube			
			Skin	Heat shrink plastic			

The humpback whale has a unique maneuvering ability to undertake sharp movements to catch prey. The sharp and high speed banking turns of the humpback whale are favoured by the high lift or drag characteristic of the combination of the tubercles and the high aspect ratio of the flippers. The tubercles provide the benefit in maneuverability and in capture of prey by acting as leading edge control devices to maintain lift and avoid stall at high angles of attack [55], [56], [83]. The presence of tubercles of the humpback whale flipper inspired the design of airplane wing and underwater vehicle. The simultaneous achievement of increased lift and reduced drag results in an increase aerodynamic efficiency.

A. Literature Related to Aerodynamic Perspectives of Tubercles Leading Edge (TLE)

Current numerical and experimental studies for the tubercles on the leading edge of wings investigated the effect of sinusoidal tubercles pertaining to the aerodynamic characteristic of airfoils [12], [14], [84], [85]. In most researches, the numerical studies are the application of computational fluid dynamics (CFD) to study various parameters related to the aerodynamic characteristic, whereas the experimental studies refer to the experiment of wind tunnel flow visualization that carried out to be compared with the simulation. Furthermore, the studies covered several issue regarding the applications of tubercles in relation to aerodynamic perspectives. Those issues are categorized, as follows:

i. Tubercle designs and tests,
ii. Tubercles mechanisms, and
iii. Effect of tubercles on wing performance.

The tubercle design and tests covered the aspects of tubercular geometry and conditions and types of wings tested. As proposed by [86], the tubercle geometric parameters are amplitude, A and wavelength, λ, by which the optimal ratio for determining the shape of foil at the leading edge, as depicted in Fig. 7.

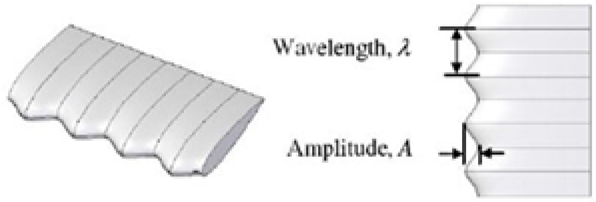

Fig. 7. Amplitude and wavelength of sinusoidal tubercles [86]

The thickness-to-chord ratio would affect the airfoil performance. In the aspects of conditions and types of wings tested, low Reynolds number flow is main issue related to the aerodynamic performance which found in the application of micro-aerial vehicles [87]. Miklosovic et al.[13] stated that the higher lift-to-drag ratio indicated better performance of airfoil. Thus, low Reynolds number lead to the formation of laminar separation bubbles on the suction sides of the foils [13], [84].

On the other hand, the tubercles mechanisms investigated various elements such as vortex generators, induced flow and vortex lift as well as greater distance for pressure recovery. Miklosovic et al.[14] proposed that the stall benefits of tubercles do act like vortex generators, which produced a delayed stall due to increase momentum of the boundary layer through mixing with free stream. However, [88] found a major difference of vortex generator foil between tubercles (amplitude of 7.1mm and wavelength of 36.5mm) and vane vortex generators, which concluded that tubercles do not act like vortex generators. Hansen [86], Seshagiri et al.[89]& Levshin et al.[90] conducted the same experiment with other tubercle geometries and proved that vane vortex generator yields similar lift characteristic to the tested tubercled foil. The second element of the tubercles mechanisms is induced flow and vortex lift. The theory for this element is the lift produced less susceptible to stalling due to the delayed flow separation at the vortices that created over the suction side of a wing or foil [91]. Miklosovic et al.[13] showed that the significant amount of vortex lift produced during post stall for both tubercled wings and foils. The study is extended dependent of sweep angle by [90], [86] considering three geometries of tubercle wings (A2λ7.5, A4λ15 and A8λ30). The study resulted lower lift for angles of attack before stall and amount of vortex lift created by tubercles is very small. The greater pressure distance for pressure recovery of the third elements is hypothesized by the addition of tubercles periodically increased the chord along the span, hence resulting in a lower thickness-to-chord ratio. Van Nierop et al.[92] showed lower pressure gradient and stall at higher angle of attack of the reduction in thickness-to-chord ratio. On the other hand, Hansen et al.[93] found soften stall along each tubercular design with thickness-to chord ratio.

The third issue is the effect of wing performance, which separated into stall characteristic and noise reduction. The stall characteristic for tubercles wing comparing with smooth wing, studied by [13], [86], [90] is described as Table 6.

Table 6. Stall characteristic [84]

Stall characteristic	**Description**
Pre-stall	The presence of laminar separation bubble (LSB) which can increase the lift of wing with less effect on drag. $Tubercle_{LSB} < Smooth_{LSB}$
Stall	Reduction in drag and increase the maximum lift $Tubercle_{stall} > Smooth_{stall}$
Post Stall	The increment of stability of wing at the stall angle $Tubercle_{stability} > Smooth_{stablility}$

Besides that, noise reduction also important in determining the effect of wing performance. Two theories have been made in regards to noise, which are: noise produced by coherent vortex shedding at trailing edge and tubercles vary the separation line long the span of foil [94].

Hansen et al.[95] reported that the tubercles suppress the tonal noise frequency of a lower sound pressure level at a higher frequency. Lau et al.[96] supported the hypothesis, whereby tubercles were found to reduce coherence during gusts with an increase of A/λ.

In overall, the UAV applications of tubercles have drawn a great interest in the researches especially in terms of its effects on the performance of wings and foils. Various researches were done with application of computational numerical method on the implementation of tubercles on the leading edge also been applied in UAV at low Reynolds number, which able to achieve stability by reducing the sensitivity to turbulence. Hence, their significant benefits such as more gradual stall with the increase of angle of stall, increase maximum lift, decrease drag in the post-stall region, decrease gradient of lift near stall, reduce tonal and gust induced noise will direct the researches towards the noteworthy impacts in terms of structural perspectives of tubercles.

B. Structural Overview of TLE Wing

Based on the aforementioned studies on tubercle design, geometric parameters of tubercles such as amplitude and wavelength play important role in improving the tubercles performance. Varying amplitudes and wavelength with respect to chord length drawn attentions towards the effect of tubercle leading edge (TLE) particularly substantial gain in aerodynamic characteristics [91], [97]. The geometric parameters of amplitude and wavelength may determine the shape of the leading edge, whether in form of sinusoidal or spherical. The sinusoidal form is referred to the wavy patterns or saw-tooth edge attached at the leading edge of airfoil, as in Figure 7. Whereas, the spherical shape is referred as round-ball patterns or scalloped-edge attached at the leading edge of airfoil, as depicted in Fig. 8(a). The side view of spherical is in Fig. 8(b).

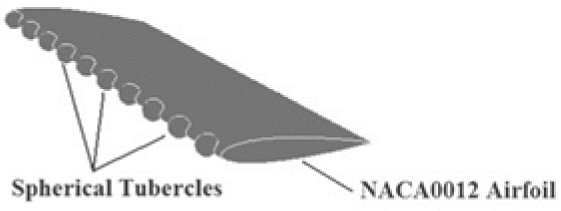

Fig. 8(a). General view of spherical tubercles [98]

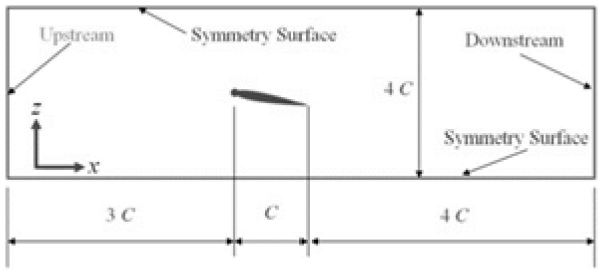

Fig. 8(b).Side view of spherical tubercles [98]

With regards to aerodynamic advantages, the TLE of sinusoidal patterns had received tremendous attentions aiming for increase lift or stall angle, reduced skin friction drag and possible drag reduction with studies on shape optimization, flow control, vortex lift generation and many more [86]. One study was found using spherical patterns of TLE by [98]. The author proposed spherical TLE of NACA0012 airfoil to be compared with the sinusoidal tubercles. The analysis objective is to obtain optimum performance in terms of optimum values of C_L and C_D at different operating condition such as pressure, angle of attack, amplitude and wavelength. The results shown that the values of C_L of spherical tubercle airfoil is almost similar to sinusoidal tubercle at certain value of angle of attack, which almost constant without appearance of stall. The author also highlighted the advantages of using spherical design on the leading edge due to ease to manufacture and fabricate from lighter material compared to sinusoidal tubercles. Furthermore, the amplitude and wavelength of the spherical tubercle can be easily controlled by selecting the sequence of the active tubercles. Hence, the advantages mentioned has provide confidence to use the design of spherical tubercles for further research on structural assessment and manufacturing practices.

C. Manufacturing of TLE

Typically, in most studies, the tubercles leading edge were undergone a wind tunnel experiments to determine the hydrodynamics of flow around the flipper, as a validation to computational and numerical analysis. Fish & Battle[11] initiated the cross-sectional design of actual pectoral flipper length at 20% maximum thickness similar to conventional turbulent-flow airfoil. The authors used the sinusoidal pattern on both inter-tubercle spacing and a tubercle amplitude that decrease with span-wise location. This idea has driven [14] to construct a sinusoidal leading edge model based on a symmetrical airfoil section of NACA0020. The flippers are modelled and machined by using CNC mill from clear polycarbonate of 3.81cm thick with a maximum chord length of 16.19cm and a span of 56.52cm. The surface of the flipper was coated with epoxy and cured before wet sanded with finer emery paper down to 600grit. The flipper was tested for aerodynamics simulating the hydrodynamics of flow around the sinusoidal flipper. Unfortunately, the study on TLE has limitation in terms of structural and manufacturing aspects due to the realistic airfoil for UAV models, geometric repeatability, ease of manufacture, surface finish quality and price for preparing the materials and manufacturing process.

VI. LITERATURE ASSERTIONS

The importance of UAV in wide applications is growing as the next-generation aircraft with low-cost and efficient configurations. The application of TLE had proven to have positive effects towards improving the aircraft performance, especially from aerodynamic perspective. According to literature survey, each literature revolving in the conventional normal airfoil of UAV wing and tubercles design were studied by discussing the structural optimization of the UAV wing and the manufacturing processes involved for producing an actual UAV wing.

From the literature, the gap in the available literature and their justification are stated in the literature findings. It can be discussed from two perspectives; structural optimization and manufacturability. Each perspective in the literature findings will be briefly discussed in the next sub-sections.

A. Structural Optimisation

One of the essential criteria of structural optimization is the structural design of the wing. The structural design had been reviewed in terms of the wing structural layout which contributed to the support elements and strength to the wing. Review on the wing structural layout is compared between the conventional UAV wing with the TLE. The wing configuration for conventional UAV contributed various reviews for structural optimization that incorporating the wing sections such as skin, spars, ribs, stringers as well as the connectors. Jiapeng et al. [99] stated that structural design of aircraft wing required a layout of spars, ribs and stringers based on the reference plane of the wing and generation of a skeleton model of wing structure. The authors also technically reviewed on the process of structural design and analysis for the aircraft wing incorporating the major elements of input, finite element modelling and optimization, and output of finite element results. All the finite element information of wing structure was well-explained considering the key technical basis such as parametric analysis and optimization design. However, there is no publication discussed on the wing structural layout with regards to tubercles leading edge, except in aerodynamic perspective. This may be due to the complex surface element of the wavy pattern or spherical shape at the leading edge of the wing. Yet, the wing structural layout are essential in determining and predicting the fail-safety and fatigue of the wing prior to be built for flying, where the structural optimization will be carried out depending on the design of the wing [67], [76].

In contrast to conventional normal leading edge, the study on tubercle leading edge has only available from aerodynamic perspective instead of structural analyses. Most research in tubercles designs focused on aerodynamic analysis using CFD analysis tools or even experimental test of wind tunnel. Consequently, this will lead to critical acknowledgement of the reliability and robustness of wavy pattern wing. This is because the sinusoidal pattern of the wing at the leading edge may lead to the deformation or failure when applied load along the center between the crest and through the tubercles on the lower surface of the wing. As stated by [100], correlation between some design variables such as parameters adding additional tension struts to the structure will change the force flow within the structure in such a significant way. On top of that, according to the literature reviewed, various structural analysis software of finite element was used to perform the structural analyses of static, dynamic and buckling such as ANSYS, PATRAN/NASTRAN, ABAQUS, Pro Engineer and CATIA Generative Structural Analysis [101]. Review on all structural analysis software under finite element method is depicted in the form of trend chart to present the usage of software by year, as in Fig. 9.

Referring to Figure 9, the literature of the numerical method of finite element based on software application is reviewed from the year 2006 to 2017. From the observation, ANSYS and PATRAN/NASTRAN received tremendous attention from researchers in achieving objective for performing structural analysis. This is due to the capabilities of the software in performing the analysis and providing great results in the theoretical perspectives. Meanwhile, ABAQUS received less attention, which mostly applied on 2009 and the least preferred by the researchers are CATIA and ProEngineer. Technically, the strength of major finite element method providers is based on user interface, performance and academic and industrial usage. However, the use of commercial finite element modelling and analysis packages available is very subjective. Depending on the objective of the user, the basic principle of finite element method is discretisation of the continuous structure into substructures [33], [80]. Theoretically, the discretisation process is based on finite element mesh that consist of element and nodes [33]. The original structures was assumed to have infinite numbers of degree of freedom, which discretised into substructures with infinite degree of freedom. From mechanical point of view, the elements are interconnected to nodes, by which the coupling points of elements provides a compatible displacement.

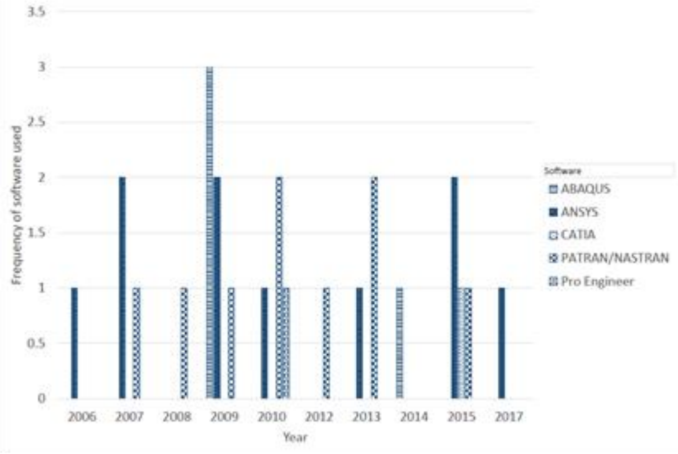

Fig. 9. Trend of software applied from 2006 until 2017

In spite of that, other criteria also should be taken into consideration in selecting the software such as cost, easy to use, fast analysis, CAD integration and industry standard. Thus, Ostergaard et al.[102] also stated that the way the structure is modelled and the interactions between structural parts are essential in defining the effectiveness and accuracy of the analysis output.

B. Manufacturability Elements

Another perspective in the development of UAV wing is the manufacturability elements conducted in the previous literature. These elements are described to highlight three essential point from manufacturing perspective which are design shape or geometry, material selection and fabrication.

Despite issue on structural optimization of the aforementioned structural of UAV, [103] supported the gap between conventional wing and TLE wing in relation to the manufacturability aspects. Thus, the limitations and the gap between conventional wing and tubercles wing of each element in the manufacturability aspects will be explained briefly.

- *Design shape or geometry*

According to discussion in the previous section, which is the structural optimization criteria, the wing with TLE had received less attention compared to conventional wing. This is due to the limitation of interpreting the wavy-like pattern and internal structures as the fundamental of optimizing the overall structure of the wing [85]. However, fabricating the wavy-like or spherical-like pattern of tubercles wing is the critical issue especially in manufacturability aspect. Referring to the previous literature on manufacturing the tubercles wing, [98] agreed that the tubercles with spherical-like pattern is far superior and easier to manufacture where the tubercles able to be manufactured separately and fixed into pre-prepared places at the leading edge of the airfoil, as proven by [103]. Yet, to date, research pertaining to fabrication of wavy-like tubercles wing still insufficient. Another issue regarding the shape or geometry is the internal structures of the tubercles wing. As discussed previously in structural optimization, the internal structures provide the strength elements towards the overall structure of the wing requires to be manufactured depending on the factors such as cost and weight reduction.

- *Material selection*

The application of materials for UAV structures had been widely used by the researchers or even industrial practitioners, particularly focusing on high-strength with low weight materials [104]. Composite materials had been widely known in the aerospace field which offers the design flexibility and structure dimensional stability that meet the requirement of the high strength-to-weight ratio [105]. Referring to Table 3, the manufacturing of conventional UAV wing can be summarized that most of the manufacturing category using the manufacturing composite, which can save the time for preparing the structures compared to conventional machining. From economical point of view, the integrating of reinforcement materials like fiber and the matrix materials like resin can create an excellent characteristic compared to material solely [51], [106], [107], [39], [108]. Using special type of adhesive may assemble the structures together, but it also may affect the assembling parts when undergone the structural analysis such as vibration [109]. Hence, the manufacturability elements should consider both design and material for improving the manufacturing of the aircraft wing and taking the cost, weight and safety into account.

VII. REMARKS FOR FUTURE DIRECTIONS

The recommendations for future work are as follows:

- In the development of tubercles wing, the external and internal design should be taken into account replicating the structural principle used in normal –wing of conventional UAV. The mechanisms of the ribs and spars should be modelled and should not assumed to be rigid enough to support all the deformation loads with negligible deformation of their own in order to create a more realistic model of tubercles wing. Referring to the structural optimization on the conventional normal-airfoil at leading edge wing by [68], the combinations of the internal components of the wing greatly contributes to the stress action of the wing structure with respect to their material properties. With regards to the tubercles wing pertaining to the wavy-like or spherical-like shape, the structural configurations of ribs and spars are crucial as it may affect the whole structural optimization of the wing. Hence, from the trends in software, ANSYS can be used in analyzing the structural response using finite element static or dynamic structural.
- From the gap of structural optimization in the case of normal-wing of conventional UAV, the reliability of structural elements of wing is mainly essential to determine how well the wing structure performed under specified operating condition. The essential part of design of a reliable and robust system involves the identification of accident consequences. This idea lead to the utilization of the failure mode analysis for both structures and mechanisms of the manufactured tubercles wing should be analyzed to validate its reliability problem and determine the fail-safety requirement [110]. This can be explained after considering the aerodynamic loads on the wing surface and deformation of the wing occurs. Hence, this leads to the support deviate from their normal position and the contact forces between the wavy-like or spherical-like shape of the leading edge and internal configurations of spars and ribs that increase to make the support hold the same deformation with the wing. Thus, failure mode analysis plays an important role in

analysing the potential failure critical and severity level of both structures and mechanisms of the tubercles wing. Although the analysis will be very time consuming and expensive, the reliability and safety of an aircraft may influence the performance of the manufactured tubercles wing.

- The application of the structural analysis model integrated with cost analysis model is more practical and significant as a trade-off between manufacturing cost and weight. The analyses conducted by [111], can become a reference in manufacturing a tubercles wing considering the constraints of material properties such as strength requirement, failure criteria and buckling criteria. In the case of tubercles wing, the integration of manufacturing cost into the wing structural optimization can be improved from the determination of optimal set of minimum structural weight and manufacturing cost by incorporating several optimization procedures such as the parametric geometry definition, generating 3D CAD model, generating finite element method, structural dimension optimization, cost estimation and layout optimization, with the aid of computational software.

Various approaches of computational methods in assessing the performance of conventional design of normal –airfoil by researchers. In most cases, the loading condition is varied either imported the lift load from CFD or calculated load from the total weight of aircraft, and many more. With the advance technologies pertaining to advance computational tools, the use of fluid-structure interaction (FSI) simulation may help to predict the fundamental physics of the problem in more accurate and practical way. The FSI is the advanced computing techniques that can be applied in optimizing the performance of wing through the interaction between a flexible structure and the surrounding fluid. Technically, this technique involved the presence of aerodynamic loading to be accounted for structural deformations. It is a current emerging software applications especially in aircraft industry [112]–[114]. Since the tubercles wing received tremendous attention from aerodynamic perspectives, FSI for tubercles composite wing is a new and novel research which can be used to exhibit the capabilities to predict wing characteristic in an accurate manner. It also provide significant insight into several numerical issues encountered in order to conduct this computations.

VIII. CONCLUSION

This paper has conceptually discussed the evolution of conventional UAV wing with clean/normal airfoil subjected to designs, mechanisms, materials and manufacturing in terms of simulation and experimental studies. Several aspects such as structural optimization and manufacturability elements are highlighted. The similar concept of fundamental UAV conventional wing can be used in the recent and advances designs of tubercles at the leading edge of airfoil. Hence, the direction of research can mainly focus on the structural analysis and manufacturing procedures of the conventional wing as the reference for the development of tubercles wing. The practicality of the finite element method can be applied to analyse the structural optimization of the tubercle wing whether it meets the requirement for the subsequent manufacturing procedures. The finite element analysis can be conducted on the tubercles wing without and with the internal structures. The materials of the conventional wing that suits the tubercles wing design should be considered. The results from the finite element analysis becoming the main contribution of the research towards the manufacturing of tubercles wing. In fact, with the incorporation of reliable data can serve as relevant decisions to carry out the manufacturing procedures, which is more practical to real industry practice.

APPENDIX

It is optional. Appendixes, if needed, appear before the acknowledgment.

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