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Importance, Relevance and Applications of Smart Materials in Aircraft Control

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ABSTRACT
In this work, we have sought to outline the basics of conventional hydro-mechanical flight control and its limitations, before addressing how smart materials, specifically shape memory alloys, can help overcome the inherent drawbacks of hydro-mechanical control and also allow design and reliable control of more aerodynamically feasible wing configurations. The advantages of smart materials and the difficulties associated with their implementation in mass produced are also delineated.

Keywords: *Hydro-mechanical control, smart materials, shape memory effect, morphing*

I. INTRODUCTION

In most conventional aircraft, there are three principal motions used to achieve controllable flight. They are “roll”, “pitch” and “yaw”, which indicate rotation about the X, Y and Z axes of the plane respectively. Each of these rotations is achieved by manipulating certain control surfaces, namely ailerons, elevators and the rudder (corresponding to roll, pitch and yaw respectively). There are also other control surfaces in addition to those aforementioned, such as flaps and air-brakes, which perform auxiliary functions for an aircraft in flight.

Conventional mechanisms

Commercial aircraft achieve the manipulation of these control surfaces using a hydro-mechanical circuit. A hydro-mechanical flight control system has two parts, namely, the *mechanical circuit*, which links the cockpit controls with the hydraulic circuits. Like the mechanical flight control system, it consists of rods, cables, pulleys, and sometimes chains and the *hydraulic circuit*, which has hydraulic pumps, reservoirs, filters, pipes, valves and actuators. The actuators are powered by the hydraulic pressure generated by the pumps in the hydraulic circuit. The actuators convert hydraulic pressure into control surface movements. The electro-hydraulic servo valves control the movement of the actuators. The pilot's movement of a control causes the mechanical circuit to open the matching servo valve in the hydraulic circuit. The hydraulic circuit powers the actuators which then move the control surfaces. As the actuator moves, the servo valve is closed by a mechanical feedback linkage - one that stops movement of the control surface at the desired position[1].There are numerous disadvantages to hydro-mechanical control, including their weight as well as the need to route the control cables carefully through the fuselage. Also, the shape of the fixed-wing itself is limited to nearly-linear profile during flight, in order to reliably manipulate the control surfaces.

Aircraft wings are the principal surfaces responsible for generating the lift required to sustain the flight of an aircraft. However, there are no generic or one-size-fits-all solutions to achieve both manoeuvrability and cruise in an aircraft. The wings are designed on a case-by-case basis, depending upon the mission requirements. For example, in commercial aircraft, emphasis is laid on cruising whereas the focus shifts to manoeuvrability in military applications. The performance of a wing outside its intended operating range is sub-optimal.

This predicament is analogous to the “shape” of commonly used modern day smartphones, most of which possess a "rectangular" profile. This ubiquitous profile is influenced to a certain extent by the shape of the batteries used (generally lithium ion), which possess a rectangular profile. Recent studies and developments are indicative that by introducing differently shaped batteries, a greater diversity in the shape of smartphones can be expected to follow.

"Morphing" of wings and its need

Using an adaptive wing, whose geometry varies according to changing external aerodynamic loads, the airflow in each part of the aircraft mission profile may be optimized, resulting in an increase of aerodynamic performance during cruise and manoeuvres. The ability of a wing surface to change its geometry during flight has interested researchers and designers over the years as this reduces the design compromises required. The feature is broadly referred to as "*morphing*" and encompasses a wide variety of controlled structural changes, including but not limited plan form alteration (span, sweep, and chord), out-of-plane transformation (twist, dihedral/gull, and span-wise bending), and airfoil manipulation [2].

Just as creatures in flight adopt different configurations to get the best shape for their flight, thus conserving energy, there is a need for an aircraft that adopts the best shape for the given flight conditions and spends the minimum energy possible. Introducing morphing capabilities on aircrafts will allow them to fly with minimum drag, having better performance in all flight stages. This has an effect on fuel consumption, range or maximum speed. Other possibilities include having aircrafts with the same weight but that are able to carry more payload [3].

The idea of in-flight alteration of the components of an airplane is not new. The Wright Brothers employed the wing warping technique to change the twist of a flexible wing and provide roll control for their first flying machine. However, as significant advancements were made in terms of the operating airspeed ranges, the advantages offered by the fixed-wing design in terms of aerodynamic stability and load bearing capacity offset the complexity posed by "morph-capable" wings as, historically, morphing solutions always led to penalties in terms of cost, complexity, or weight.

Recent developments in material science, particularly in the field of composites and "smart materials" are of interest as they offer the possibility of reliable control of flexible wings, while simultaneously reducing the impact of such designs on the overall weight of the aircraft.

Smart materials and SMAs

Smart materials are new generation materials surpassing the conventional structural and functional materials. These materials possess adaptive capabilities to external stimuli, such as loads or environment, with inherent "intelligence". According to SusmitaKamila (2013), one of the most widely accepted definitions for smart materials states that "Smart materials are those materials which possess the ability to change their physical properties in a specific manner in response to specific stimulus input"[4]. Smart materials are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli such as stress, temperature, moisture, pH and electromagnetic fields, among others. This change is reversible and can be repeated many times. Examples of smart materials include piezoelectrics, thermochromics and ferrofluids, among others.

Shape memory alloys (SMAs), are a particular class of smart materials which are responsive to temperature-based stimuli. They are metal alloys which are capable of undergoing solid-to-solid phase transformation and can recover completely when heated to a specific temperature (called the memory transfer temperature), which is usually characteristic of the alloy composition. A shape memory alloys can be "trained" to remember a physical configuration by heating it to its memory-transfer temperature, i.e. austensitic phase. After it is cooled down (its martensitic phase), it can be deformed to other physical configuration(s), but when heated to its memory temperature (in its austensitic phase), it re-acquires its original "trained" physical configuration, before it was deformed. The memory temperature can be very precise, within 1-2°C of the desired temperature. These features, coupled with other advantageous properties such as super elasticity, mark SMAs as particularly promising materials for the development of "morphing" wings.

SMAs in Aerospace Applications

As discussed before, due to the nature and inherent limitations of the hydro-mechanical control systems, the wing profiles employed are always nearly-linear throughout the flight path. Although more aerodynamically feasible solutions exist to maximise lift while reducing the effects of drag, none have been satisfactorily implemented till date simply because conventional control systems cannot provide reliable and accurate control for manipulating the wing into and out of such "aerodynamically optimal" configurations.

By including SMAs in the design of the wings, these limitations can be overcome to an extent. Since SMAs can be "trained" to acquire even complex physical configurations, a number of previously "infeasible" solutions can now be revisited.

Fig1: Standard, loiter, dash and manoeuvre

As shown in Fig. 1, there are four main configurations that morphing aircrafts should be able to perform in order to keep the optimized shape for the best performance possible: standard, loiter, dash and manoeuvre and cruise[3].

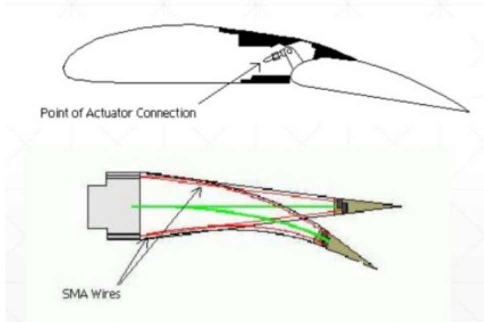

Fig2: Cross sections of a hydro-mechanical wing and a SMA wing

Consider the cross section of a wing(as shown in Figure 2). Conventionally, the control surface (say aileron), which would be a separate component assembled to form a part of the wing, would be deployed using an actuator. However, by using smart materials, such as the SMA wire, across the wing span, one can manipulate the entire wing as a single unit. The most aerodynamically feasible profile can be "trained" into the SMA beforehand and by manipulating the temperature or potential difference across the wing, the "trained" shape can be re-acquired. The memory transfer temperatures are characteristic of the alloy composition of the SMA and are fairly accurate; hence two SMAs can be used, antagonistically, to cause the wing to acquire different profiles, for achieving the flight condition necessitated at that point in time. Certain SMAs can also be made to acquire "two-way shape memory effect (TWSME)" which can eliminate the need for a second SMA, which was illustrated in the aforementioned example.

According to J. Matovic and K. Reichenberger(2010), highly reliable actuators based on TWSME have been demonstrated. Under life test, the actuators endured 300 loading cycles without performance degradation. Further, there has been development of manufacturing technology which enables programming of the actuator deformation in austenite and martensite phase within the tolerance of ±6 %. The actuators are based on 50μm thick NiTi alloy foil, doped with Cu. These novel actuators for the spacecraft thermal management system can reduce the mass of vane louvers from the current 4-5 kg/m^2 to less than 500 g/m^2, which is extremely significant[5].

George Akhras(2008) also states that along with "morphability", structures based on smart materials alsoexperience significant suppression of structural vibration and noise [6].

Conclusion

There is no doubt that smart materials are a disruptively growing technology which will have an impact in aerospace applications in the not too distant future. It will allow one to actively monitor the various aspects of the health of an aircraft along with its loading conditions and also develop aircraft which can carry out missions with a wide variety of flight conditions. However, there are many aspects which need to be improved upon, including but not limited to the expenses involved in fabricating structures from smart materials. Further, the structure has to meet the requirements of fuel sealing and provide access for easy maintenance of equipments. Passenger carriage requires safety standards to be followed and these put special demands of fire-retardation and crash-worthiness on the materials and design used. Hence, there is also a need to develop codes and standards for these materials to enable proper quality and safety assessments, which is a vital process for materials used in any sensitive applications, specifically aircraft.

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