PRESSURE ADAPTIVE HONEYCOMB: A NOVEL CONCEPT FOR MORPHING AIRCRAFT STRUCTURES

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Abstract

A new adaptive structure is presented that relies on pressurized honeycomb to induce gross structural deformation at a relatively low power consumption. The honeycomb cells extent a significant length with respect to the plane of the hexagons and each of them inhibits an airtight bladder. Pressurization of that bladder alters the stiffness of the honeycomb material. The higher the pressure, the higher the resistance to external loads. When these loads are present, a change in pressure induces a change in structural deformation. Overall strains of 50% can be reached with a theoretical energy density of 10kJ/kg when pressurized at 0.9MPa. The paper details how two different kinds of actuation mechanisms can be employed, one based on active pressurization (controlled by the pilot) and one based on the change in ambient pressure (indirectly dictated by altitude), to change the honeycomb shape. A pressure-adaptive flap is presented based on the first actuation concept, while an altitude-adaptive Gurney flap is presented for the latter concept. Wind tunnel results on the pressure adaptive flap (35%c) demonstrated an increase in section $C_{l\,max}$ *of 0.3 when the pressure was altered by 40kPa.*

Nomenclature

c	chord, m
h	altitude, gpkm
m	mass, kg
p	pressure, Pa
R	Gas constant, J/kg/K
T	Temperature, K
V	volume, m^3
ϕ	latitude, deg
ρ	density, kg/m^3

subscripts

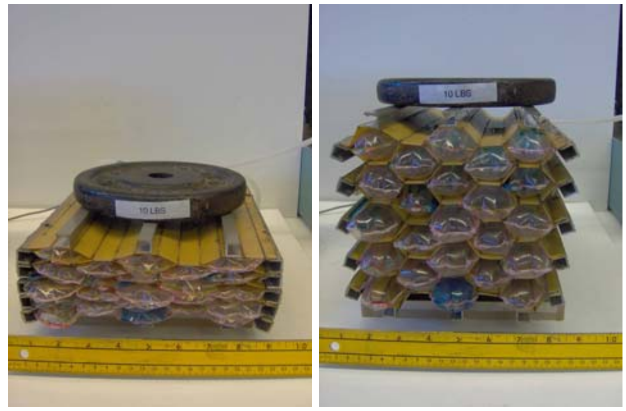
0	zero altitude
a	ambient
ea	engagement altitude
gp	geopotential

1 Introduction

Aircraft wing design is generally driven by two disparate design requirements: a maximized lift coefficient during landing and a maximized lift-to-drag ratio during cruise. To accommodate both requirements, aircraft are traditionally equipped with high-lift devices, like flaps and slats. These devices have been shown to increase the lift coefficient of aircraft significantly. Their additional weight, complexity, and cost penalties have historically been outweighed by their performance gain.

Since the beginning of powered, manned flight, aircraft designers have worked on the concept of wing morphing to enable flight control or to optimize the wing shape for various flight conditions.[1] Over the past one hundred years this has resulted in various patents that present mechanisms that change wing camber, thickness, sweep, and surface area.[2–6] Over the last two decades, the benefits of adaptive materials such as shape memory alloys (SMAs) and piezoelectric materials have been investigated for their capability to change their shape as a function of a particular stimulus.[7] Even though some of the designs that resulted from these efforts showed promising results, the absence of a material database prevents these materials from being used in primary and secondary structure of FAR 23, 25, 27 and 29 certified aircraft.

In an effort to reduce part count, complexity, and cost of conventional high-lift devices a new type of adaptable structure was conceived based on conventional, certified aerospace materials. This structure relied on a grid of conventional, hexagonal honeycomb cells that extended over a significant length perpendicular to the plane of the cells. Inside each of the cells a pouch resided which could be inflated such as to form a circular tube inside the hexagonal honeycomb cells. By varying the so-called cell differential pressure (CDP) the overall stiffness of the pressurized honeycomb could be varied. With the addition of external or internal restoring forces this stiffness variation translated to a structure that could deform as a function of the CDP. The high level of compliance of the honeycomb ensured overall elastic strains exceeding 50%, an order of magnitude higher than for example SMAs. Figure 1 shows the principle of pressure-adaptive honeycomb for a Kevlar-based test-article and an external restoring force in the form of a constantly applied weight.



(a) Initial Geometry: CDP $= 0$ (b) Inflated Geometry: CDP $= 40kPa$

Fig. 1 Pressure Adaptive Honeycomb

2 Actuation Sources for Pressure Adaptive Honeycomb

Two types of actuation sources are discussed; in the first actuation concept, the pilot is able to directly influence the stiffness of the honeycomb (Subsection 2.1); similarly, in the second concept, the stiffness of the honeycomb is indirectly controlled by the altitude of the aircraft (Subsection 2.2).

2.1 Pressure-Controlled Actuation

The mechanics of pressure adaptive honeycomb allow for two different kinds of actuation methods. The most obvious way of controlling the amount of deformation is by controlling the pressure, as was also done in the example of Figure 1. Within the aircraft this would require a system architecture of tubes and valves in order to control the pressure inside the pouches. Such a system could be connected to one of the compressor stages of the jet engine (see Figure 2) or, in case of a propeller aircraft, the exhaust manifold pressure could be used as a high-pressure source. Both cases would allow the pilot to accurately control the pressure inside the pouches and hence the amount of structural deformation in the wing.

The generated CDP (CDP $= p - p_a$, with p pressure in the cell and p_a the ambient pressure) in the aircraft has an effect on the overall weight of the system. High CDPs require a dedicated infrastructure of tubes and hoses to connect to the pouches inside the honeycomb. For the envisioned applications, a low actuation bandwidth is required. Relatively small diameter tubes could therefore be used in order to minimize added system weight. Another effect of high pressure is that the pouch material incurs a much higher circumferential stress level. In order to keep this stress level below the material yield stress either

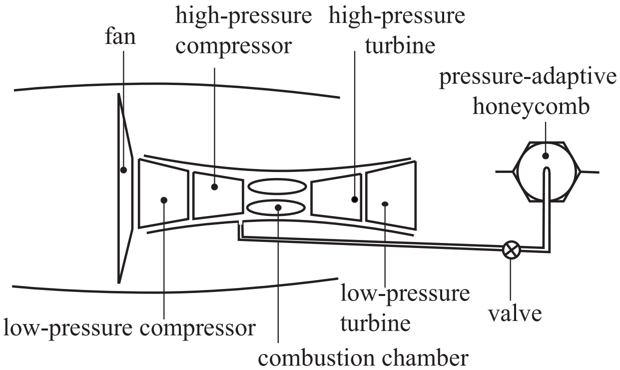


Fig. 2 Pressurizing adaptive honeycomb from the high-pressure compressor

the thickness would need to be increased or the radius decreased. The first option, obviously has a negative effect on total weight. However, the latter option has a similar negative impact because it increases the cell density of the honeycomb and consequently the total weight of the system, for a given volume. Because of those possible negative effects on the total weight of the system, the designer is advised to carefully review the impact of a higher CDP on the total weight of the system. A measure for the effectiveness of the adaptive actuation system could be the specific energy density, where the total energy output is divided by the total weight of the system.

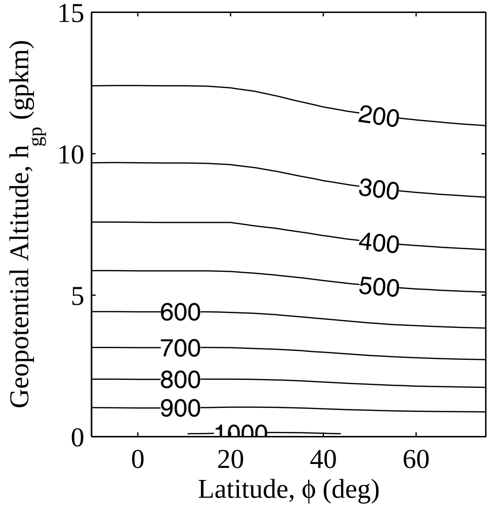
When internally generated pressure is used to power the pressure adaptive honeycomb, there should be a back-up system to supply power in case the engine fails. In that case a static pressure source such as a CO_2 cartridge could be used to provide pressure over a sufficient period of time, such that the aircraft can safely land. These cartridges are commonly used on subscale UAVs with inflatable wings and can supply sufficient gage pressure for more than eight hours, providing that there is no significant leak.[8] Alternatively, it could be argued that self-healing bladders could be developed analogous to self-healing tires, which are commonly used in road vehicles.

2.2 Altitude-Controlled Actuation

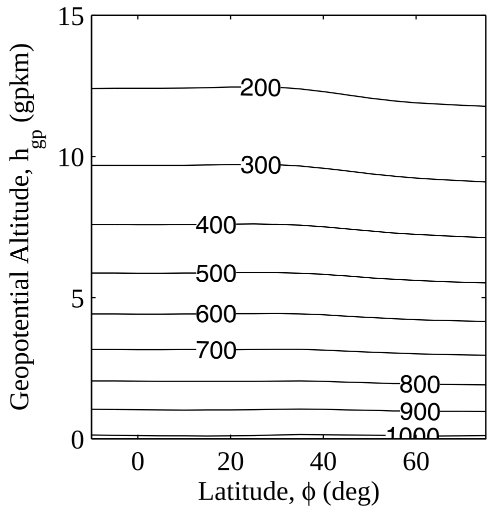
A second means of actuation could be achieved by relying on the atmospheric pressure change with altitude. By filling each of the pouches with a fixed amount of air a decrease in ambient pressure induces an expansion of the air within the pouches. This works analogously to an increase of the pressure within the cells. If such a system were to be incorporated within part of the wing, this would allow for a high degree of adaptivity. In this case, the structure would automatically adapt to a change in altitude, which, in turn, is associated with a change in flight status. For example, in cruise, a typical jet aircraft is at an altitude of at least 30kft. Based on ISA conditions, this yields a decrease in atmospheric pressure of 70kPa with respect to sea level conditions. This higher level of adaptivity where the pilot is out of the control loop could be especially interesting for non-critical surfaces such as adaptive Gurney flaps.

The application of such a truly adaptive structure can only work when the stimulus (in this case ambient pressure) can be accurately predicted over time and space. To that extent a small survey was carried out to investigate how the ambient pressure changes with season and latitude. The result is shown in Figure 3. It can be easily seen how the mean ambient pressure shows little variation with season (difference between Fig. 3(a) and 3(b)). In addition, there is a very small variation of pressure with latitude. Both characteristics make the ambient pressure a fairly reliable stimulus source for an adaptive structure. The advantage of having such an actuation system is that it requires less systems architecture for actuation and it does not consume any power. This makes this system comparable to the adaptive chevrons that Boeing introduced in 2006, where the noise automatically reduced through increased exhaust mixing at lower altitudes.[9] The main difference is that the present structure can be made out of certifiable material, while the adaptive chevrons relied on shape memory alloy for actuation.

The initial objective of this adaptive structure is to induce deformation between take-off



(a) Atmospheric Pressure distribution during winter, p_a (hPa)



(b) Atmospheric Pressure distribution during summer, p_a (hPa)

Fig. 3 Isobars for mean winter and summer atmospheric conditions[10]

and cruise altitude. Take-off altitude can vary considerably between airfields around the world with altitudes as high as 4km (El Alto International Airport[11]). If a pressure adaptive structure is used in any type of high lift device, it should be fully deployed at these high altitude airports. Airtight honeycomb cells would not suffice for this purpose. The difference in altitude between sea level and local airport altitude could already induce a significant change in structural geometry. In other words, a potential high lift device powered by such a pressure adaptive structure would already be partly retracted at these high altitude airports. By implementing separate air bladders (pouches) inside each of the honeycomb cells this issue can be avoided. By carefully inflating the pouches with a fixed amount of gas at a known pressure and temperature it is possible to control the pressure differential at which the pouches pull taut, and start pushing against the honeycomb wall. During the initial altitude gain, the decreasing pressure does nothing else than expanding the gas in the pouches up until the pouch is constrained by the honeycomb structure. Then, as the pressure difference increases, the pouch attempts to reach its perfect circular shape, taking the honeycomb to a grid of near perfect hexagons (see Figure 1).

A more thorough analysis of this process is detailed in below. To see how a pressure adaptive structure would be deployed, the reader is asked to consider the mission profile in Figure 4. This diagram is typical for a jet transport or business jet. It shows the engagement altitude, and full pressurization altitude. In between those two altitudes the pressure adaptive structure deforms between its two states. If the pressure adaptive structure is used to enhance high lift devices it is fully deployed between sea level and engagement altitude. Above full pressurization altitude it is completely retracted. This means that during the climb and decent phases of the flights, the structure continuously changes its shape between these two states without any pilot interference.

When an external pressure source is used to regulate the CDP in the pressurized honeycomb, the stiffness can be controlled quite easily. How-

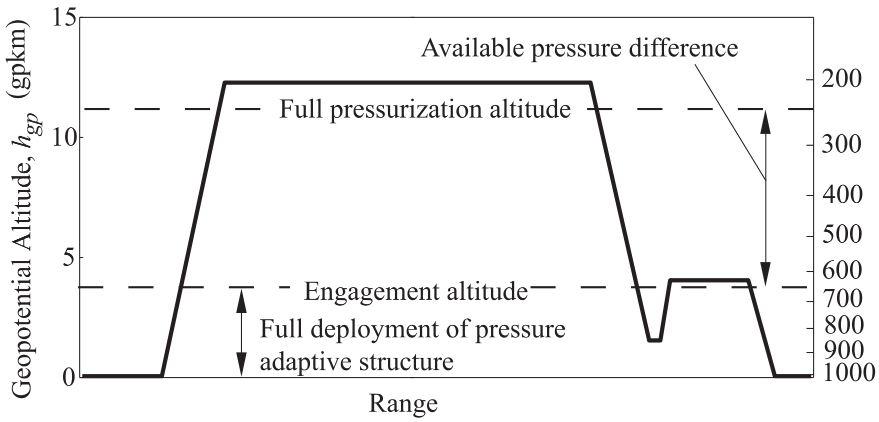


Fig. 4 Notional mission profile with outlined engagement and full pressurization altitude

ever, when the more adaptive variant is used, where a constant mass is present in the pouches, controlling the stiffness can only be done by increasing or decreasing aircraft altitude. As was briefly shown in Figure 4, one thing that can be controlled is the altitude at which the stiffening starts. This altitude is referred to as the 'engagement altitude' and can be anywhere between the take-off and cruise altitude. In general, however, it would be wise to set this altitude to where the aircraft can serve for example 95% of all major worldwide airports with the adaptive honeycomb structure fully deployed. In the next paragraphs it is shown that a trade-off needs to be made between the elevation of the engagement altitude and the amount of mass that is available in the pouches. Remembering that the mass in the pouches has a positive correlation with the pressure stiffness it is generally desired to optimize the amount of mass inside the pouches. When a particular pressure engagement altitude (*ea*) is desired the mass inside the pouch is:

$$m < \rho_0 V_{ea} \tag{1}$$

This results in a partly inflated pouch with a fixed amount of air at a pressure, p (see Figure 5). Decreasing the ambient pressure results in an expansion of the gas inside the pouch (according to $p = mRT$) until the perimeter pulls taut. When the ambient pressure decreases further, the pouch tries to form a perfect circle, such as to minimize its circumferential strain energy. By doing so it forces the strained honeycomb cell into a perfect hexagon. The ambient at which the pouch pulls taut and starts to do work on the structure is termed the "engagement pressure." It corresponds to a unique altitude in the international standard atmosphere.

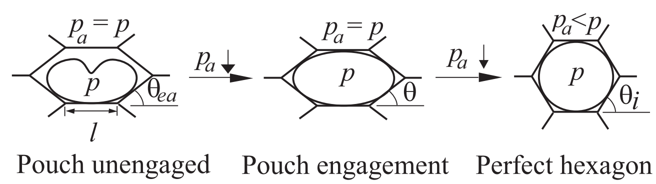


Fig. 5 Sketch of honeycomb deformation with ambient pressure, assuming constant mass

3 Potential Applications of Pressure Adaptive Honeycomb

In this section two applications are discussed. The first application (Subsection 3.1) is a pressure-adaptive flap, which is controlled by altering the pressure, according to the actuation concept discussed in Subsection 2.1. In Subsection 3.2 an altitude-adaptive Gurney flap is presented corresponding to the actuation concept discussed in Subsection 2.2.

3.1 Pressure-Adaptive Flap

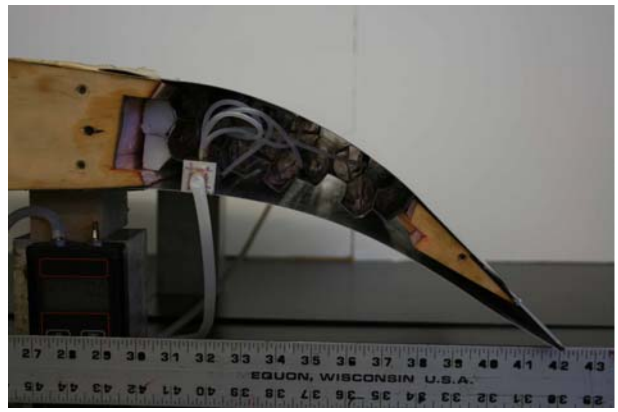
Pressure adaptive honeycomb can easily embedded in conventional aircraft structures. It would be most useful in low-bandwidth applications such as adaptive flaps, slats and/or trim tabs. In this section the application of pressure adaptive honeycomb into a morphing flap is investigated. To that extent, a proof-of-concept wing section was built to test in the low-speed wind tunnel of The University of Kansas. The model had a 91cm chord and was based on a NACA2412 airfoil. It employed a pressure adaptive flap over the aft 35%c. By applying a CDP of 40kPa, the average trailing-edge angle was changed by 25 degrees as can be seen in Figure 6.

By examining Figure 6 closely, the reader notices the simplicity of this actuation structure. The embedded honeycomb contained only 13 cells. Each cell was individually fed from a small plenum chamber near the root of the flap. The honeycomb was bonded to the top skin of the flap, which was pre-curved such as to provide the necessary restoring force to deploy the flap when no CDP existed. The bottom skin of the flap was attached to the root of the flap and connected to the trailing edge by means of a free sliding mechanism. The bottom skin was also pre-curved to assist the top skin in providing the required restoring force to the honeycomb.

Wind tunnel testing at a Reynolds number of approximately one million clearly showed the influence of the cell differential pressure on the $c_l - \alpha$ curves. As can be seen in Figure 7, a decrease of pressure results in an average Δc_l of 0.3. This resulted in an increase of $c_{l_{max}}$ from 1.24 to 1.52. This very basic experiment demonstrated the potential of pressure-adaptive honeycomb as a substitution for conventional high-lift devices.

(a) CDP = 0kPa

(b) CDP = 40kPa



(c) CDP = 0kPa

(d) CDP = 40kPa

Fig. 6 Side View of Wind Tunnel Model with Pressure-Adaptive Flap

3.2 Pressure-Adaptive Gurney Flap

The pressure-adaptive flap is a good example of relatively large-scale morphing structure which could replace a conventional flap on, for example, LSA-class aircraft. It is recognized that it is unlikely that these structures will be used to replace the highly-efficient (multi-) slotted flaps on commercial transports and business jets. However, pressure-adaptive honeycomb could still assist in creating a higher lift coefficient by actuating

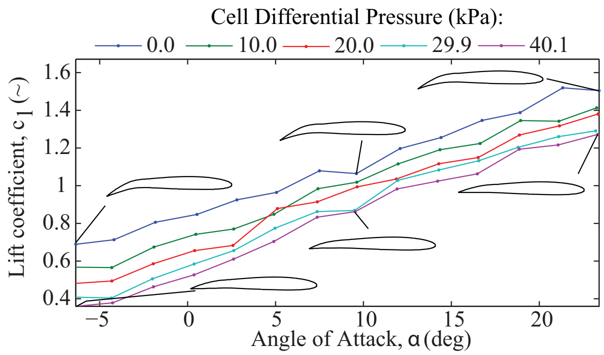


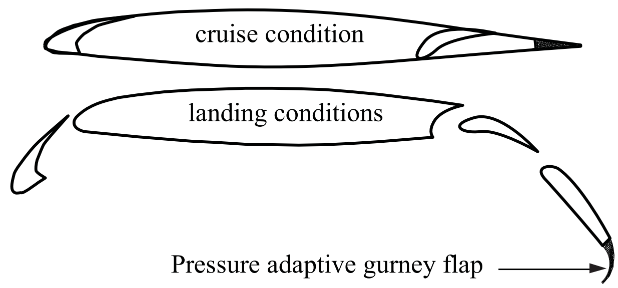
Fig. 7 Section Lift Coefficient vs. Angle of Attack at Various CDP (after wall corrections[12])

small, autonomous features such as smart vortex generators or pressure-adaptive Gurney flaps. The pressure cycle that is encountered during a typical mission profile of high-subsonic jets can be employed to induce the necessary CDP to ensure the desired structural deformation. This implies that this is an adaptive structure that can operate fully autonomously.

This concept was explored for the case of a simple pressure-adaptive Gurney flap for the use on a transonic wing. A proof-of-concept test article was constructed that measured 15cm in span and 25cm in chord. Honeycomb cells with ligaments of 1cm were manufactured from 25μm steel sheet stock. Mylar pouches with each having 20cc of air in them were sealed and inserted into each of the cells. The test article was subsequently subjected to a lowering of ambient pressure by positioning it in a transparent vacuum chamber. As can be see from Figure 8, a significant shape change took place when the ambient pressure was lowered. This demonstrated the potential capability of this morphing concept.

4 Comparison to State-of-the-Art in Adaptive Actuators

Pressure-adaptive honeycomb has significant benefits with respect to conventional (electromechanical) actuators. There are no sliding or hinged parts which means there is reduced wear and tear through operation. Manufacturing, assembly, and integration into conventional wing



(a) Schematic Outline of Concept

(b) Deployed Position: $p_a = 100$kPa

(c) Stowed Geometry: $p_a = 20$kPa

Fig. 8 Experimental Investigation into Pressure-Adaptive Gurney Flap structures are all straightforward and can rely on conventional techniques and certified materials. In terms of compliance it has been estimated based on prior experiments on conventional honeycombs that strains in excess of 50% can be achieved in either principal direction. In Figure 9 it is schematically shown how these strains could be realized.

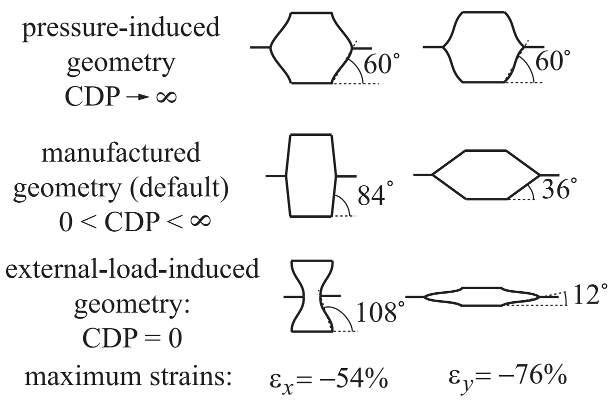


Fig. 9 Maximum strains of pressure adaptive honeycomb

The blocked stress is another important parameter that needs to be established for any actuator. An analytic model (based on energy conservation principles) was developed that related blocked stress to strain and CDP.[13] This model was empirically verified by a series of tests and was used to calculate the blocked stress in the case of $CDP = 0.9$MPa (typical exit pressure of high-pressure compressor of modern turbofan engines at 11km cruise altitude) and in the case of atmospheric pressure drop of 40kPa. These two cases represent the two different options that can be employed to actuate the pressure adaptive honeycomb: the powered approach (as in the case of the pressure-adaptive flap), and the autonomous approach (as in the case of the pressure-adaptive Gurney flap), respectively. Based on these assumptions the maximum blocked force of pressure adaptive honeycomb could be calculated.

In Figure 10, a comparison of pressure-adaptive honeycomb with alternative active materials as well as an exemplary electromechanical flight-control actuator is presented. On the diagonal of Figure 10(a) the volumetric energy density, E_v, is displayed. It can be seen that pressure-adaptive honeycomb displays relatively large strains compared to other adaptive materials. Its volumetric energy density rivals that of the electromechanical servo. Additionally, Figure 10(b) shows that the mass specific energy density of this pressure-adaptive honeycomb is close to that of SMAs, which have the highest mass specific energy density of all adaptive material classes.[14] However, pressure adaptive honeycomb shows strains that are five times higher at a transfer efficiency that approaches unity.

5 Conclusions

Pressure-adaptive honeycomb is a new type of adaptive structure that relies on a pressure differential for actuation. It has been shown that this pressure differential could stem from two sources: either direct from an on-board source in the aircraft or from a change in ambient pressure due to an altitude increment. For either application, overall strains of more than 50% can be obtained while remaining in the elastic realm of the honeycomb material. Furthermore, a theoretical mass-specific energy density of 10kJ/kg can be available when the honeycomb is connected to the high-pressure-compressor of a turbofan engine (0.9MPa pressure differential at sea level). This is on the par with shape memory alloys, but with five times higher strains and a transfer efficiency that approaches unity. It is demonstrated how pressure adaptive honeycomb can be successfully applied in a 35%c flap and that the resulting camber change induces an increase in maximum lift coefficient of 0.3 Furthermore, it is shown that altitude adaptation of a Gurney flap is a realistic option to improve the high-lift characteristics of jet transports.

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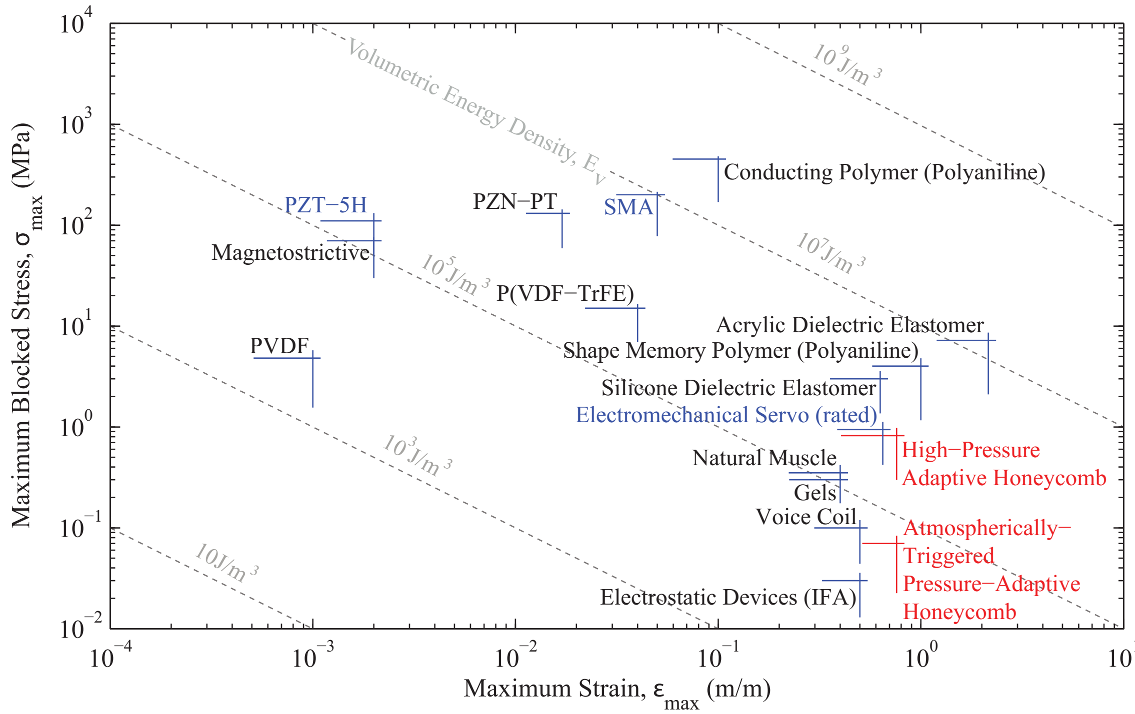
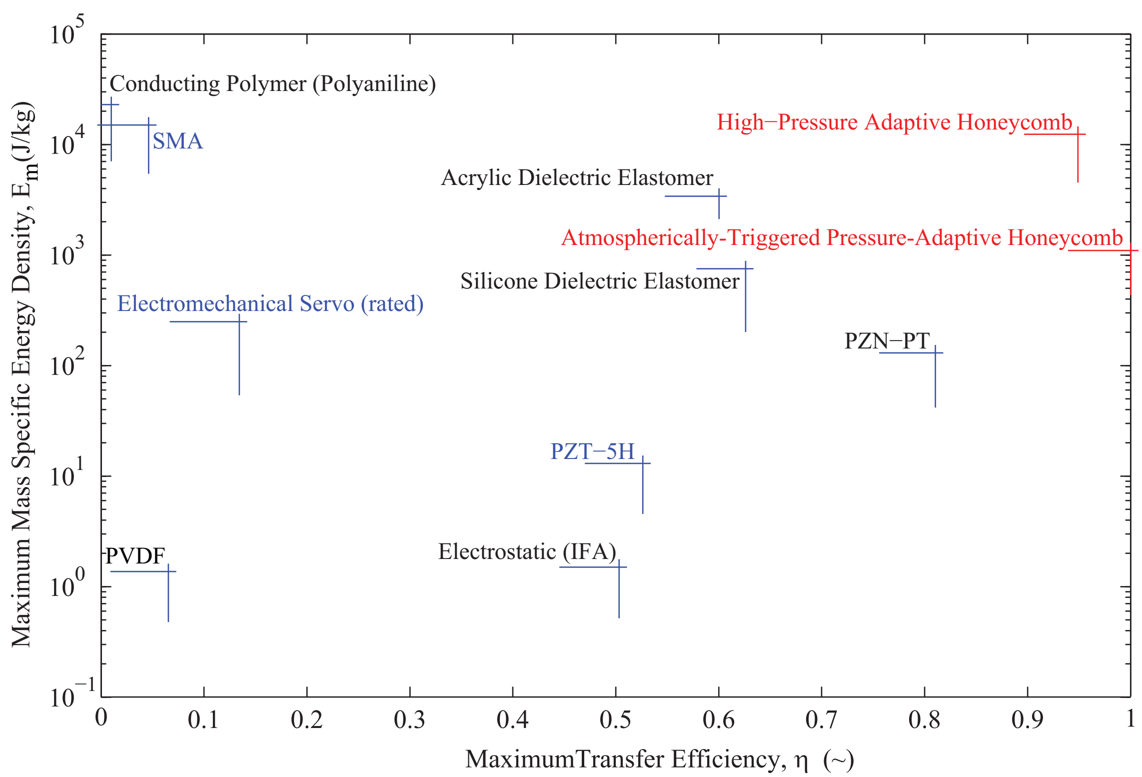


(a) Maximum stress-strain for various adaptive actuators [14]



(b) Maximum specific energy density for various adaptive actuators [14]

Fig. 10 Comparison of pressure-adaptive honeycomb to alternative active materials

search. The authors would also like to recognize Ms. Lauren Kerth, Mr. Thomas Stastny and Mr. Ryan Barnhart for their tireless efforts in assisting fabricating the test articles.

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