From Static to Kinetic: A Review of Acclimated Kinetic Building Envelopes

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ABSTRACT

Thermophysical and optical properties of building envelopes play an important role in building energy consumption and indoor environmental conditions. Innovative building envelopes are more adaptive and interactive by actively responding to prevailing climatic conditions for enhancing energy performance and indoor comfort levels. Components related to these kinetic buildings range from automated blinds, to smart glazing, variable insulation, moveable roofs, etc. The purpose of this paper was to review state of the art acclimated kinetic building envelopes through existing and emerging technologies. Based on the conceptual research model and the climate analysis, this study reviews representative systems or designs grouped into three key climatic categories: solar-responsive systems, air-flow-responsive systems and other natural sources responsive systems, along with some useful remarks concluded from the available literature and designs.

Key words: building envelopes; building energy consumption; indoor comfort; acclimated design

1. INTRODUCTION

1.1 Building Envelopes and Energy

Highly conditioned buildings via mechanical devices may make the building insensitive to its environment, and uncouple the building envelope from its role as an environmental moderator. However, this ignores the nature of sustainable buildings to acclimate (climatically respond) to the environment and take full advantages of the positive influences found in nature.

In the field of the buildings’ “acclimation”, we can find many studies around the world involved in building envelopes and their impacts on building energy usage and indoor environment issues. Building envelope is one of the most important design parameters determining indoor physical environment related to thermal comfort, visual comfort and even occupancy working efficiency, thus affecting energy usages in buildings [1][2][3]. In particular, thermophysical and optical properties of building envelopes are the key factors which should be defined by materials and geometry of building envelopes components. As interest increases towards net-zero energy buildings, even current high performance envelopes can hardly achieve the goal. Most available envelopes design works either heating or cooling is the dominant climate, but not both. In short, such envelope designs provide less-than-optimal building performance during some periods of the year. One way to improve building energy efficiency would be to develop kinetic building envelope systems that can alter their thermal and optical properties according to seasonal/daily climatic variations.

1.2 Definition and Concepts

In recent years, some promising and innovative building envelopes tend to be more adaptive and interactive with the climate, space functions, indoor environments, occupants and visitors. If we scan the literature on this type of building envelopes, it is easy to notice they relate to a number of closely associated words such as (climate) responsive, active, intelligent, (climatic) adaptive, smart, interactive, (high) performative, kinetic, dynamic and so forth. These words combined with building envelopes, are taken as being synonymous with one another in many research literatures. Within the scope of this research, the type of building envelopes is defined by three characteristics:

- To manifest the strong correlations to climate and environment with its connotation of indoor environmental conditions and energy efficiency.
- To integrate a particular degree of physical motion or behaviors with the potentials to enhance architectural aesthetics.
- To imply biological metaphors with the idea of optimal performance and access to natural sources.

The term “acclimated” is from biology and refers to a process in an individual organism adjusting to a gradual
change in its environment (such as a change in temperature, humidity and etc.) through its morphological, behavioral, physical changes \[4\]. This term exactly relates to the design aims in architecture. The term kinetic, on the other hand, is originated in the Greek word κίνησις (kinesis) pertaining or associated to motion, and also indicates an organism’s response to a particular kind of stimulus in biology \[5\][\[6\]. In the context of architecture, in 1970, Professor William Zuk \[7\] described kinetic architecture in his book *Kinetic Architecture* as a field of architecture in which building components or whole buildings have the capability of adapting to change through kinetics in reversible, deformable, incremental and mobile modes. Thus, the term of is more appropriate to be called “Acclimated Kinetic Envelopes (AKE)”. It is defined as responding to variable climatic environment by means of visible physical behaviors of building envelope components. Also, in this research, the definition has two boundaries: one is that the kinetic components should be integrated into buildings rather than separated devices like wind turbines; another one is that the kinetic behaviors are related to visible changing processes rather than to inner changes of material properties (e.g. phase changed materials). Thus, a number of building envelopes with seemingly kinetic features were not included in the analysis.

This paper reports the investigation results of AKE issues in buildings in a three categories related to climatic sources including solar, air flow and others. Within each category, the general kinetic mechanism and current representative projects, designs and studies are given. Finally, this work gives a table about reviewed cases with valuable information concerning AKE and its features. Also, some ongoing and future studies about AKE implementations are discussed.

2. Research Model and Methods for Reviews

Compared with conventional building envelopes, there are more variables existing in AKE systems. Thus, for clear understanding the nature of AKE, it is necessary to establish a conceptual model to lay out the key variables in terms of AKE and the relationships between variables. As it is shown in Fig 1, *functions of building envelopes* act as a mediator that accounts for the relation between *properties of building envelopes* and *envelope-related performance*. The design context variables including site and climate information play the role of moderator affecting the relations between *properties of building envelopes* and *functions of building envelopes*. Through mapping the variables, we can further categorize them into three types of parameters about design, context and performance \[8\]. In order to select and review design cases and categorize its’ traits, we expand above three types of parameters (design, context and performance) to the following criteria:

1) Design category:
- What is the basic building information including building type, building height and others?
- Which component of the envelope has kinetic features?
- What kind of kinetic modes or mechanisms do the kinetic components have?
- Does AKE have energy generation solutions?
- Does the case combine other conventional sustainable design solutions with AKE?

2) Context category:
- What are the climatic variables related to the case or the design study?
- Are there any design context constraints affecting the design solution of the case, such as site size, orientation and etc.? (For some experimental design studies, the consideration will be whether the design solution aims at specific context conditions.)

3) Performance category:
- What is the energy performance compared with the requirements of standards or alternative solutions?
- Whether does the solution of AKE facilitate occupancy satisfactions on physical environment or working efficiency or more options to control the environment?
- Do visitors or future users generate any feedback on interactions with AKE?

![Fig. 1: The conceptual model of this research](image-url)

3. Climate-responsive Categorization of current AKE

Since AKE are shaped strongly by climate, it makes sense to categorize them into distinct climate-responsive characteristics related to solar radiation, daylight, air flow, air temperature and other climatic sources. These traits may exist separately in one single AKE module or can be combined in some AKE systems and building design cases. Technically, the AKE can be analyzed at the system’s level and the building’s level. At the module’s level, it is mostly designed for responding to a central climatic source, which generally refers to solar and air flow. The following figure (Fig. 2) shows the relations among different modules about the climatic sources. At
the building’s level, there are not so many design cases
suiting to our focuses which are both related to visible
kinetic components and building energy efficiency; for
example, the Sliding House and the Dynamic Tower.

3.1 Solar-responsive AKE

The solar conditions including solar radiation and
sunlight forms solar-responsive AKE’s kinetic behaviors,
so these modules fall into three basic types.

3.1.1 Solar heat
The first type of solar-responsive AKE is only about solar
heat, and aims to maximize the acceptation of solar heat
in winter and minimize solar gains in summer. The nature
of this type is to alter the thermophysical properties of the
AKE module. The simple example is Solar Barrel Wall
(Fig. 3) designed in 1973 by Baer [9]. Functionally, the
water-filled oil barrels can store solar heat in a day by
opening its covered wall, and stop get the heat by closing
the covered wall and also diffuse heat for the room [10].
Similarly, Jonathan Hommond house (Fig. 4) has water
storing bags on the roof with operable lids which can be
opened or closed according to outside solar radiation [11].
At the visible scale, besides movable components, some
smart materials are also involved in this type. For
example, thermochromic materials can change color due
to temperature changes and can be designed to specific
temperature ranges [12]. Some designs (Fig. 5) of Juergen
Mayer H. use thermochromic materials to imprint color
shapes formed by human body temperature [13]. Using the
materials on the building surfaces to get appropriate color
and reflectance for responding to outside temperature
could be one solution for climate design. However, current
available thermochromic paints for building exterior may lose color changing features because of
exposure to ultraviolet [13].

In addition, some recent conceptual design combined
solar-responsive AKE with bio-inspired design. For
instance, the concept of the Kinetic Honeycombed
Canopy (Fig. 6) was designed by a BIM parametric
method and achieved some kinetic features. The kinetic
movements inspired by butterfly wings’ honeycombed
structure may maximize the acceptance of solar heat or
minimize that based on different season and solar
radiation [14]. Another example is about mammal’s hair
inspired design (Fig. 7) which translated the hair systems’
behavior related to temperature changes into the building
surface. The adjustable system consists of water and
porous materials to be able to inflatable for thermal
comfort [15].
lighting and cooling. Currently, there is a wide array of AKE’s fenestration systems, which are generally based on two kinetic mechanisms: mechanical driven devices and smart glazing (or translucent materials).

1) Traditional mechanical AKE
Regarding mechanical driven fenestration devices, these can be as simple as motorized blinds, or as complex as façade system of the Institute du Monde Arab in Paris. The characteristic example is the venetian blinds which are well established technologies to control daylight and heat gains in the front of, behind or between windows [18]. Substantial research, especially from LBNL, has been devoted to this area, and through simulation, laboratory tests or scale field tests to demonstrate that the visual comfort and energy benefits can be associated with these kinetic systems; e.g. interior automated venetian blind full-scale test in R&D project [19], automated venetian blinds between panes controlled by temperature and solar positions [20].

By full-scale test and monitored records, compared to static blind systems with daylighting controls, the similar automated venetian blind/lighting systems can obtain daily lighting energy savings averaged 35% in winter and ranged from 40–75% in summer in Oakland [19]. Also, DOE-2 simulations shows 16-26% annual energy savings in Los Angeles for all directions except north by using kinetic blind systems compared with an advanced spectrally-selective window system [19]. Similarly, LBNL set up a mockup and conducted field tests for automated roller shading system which is planned to use in the New York Times Headquarters (Fig. 8). They found that the automated roller shading system can provide better uniform lighting distribution, sun penetration depth, and glare control simultaneously with lower cost [21]. Another important effect is on human factor issues. Kinetic window systems are often reported to increase the occupants’ satisfaction and have the potentials to facilitate working efficiency [22]. However, some research pointed that the efficient mechanical daylighting systems should be only with an automatic one-axis tracking system [23].

Fig. 8: New York Times Headquarters mockup [21]

Another representative design with kinetic shading is double-skin façades. It is hard to categorize double-skin envelopes as they have obvious integrated features about solar radiation, daylight and ventilation. However, most kinetic movements of double-skin façades are incorporated with shading and natural ventilation (the natural ventilation type will be discussed in next section). The motorized shades or blinds can work between the double-skin façades such as the Eurotheum building in Frankfurt [24], or outside of double-skin façades such as GSW Headquarters [25].

2) Innovative mechanical AKE
In addition, recently there are many aesthetically pleasing design cases which are with more visible or dynamic mechanical fenestration systems and more to do with visual impacts on visitors and occupants. Although some overly maintenance needs and non-functioning problems exist in the project of Jean Nouvel’s design, it is always arousing architects’ interests because of its cultural symbols and aesthetical expression. Recent years, more projects or experimental designs with visible and aesthetical AKE were conducted. The mechanical movements can be rotational, retractable, sliding and self-adjusting [26].

One example of the rotational kinetic module is from the Devonshire Building at the University of Newcastle. The external large shades can rotate in the range of angles to track the amount of sunlight entering the windows and take account the time of day and season [27]. Another interesting case is the Flare (Fig. 9) designed by Staab Architects Berlin, which created a dynamic hull by rotating the metal flakes interacted with natural light [28]. Although the application is not clearly aiming at visual comfort or energy conservation, the modules have the potentials to be utilized in the area. Regarding the sliding cases, the project of Sliding House (Fig. 10) designed by dRMM architects offers a creative kinetic design concept. The whole enclosure including walls, windows and roofs can slide on two tracks along with the house and in turn adjust its thermal and visual properties according to seasons, weather or a remote-controlled desire to delight [29]. Another sliding case is about the Showroom project in Kiefer. This is a promising design and a typical sliding movement case by integrating external sliding shades to form a dynamic façade sculpture for each day and even each hour [30]. The retractable example can be explored through the project of the Madrid’s City of Justice (Fig.11) designed by Foster + Partners creates a 2-D retractable hexagonal shading unit which occupies the central circular atrium as well as the atria, and can extend to cover the roof or disappear into the structural profiles of the roof [31]. On balance, these creative buildings or design concepts work in close conjunction with climate and takes full advantage of the positive natural factors, but currently there is little documentation on the energy performance and physical environmental comfort.
progressed field tests using large area electrochromic windows with daylighting controls, and RadianceMathematica simulation in Berkeley, California. Compared to the blinds-down spectrally selective low-e window basecase, they found 10±15% savings of lighting energy and 0±3% savings of cooling loads [35]. Also, the electrical chromic windows are able to deliver adequate control of glare and maintain luminance ratios within recommended limits, and more desirable visual and thermal environment [36].

3.1.3 Solar electricity
The third type of solar-responsive AKE is involved in solar electricity which often deemed as a kind of active solar energy techniques. According to this research’s boundaries, we are focusing on the Building Integrated Photovoltaic (BIPVs) with the ability to be kinetic rather than separated moveable PV panels on buildings. The most typical kinetic movement is sliding or rotation enabling panels to track maximum solar energy, which is often called as heliotropic sun-tracking systems. Consider the EWE Arena (Fig. 10) [36] in Oldenburg and the Gemini Haus [37] in Weiz, the floating shading or curtain walls are mounted PV modules that can rotate on its tracks around the building to capture maximum solar energy and hence maximize electrical output. Another advantage is that PV-walls can also provide shading and better daylighting performance for interior. Similar technologies combined with building roofs including the Sündreyer project [38] in Treia, Germany and the B&W House [39].

At the module’s level, the Photovoltaic Leave (Fig. 12) is an impressive design case. Designed by SMIT (Sustainably Minded Interactive Technology), the Photovoltaic Leave consists of a layer of thin-film material on top of polyethylene with a piezoelectric generator attached to each leaf. The light-sourcing leaves can move around and catch the solar to generate electrical power via the sun and wind. A 4 × 7 foot strip of this can generate 85 Watts of solar power [40].
3.2 Air-flow-responsive AKE

The modules that interact with air flow are termed as air-flow-responsive AKE embracing two classes about natural ventilation and wind electricity. For the former one, the kinetic behavior is influenced by the air exchange and circulation for indoor thermal comfort and air quality. The latter one refers to the envelopes’ kinetic process that can convert wind energy into electricity. Just the same, the air-flow-responsive AKE may impact on lighting environment and aesthetic sense.

3.2.1 Natural ventilation

The kinetic process correlated to natural ventilation is to introduce appropriate outside air (including temperature, moisture, dust, odors and others) into indoor rooms. In contrast with mechanical fans or ventilation systems, we still consider these AKE systems as natural ventilation although some systems are motorized. It serves to better thermal comfort, acceptable indoor air quality and facilitate daylighting performance in some cases.

The Kinetic Roof House (Fig. 13) [41] has been proposed by a design competition in 2001. The kinetic roof structure can be opened to the sun and direct sunlight into room during the winter’s daytime, and close it to keep the heat inside during the night. In summer days, the roof moves to a particular degree to allow natural ventilation but block the direct sunlight in a daytime, and fully opens for cooler air temperature during the night.

From above analysis on double-skin façades, some kinetic movements work for natural ventilation for air circulation of the envelopes and / or indoor rooms and hence get better indoor comfort [42][43]. The typical project is the New San Francisco Federal Building (Fig. 14). The local climate showed a chance to take advantages of natural air flow. From the building’s southeast side, external panels of double-skin façades can flip up to a 90-degree angle allowing fresh air directly into the building based on wind speed and direction [44].

3.2.2 Wind electricity

Similar to BIPVs, small scale wind turbines integrated into buildings can also be defined as a micro generation [45]. This research focuses on integrated wind turbines design rather than stand-alone wind energy systems, such roof-top wind turbines. One of the most interesting kinetic building designs with wind turbines is the Dynamic Tower planed by David Fisher. Wind turbines fitted horizontally between each floor and then produce electricity [46].

Other well integrated AKE cases with wind electricity include the COR Building in Miami, the Greenway Self-park Garage in Chicago, etc. (Fig. 15). Besides economics and regulatory issues [47], the use of existing wind turbines technologies may be problematic due to its severe noise issues and the ability to match the structural and aesthetical integrity of buildings [48].

4. CONCLUSIONS

Current energy efficient design strategies and technologies of building envelopes have led to significant building energy savings. However, for most climates, the conventional building envelopes with static properties may not be an optimal solution. These representative cases and studies manifest a growing interest in kinetic envelope technologies which are proposed for improving energy performance, indoor comfort (especially about visual qualities), and occupancy interactions with buildings as well. The main objective of this paper is to review the current practices and concepts of the acclimated kinetic building envelopes (AKE). In order to clarify the
characteristic properties that distinguish AKE, a number of application cases are examined and formed a table with important information and data of the cases.

Based on our reviews of representative examples, we found: (i) because solar energy (solar radiation and daylight) tends to be climate specific and has certain conflicting circumstances for buildings, most design cases are about the type of the solar-responsive AKE, (ii) the most resent AKE systems are design or hypothesized to integrate solar heat, daylight and airflow features for a hybrid AKE system, and (iii) except for LBNL’s in-depth research, there are few reports with detailed results about energy consumption, indoor comfort or human factors in available AKE systems.

There are also some challenges to AKE technology development. Most AKE systems will consume energy which is mostly from mechanical devices. Are there still significant energy benefits from these technologies compared with conventional energy-efficient envelope design? Further, similar to other new high-tech systems, expensive initial costs and maintenance inputs for the AKE systems may cause failures strictly on the basis of energy savings. Actually, the AKE systems are design for not only energy performance but also visual comfort and human factors as well. However, how to evaluate the benefits of these new technologies from multiple-dimensions beyond current energy-centric evaluation approaches? Note that future studies should establish a comprehensive evaluation approach which can assess the AKE’s contributions on occupancy satisfaction, including indoor comfort, acoustical performance, and access to fresh air. Based on the reasonable evaluation method, the research can further examine the differences and applicability of AKE in various climates.

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