Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

MBS Analysis of Kinetic Structures using ADAMS

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Abstract

The present paper considers multibody system (MBS) analysis of kinetic structures using the software package ADAMS. Deployable, foldable, expandable and reconfigurable kinetic structures can provide a change in the geometric morphology of the envelope by contributing to making it adaptable to e.g. changing external climate factors, in order to improve the indoor climate performance of the building. The derivation of equations of motion for such spatial mechanical systems is a challenging issue in scientific community. However, with new symbolic tools one can automatically derive equations in so-called multibody system (MBS) formalism. The present paper considers MBS modeling of kinetic architectural structures using the software packages *ADAMS.* As a result, it is found that symbolic MBS simulation tools facilitate a useful evaluation environment for MBS users during a design phase of responsive kinetic structures.

Keywords: Kinetic architecture, deployable structures, tensegrity, redundancy, robustness.

1. Introduction

Kinetic structures in architecture follow a new trend which is emerging in *responsive architecture* coined by Nicholas Negroponte when he proposed that architecture may benefit from the integration of computing power into built spaces and structures, and that better performing, more rational buildings would be the result (Negroponte 1975, Beesley, Hirosue, Ruxton and Trankle 2006). This kind of interactive spaces are built upon the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of human and environmental interaction (Fox 2001a, b, Kronenburg 2002). Deployable, foldable, expandable and reconfigurable kinetic structures can provide a change in the geometric morphology of the envelope by contributing to making it adaptable to e.g. changing external climate factors, in order to improve the indoor climate performance of the building. Structural solutions for kinetic structures have to consider in parallel both the *ways* and *means* for kinetic operability. The *ways* in which a kinetic structural solution performs may include among others, folding, sliding, expanding, and transforming in both size and shape. *The means* by which a kinetic structural solution performs may be, among others, pneumatic, chemical, magnetic, natural or mechanical (Fox 2001a, b). Kinetic structures have often a defined 'open-closed' or 'extended-contracted' body shape, i.e. transformations occur between two body shapes (Zuk and Clark 1970, Escrig 1996, Gantes 2001, Kronenburg 2002). Most of the previously developed kinetic structures have 'open-closed' or 'extended-contracted' body shapes based on scissor-like elements such as those proposed by the key designers/researchers (Piñero 1962), (Escrig 1985), (Hoberman 1993), (Calatrava 1981) and (Pellegrino and You 1997).

Recently, proposals for adaptive kintic structures using scissor-like elements have been given, i.e. structures where transformations occur between more than two different shapes to constitute more flexible shape alternatives (Akgün, Haase and Sobek 2007, Inoue 2007). Tristan d'Estree Sterk of The Bureau for Responsive Architecutre and Robert Skelton of UCSD in San Diege are working on shape-changing "building envelopes" using "actuated tensegrity" structures, i.e. a system of rods and wires manipulated by pneumatic "muscles" that serve as the building's skeleton, forming the framework of all its walls (Beesley, et al. 2006, d'Estree Sterk 2006). In general, developing of responsive kinetic architecture requires experimental investigations for validation of the kinetic system and inherent shape control approach. Alternatively one could simulate such mechatonic systems based on multibody system equations of motion mathematically expressed as system of nonlinear ordinary differential equations. The effective derivation of equations of motion for spatial mechanical system is still a challenging issue in scientific community. However, with new symbolic tools one can automatically derive equations in so-called multi-body system (MBS) formalism. The present paper considers MBS modeling of kinetic architectural structures using the software packages *(ADAMS 2009)* which is a tool for modelling three-dimensional mechanical systems. Instead of deriving and programming equations, one can use this MBS simulation tool to build a model composed of bodies, joints, constraints, and force elements that reflects the structure of the system. The automatically built models of MBS dynamics and kinematics can significantly speed up the design and ensure the validity of a given responsive kinetic architectural structure. The present paper outlines this approach and show that symbolic MBS simulation tools facilitate a useful evaluation environment during a design phase of responsive kinetic structures.

2. Kinetic structures in architecture – responsive architecture

Generally, kinetic structures in architecture can be defined as buildings and/or building components with variable mobility, location and/or geometry (Fox 2001a), i.e. kinetic architecture can refere to buildings or structures with variable location or mobility such as portable buildings like caravans, tents and prefabricated barracks (Kronenburg 2002). However, it can also be buildings or structures with variable geometry or movement, i.e. soft form buidlings with transforamtion capacity made by membrane structures, cable-nets pneumatic structures, or rigid form buildings with deployable, foldable, expandable or rotating and sliding capacity of rigid materials which are connected with joints (Güçyeter 2004, Korkmaz 2004).

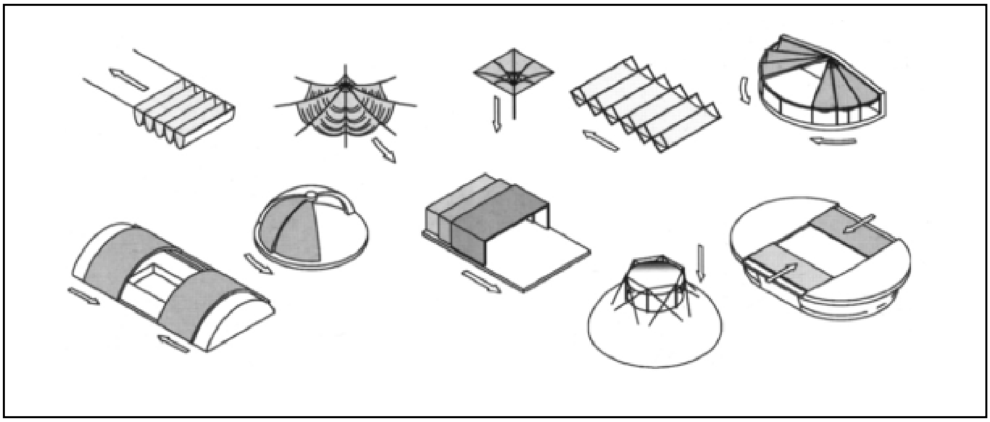

Figure 1: Types of various kinetic systems (Güçyeter 2004).

Kinetic structures can also be classified according to their structural system. In doing so, four main groups can be distinguished: spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, strut-cable (tensegrity) structures and membrane structures (Hanaor and Levy 2001, Temmerman 2007). These structural systems have been classified by their morphological and kinematic characteristics in figure 2 (Hanaor, et al. 2001). Much research has been done with respect to improve the efficiency of these kinetic structural systems which can faciliate a flexibility in bulding design and give rise to a search for responsive architecture which can physically convert themselves to adapt to the ever-changing requirements and conditions (Zuk, et al. 1970, Fox 2001a, Beesley, et al. 2006, Temmerman 2007, Liew, Vu and Krishnapillai 2008). This could theoretically be buildings consisting of rods and strings which would bend in response to wind, distributing the load in much the same way as a tree. Similarly, windows would respond to light, opening and closing to provide the best lighting and heating conditions inside the building. However, any approach to producing responsive, adaptive achitecture must consider architectural and engineering knowledge to ensure robustness of the structure (Kirkegaard and Sørensen 2009).

As mentioned in the introduction kinetic structures have often a defined 'open-closed' or 'extended-contracted' body shape, i.e. transformations occur between two body shapes (Zuk, et al. 1970, Escrig 1996, Gantes 2001, Kronenburg 2002) based on scissor-like elements such as those proposed by the key designers/researchers (Piñero 1962), (Escrig 1985), (Hoberman 1993), (Calatrava 1981) and (Pellegrino, et al. 1997). However, proposals for adaptive kintic structures using scissor-like elements have been given, i.e. structures where transformations occur between more than two different shapes to constitute more flexible shape alternatives (Beesley, et al. 2006, d'Estree Sterk 2006, Akgün, et al. 2007, Inoue 2007).

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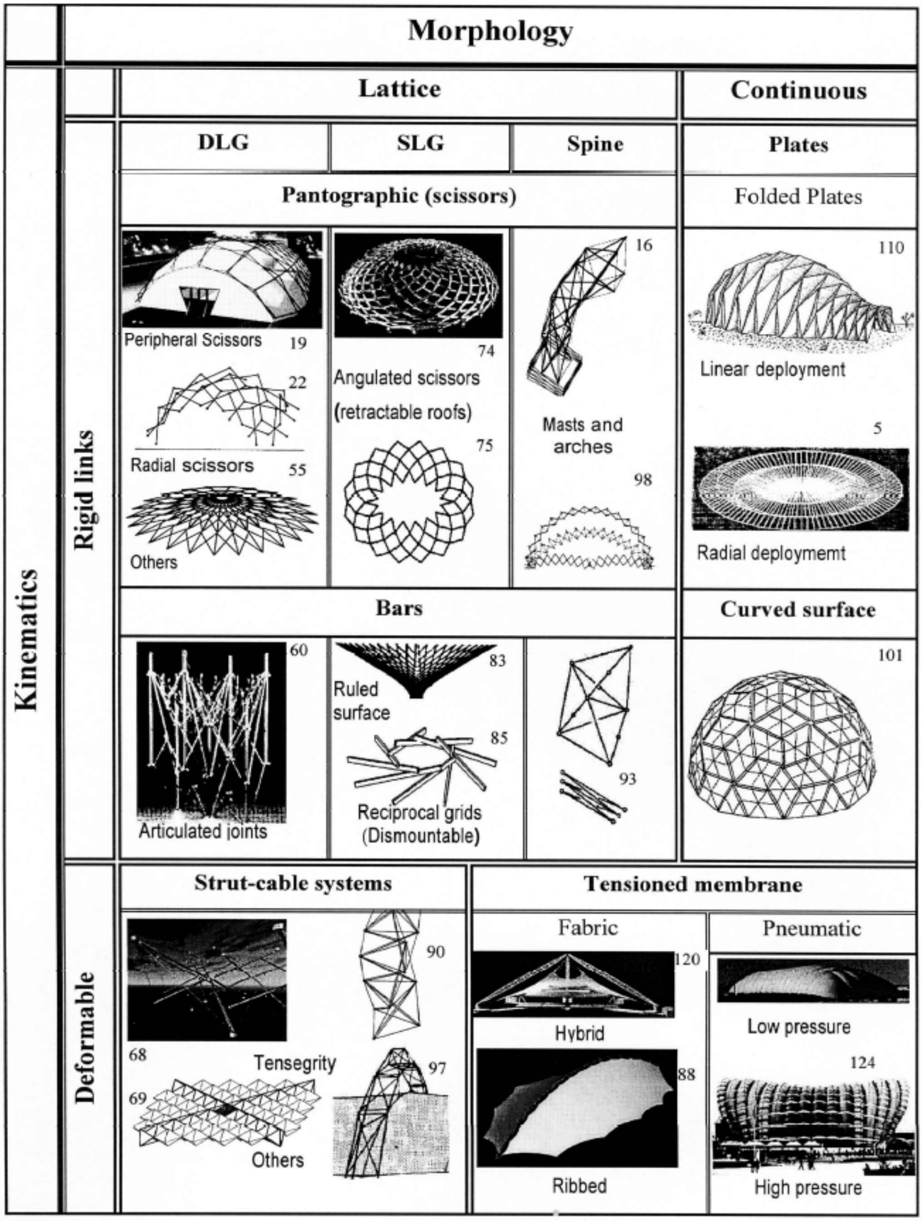

Figure 2: Deployable structures. Numbers indicate references in (Hanaor, et al. 2001).

Tristan d'Estree Sterk of The Bureau for Responsive Architecutre and Robert Skelton of UCSD in San Diege have been working on shape-changing "building envelopes" using "actuated tensegrity" structures, i.e. a system of rods and wires manipulated by pneumatic "muscles" that serve as the building's skeleton, forming the framework of all its walls (Beesley, et al. 2006, d'Estree Sterk 2006). Within the projects sensor/computer/actuator technologies are used to produce a series of intelligent building envelopes that seek fresh relationships between 'building' and 'user'. These responsive buildings are covered by skins that have the ability to alter their shape as the social and environmental conditions of the spaces within and around each building change, see figure 3. New, more personalized relationships with space will inspire fresh interpretations of architecture. Finally relationships that emerge from the juxtaposition of experimental performance and responsive architecture could lead architects to new sets of ideas that uncover new possibilities within architecture as well as provide performance artists with spontaneous, unanticipated, and serendipitous moments that further artistic expression

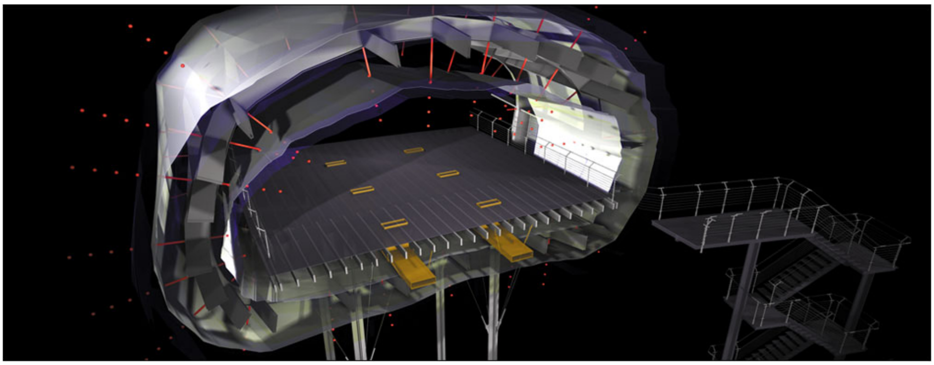

Figure 3: A responsive space (d'Estree Sterk 2006).

Use of scissor-hinge elements combined with actuators was considered in in (Akgün, et al. 2007). Scissor hinge structures possess unique extension and rotation capabilities, and the modified scissor unit developed herein greatly increases the form possibilities for the structure. This modified scissor unit differs from common scissor units in the addition of two joints at a specific point in the mechanism. With the development of this modified unit, it is possible to change the shape of the whole system without changing the dimensions of the struts or the span. The proposed scissor structure is two-dimensional, but it is also possible to combine structures in groups to create three-dimensional systems.

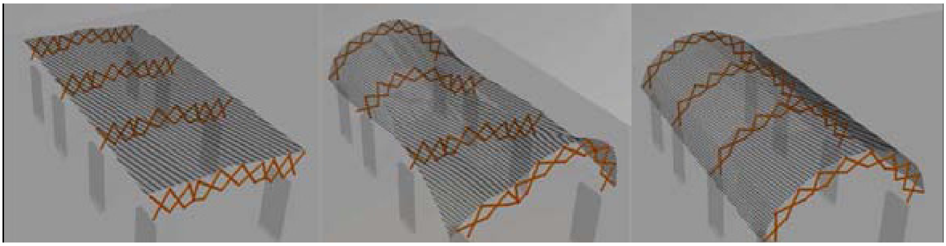

Figure 4: Use of proposed scissor structures as parallel beams(Akgün, et al. 2007).

(Inoue 2007) presents a large-scale movable monument exhibited at the International Expo 2005, Aichi, Japan, as the first application of an adaptive structure using a VGT mechanism. This monument is composed of three identical movable towers comprising four truss members combined by VGT at joints. The VGT is an adaptive truss with an extensible actuator, so the monument's shape can be changed variably by controlling the length of each of its extensible actuators. In the application of the VGT to the movable monument, security against accidents was examined and authorization for the

design was acquired. Further, the control system's safety mechanism, management and operation manual were studied and approved. During the 185 days of the Expo, the monument was operated continuously for about 13 hours a day, and there was not a single breakdown or accident. Continuous safe and excellent performance was achieved, and the monument received high appraisal from promoters and many attendees.

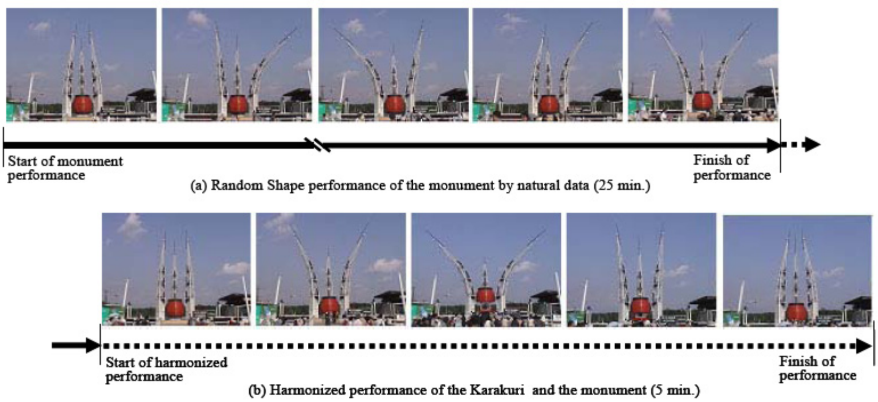

Figure 5: Shape changes of monument according to performance patterns (Inoue 2007).

3. MBS formulation

Developing of responsive kinetic architecture requires experimental investigations for validation of the kinetic system and inherent shape control approach. Alternatively one could simulate such mechatronic systems based on MBS equations of motion mathematically expressed as system of nonlinear ordinary differential equations (ODE). The effective derivation of equation of motion for spatial mechanical system is still a challenging issue in scientific community. The practical problem of MBS modelling can be solved using two basic approaches:

- Manual approach, i.e. the engineer should derive equations of motion using "pen and paper". There are two main wellknown methods: the Lagrange's equations and the Newton approach. The appropriate computer algebra software such as Maple, MathCAD, Mathematica can be used for the symbolic manipulations and so for reduc- tion of "hand work". But still, the derivation of equations for more complex system is challenging.

- Automatical derivation of equations, i.e. the procedure based on Lagrange or Newton methods mentioned above is algorithmized and implemented in so-called multibody dynamics formalism. The user species the geometry and topology (bodies, joints) of the system and algorithms prepare the mathematical model. Naturally, the automatically built models are more convenient for practical implementation.

During the last years, software packages such as e.g. ADAMS (ADAMS 2009) and SimMechanics (SimMechanics 2008) have been developed for MBS analysis using the aaproach with automatical derivation of equations. For the present study ADAMS will be used. ADAMS is a commercially available virtual prototyping and motion simulation software, which allows the user to model a mechanical system, and mathematically simulate and visualize it 3D motion and force behavior under real-world operating conditions (ADAMS 2009). Users can test and refine the model until the optimum performance is achieved.ADAMS, which is an acronym for *Automatic Dynamic Analysis of Mechanical Systems*, was developed by Mechanical Dynamics,Inc., beginning in 1977. ADAMS automatically converts a graphically defined model to dynamic equations of motion, and then solves the equations, typically in the time domain. ADAMS can resolve redundant constraints, handle unlimited degrees of freedom, and perform static equilibrium, kinematic, and dynamic analyses. Systems may be comprised of any number of rigid and/or flexible bodies and can be subjected to any variety of internal or external forces. In addition to displacement, velocity, acceleration, and force outputs, users may request many other data such as graphics output and data for subsequent finite element analysis or control systems analysis. Users can define a number of constraints such as joints, joint primitives, time-dependent motions, higher-pair contacts, and user-written subroutines. ADAMS also allows the user to define forces that act in an action-reaction sense between a pair of points in the system, or apply forces to a single point from an external source. There is no restriction as to topological interconnection of bodies. Thus, chain, tree, cluster, closed-loop, and multiple closed-loop configurations are treated in an identical fashion. The simulation codes are based on Euler-Lagrange's equation, i.e. the motion of a MBS is governed by

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right)-\frac{\partial L}{\partial q}+\Phi_q^T\lambda=Q \tag{1}$$

where the scalar L is the Lagrangian of the dynamical system, i.e. the difference beteween kinetic and potential energy for each body/component included into the system. q is the vector of generalized coordinates (rotations and translations) and the matrix Q contains the externally applied, non potential forces on the structure. The terms $\Phi_q^T\lambda$ represent constraint forces determined from constraint conditions which are imposed by given bondary conditions. The equations in (1.1) are formulated using an inertial frame serving as a global reference frame for describing the motion of the MBS. In addition, intermediate reference frames that are attached to each flexible component and follow the average local rigid body motion (rotation and translation) are often used. The motion of the component relative to the intermediate frame is, approximately, due only to the deformation of the component. This simplifies the calculation of the internal forces because stress and strain measures that are not invariant under rigid body motion, such as the Cauchy stress tensor and the small strain tensor, can be used to calculate these forces with respect to the intermediate frame. These tensors result in a linear force displacement relation. Two main types of intermediate frames are used: *floating* and *corotational* frames. The *floating* frame follows an average rigid body motion of the entire flexible component or substructure. The *corotational* frame follows an average rigid body motion of an individual finite element within the flexible component. In many papers, intermediate frames are not used instead the global *inertial* frame is directly used for measuring deformations. In this approach, the motion of an element consists of a combination of rigid body motion and deformation and the two types of motion are not separated. Nonlinear finite strain measures and corresponding energy conjugate stress measures, which are objective and invariant under rigid body motion, are used to calculate the internal forces with respect to the global inertial frame (Wasfy and Noor 2003). A detailed derivation of MBS equations and how they are implemented in ADAMS is given in (McConville and McGrath 1998, Shabana 2005).

4. Conclusions

Developing of responsive kinetic architecture requires experimental investigations for validation of the kinetic system and inherent shape control approach. Alternatively one could simulate such mechatonic systems based on multibody system equations of motion mathematically expressed as system of nonlinear ordinary differential equations. The effective derivation of equations of motion for spatial mechanical system is still a challenging issue in scientific community. However, with new symbolic tools one can automatically derive equations in so-called multibody system (MBS) formalism. The present paper considers MBS modeling of kinetic architectural structures using *ADAMS* which is a tool for modelling three-dimensional mechanical systems. Instead of deriving and programming equations, one can use this MBS simulation tool to build a model composed of bodies, joints, constraints, and force elements that reflects the structure of the system. The automatically built models of MBS dynamics and kinematics can significantly speed up the design and ensure the validity of a given responsive kinetic architectural structure.

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