Multibody Dynamics Research in Korea*

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In this paper, the research background and current activities of multibody researchers in Korea are briefly reviewed. The research trend and the future of the multibody dynamics field in Korea are also predicted. In Korea, there are 36 Korean journals and 4 English journals in the field of mechanical engineering. Searching a database of these journals, one can find more than 100 papers using the keyword 'multibody'. Recent trends in and applications of multibody dynamics in Korea are summarized from those papers published during the period from the late 1980s to the present. Since most Korean researchers in the field of multibody dynamics obtained their doctoral degrees from universities in the United States of America, the DADS program and the ADAMS program have been used in Korean industries and universities since the 1980s. However, in the 1990s, two multibody dynamics codes (i.e., the RecurDyn program and the AutoDyn7 program) were developed by Korean researchers. These codes are explained, and the ADAMS program and the DADS program are also briefly reviewed.

Key Words: Multibody Dynamics in Korea, ADAMS, DADS, RecurDyn, AutoDyn7

1. Introduction

The historical background and development of MBD (MultiBody Dynamics) in Korea are explained in this paper. It will offer a summary of MBD research activities in Korea and an introduction of key figures in Korean MBD to the participants of ACMD2002 (The first Asian Conference on Multibody Dynamics in 2002). Most Korean researchers in multibody dynamics obtained their doctoral degrees from universities in the United States of America. During the late 1980s, some of them returned to Korea and introduced

'multibody dynamics' to Korean industries. Although they obtained their expertise in MBD in the U.S.A., their research activities have adapted to the needs of Korean industries.

A variety of multibody codes, including ADAMS, DADS, RecurDyn, and AutoDyn7, are currently used in Korea. Up until the early 1990s, ADAMS and DADS were the major programs for multibody dynamic system applications in academia and industry. In the late 1990s, the RecurDyn program and the AutoDyn7 program were developed by Korean researchers.

There are about 40 journals in Korea in the field of mechanical engineering. All the papers published in these journals can be found in the Korean-based database known as METRIC (Mechanical Engineering and Technology Research Information Center, <http://www.metric.or.kr>). However, since most of the papers are written in Korean, it may be difficult for foreigners to access and understand. In the METRIC database, more than 100 papers appear when one searches with the keyword 'multibody'. Recent trend in and applications of multibody dynamics in Korea are summarized from those papers published during the period from the late 1980s to the present.

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2. Research Trends in Multibody Dynamics in Korea

Multibody research papers published in Korean journals fall into two main categories; formulation and application. More detailed explanations are contained in other sections of this paper.

2.1 Formulations in multibody dynamics

Papers in Korean journals relating multibody formulations can be categorized in 6 areas (i.e., derivation, parametrization for constrained system for DAE, integration scheme, flexible effects, modeling techniques, and contact problems).

(1) Derivation of equations of motion

Most of the derivation works are based on velocity transformation technique, recursive formulation, and Kane's method. A brief summary of these works is as follows: Velocities and angular velocities can be expressed in terms of joint velocities using the 6×1 velocity transformation vector. Using these velocity relations, the recursive formula has been derived⁽¹⁾. In Ref.(2), joint reaction forces of selected joints are computed non-recursively after using the recursive formula in the multibody dynamic analysis. Velocity transformation technique is widely used for the derivation of equations of motion. This technique has been extended to flexible multibody analysis⁽³⁾. In relative coordinate formulation⁽⁴⁾, joint coordinates^{(5),(6)} are mainly used instead of Cartesian coordinates. Kane's method and the partial velocity matrix in constrained multibody systems are presented in references⁽⁷⁾⁻⁽¹⁰⁾.

(2) Parametrization for constrained system for DAE

In order to solve DAE systems, several parametrization schemes on constraint manifold are presented. The projection methods for the formulation of constrained multibody systems are reported in the references⁽¹¹⁾⁻⁽¹⁴⁾. The orthogonal vectors defining the constraint manifold are projected to null vectors by the tangent vectors defined on the constrained manifold⁽¹¹⁾. The null space of the constraint Jacobian matrix is obtained by using the pseudo-inverse method and the projection matrix⁽¹²⁾. A hybrid scheme using LU decomposition and the projection matrix is also introduced⁽¹³⁾. The equations of motion are formulated by using the Hamiltonian formulation. Treating the constraint equations between position and velocity constraints with Lagrange multipliers, the index is lowered to two⁽¹⁴⁾.

(3) Integration scheme

A Nordsieck form of the multi-rate integration scheme was proposed for flexible multibody dynamic systems⁽¹⁵⁾.

(4) Flexible effects

Early research in the field of flexible multibody dynamics was carried out by Yoo⁽¹⁶⁾⁻⁽²⁰⁾. An efficient algorithm for dynamic stress calculation has been proposed based on a new analysis of flexible multibody dynamics⁽²¹⁾. Mechanical systems moving on flexible beam structures such as railroads have been studied^{(22),(23)}. An iterative acceleration method has been proposed for the dynamic analysis of flexible multibody systems⁽²⁴⁾.

(5) Modeling techniques

A suspension superelement technique has been introduced for simulation efficiency in vehicles⁽²⁵⁾. A subsystem synthesis method with a fictitious massless reference body has been proposed⁽²⁶⁾. For overall vehicle systems, this subsystem can be synthesized to the main body with a contribution matrix and a vector from the fictitious massless reference body of the system.

(6) Contact problems

Contact problems are crucial when precisely modeling a system. Multibody analysis for contacting rigid bodies has been studied⁽²⁷⁾. Many papers relate to the contact phenomenon, especially in the Recur-Dyn program⁽²⁸⁾. Wheel/rail contact force has been modeled for the railway models⁽²⁹⁾.

2.2 Applications of MBD in Korea

Multibody dynamics technology has been applied to the automotive and military tracked-vehicle industries since the late 1980s, especially in vehicle suspension design. Commercial software programs like ADAMS and DADS were used the early on. The Korean government and many companies provided grants to universities and research centers to develop MBD(Multibody Dynamics) software. These grants drove the boom in MBD research and development in the mid-1990s.

MBD became an essential technique which allowed CAE tools to design vehicle chassis systems. The testing departments of HMC(Hyundai Motor Company) and KIA often use MBD software to predict vehicle behavior and improve designs. Since the chassis frames of buses and trucks are long, their flexibility plays a significant role in the ride and handling of these vehicles. Flexible body dynamic analysis has been used to predict the durability of components as well as the ride and handling of buses and trucks in the HMC bus and truck division.

Tire models for vehicle dynamic analysis have been developed by tire companies to predict the behavior of tires during ride and handling maneuvers. Sophisticated FEM models have been employed to accurately predict tire behavior. Samsung and LG have used similar analyses in designing their washing

machines and printers. In the case of washing machine, the shell has been modeled as a flexible body. The backlash effects of worm gears have also been investigated using the MBD approach. Furthermore, robots on a semi-conductor assembly lines have been analyzed dynamically to maintain a high degree of accuracy in the position control of a robot arm.

In the late 1990s, the concept of toolkit systems was introduced in Korea, and this greatly facilitated and encouraged the use of MBD programs especially in the design of mechanical system applications in the automotive (cars, light trucks, heavy trucks and off-road vehicles, trains), aerospace (planes, spacecraft, military equipments, satellite), machine tool (manufacturing and assembly equipment, printing presses, etc.) and electro-mechanical (photocopiers, magnetic and optical storage devices, laser and inkjet printers, etc.) industries.

1) Automobiles

Most of the papers associated with the application of multibody dynamics in Korea are focused mainly on automobile components. Typical papers discuss vibration in the balanced shaft⁽³⁰⁾, evaluations of vehicle performances⁽³¹⁾⁻⁽³³⁾, and suspension design^{(34),(35)}.

2) Tracked vehicles and excavators

A numerical method has been proposed for the dynamic analysis of high mobility tracked vehicles⁽³⁶⁾. In such analyses, the track is modeled as a combination of elastic links connected by pin joints. The planar vehicle model is assumed to construct two kinematically decoupled subsystems, i.e., the chassis subsystem and the track subsystem⁽³⁷⁾. The recursive kinematic and dynamic formulation module of the tracked vehicle is developed⁽³⁸⁾. Dynamic analysis of an excavator is carried out to improve the design^{(39),(40)}. A three-dimensional DADS modeling of the hydraulic excavator is developed and experimental data are used to estimate the parameters for the modeling^{(41),(42)}. The contact stiffness and damping coefficients are experimentally determined⁽⁴³⁾, and dynamic optimization of a tracked vehicle is investigated⁽⁴⁴⁾. Compliant track link model of a high mobility tracked vehicle is reported⁽⁴⁵⁾.

3) Railway vehicles and robots

Railway vehicles have been modeled with contact models between wheel and rail^{(28),(29)}. Dynamic walking planning and the inverse dynamic problem of the biped robot have been investigated⁽⁴⁶⁾. A robust controller with a sliding mode has been proposed to stabilize walking biped robots⁽⁴⁷⁾.

3. Software Used in Korea

Many multibody codes, including the ADAMS

program and the DADS program, are widely used in Korean industries and universities. In the early 1990s, the RecurDyn program and the AutoDyn7 program were developed by Korean multibody researchers.

1) ADAMS

The ADAMS program was developed and marketed by MDI (Mechanical Dynamics Inc.). With this program, the equations of motion are generated in terms of Cartesian coordinates. Since the coordinates are not all independent due to the joint constraints, they are related by algebraic constraint equations. The Backward Difference Formula and the equations of motion are solved simultaneously with the position level constraint equations by Newton's method.

A sparse linear solver is used to solve the large number of resulting equations. The non-zero pattern of the sparse matrix is identified and analyzed graphically to determine the sequence of LU decomposition of the sparse matrix. Since the values of the non-zero entries change during an analysis, the sequence must be changed. Detecting the change presents a problem, because checking frequently for it is computationally expensive. However, late detection of the change leads to a large error in the solution, and it is difficult to backtrack the time sequence of the numerical integration.

Only position level constraints are considered in the solution process, while the velocity and acceleration level constraints are ignored by some solvers of ADAMS. The omission may not pose a significant problem for a smoothly varying situation. However, the velocity level constraints become significant if a problem has a near discontinuous velocity as is the case with contact problems. In order to overcome this difficulty, MDI recently releases a new solver of Stabilization Index 2 (SI2). In SI2, the velocity level constraint is stabilized during the iteration process through the use of Newton's method. The acceleration level constraints have been also implemented in the Dsolver routine, but it is sometimes so slow that users hardly choose it for practical applications.

ADAMS has many applications in the field of automotive engineering. Therefore, ADAMS has been widely used by Korean automobile makers and their part suppliers.

2) DADS

The DADS program uses the same Cartesian formulation as ADAMS. One of the big differences between DADS and ADAMS is the method used to obtain information on position, velocity, and acceleration. DADS first computes acceleration, which is then substituted into the numerical integration formula to obtain position and velocity. The iterations continue until a solution tolerance has been satisfied. The

number of iterations was become very large for a stiff system. This enforces a very small step size in numerical integration, and thus a slow simulation. To overcome this kind of difficulty, a BDF algorithm has been adapted.

3) RecurDyn

RecurDyn, which stands for the Recursive Dynamics, has been developed by D.S. Bae and his associates over the last 10 years. It is based on the well-known recursive formulation proposed by Haug and Bae⁽⁴⁸⁾. The original version of the RecurDyn program was developed and applied to the dynamic tension control systems of tracked vehicles. Expansion of the joint and force library, implementation of flexible body dynamics as well as many contact modules have been developed by FunctionBay, Inc.

In contrast with other commercial software programs, the recursive formulation is adopted in generating the equations of motion. Both the velocity transformation method and the recursive formulation use relative coordinates as their generalized coordinates. The velocity transformation method expresses the equations of motion more compactly than the recursive formulation, but it is computationally more expensive. Consequently, the velocity transformation method has been used mainly to develop general-purpose programs, while the recursive formulation has been used mainly to develop special purpose programs.

One of the main achievements of RecurDyn is that it takes advantage of both the notational compactness of the velocity transformation method and the computational efficiency of recursive formulation. In RecurDyn, the equations of motion are derived by using the velocity transformation method in matrix form. Matrix operations in the velocity transformation method are made into a library each of which is implemented as a recursive formula. Thus, the equations of motion are formed and solved recursively by employing the library of recursive formulas.

Body flexibility has become an important design consideration due to the increasing use of light materials and the high speed operation of modern mechanical systems. There are two types of nonlinear flexible body dynamics in RecurDyn. One type covers the rigid body motion of a flexible body which experiences small strain within a body. The deformation is expressed in terms of a linear combination of mode shapes. One of the disadvantages of this approach is the difficulty of selecting proper mode shapes. Poor selection of mode shapes often yields completely wrong solutions. RecurDyn resolves this difficulty by measuring for error. The error measure indicates the relative degree of solution accuracy. If a large error

is observed, the dynamic correction mode may be generated to be included in the deformed mode shapes. The other type of nonlinear flexible body dynamics covers the rigid body motion of an element within a flexible body. A body can be divided into many elements. Since the rigid body motion of an element reference frame with respect to the body reference frame is covered by the generalized coordinates, it is enough for the shape function to include the terms covering small deformation with respect to the element reference frame. The small deformation assumption of an element allows the reuse of well-developed theories and element programs.

RecurDyn's strength is in its customization modules which deal with many contact problems in tracked vehicles and media transportation equipment.

4) AutoDyn7

The AutoDyn7 program is a general purpose multibody dynamics code designed especially for automotive analysis. It was developed by a team of University of Iowa graduates (Prof. Wan-Suk Yoo⁽⁴⁹⁾, Prof. Sang-Sup Kim⁽⁵⁰⁾, Prof. Sung-Soo Kim⁽⁵¹⁾) over a span of five years beginning at 1993. The AutoDyn7 program uses the velocity transformation technique to generate an efficient and systematic formulation. It allows users to carry out kinematic, dynamic, and static analyses and also is capable of performing flexible body analysis.

Equations of motion are derived from Euler-Lagrange equations. Cartesian coordinates are used to model multibody systems in AutoDyn7 for ease of use and reference. However, internally, relative joint coordinates are used in the velocity transformation technique in order to guarantee maximum efficiency. In flexible body analysis, to reduce the number of elastic coordinates, elastic deformations are represented by vibration normal modes and static modes obtained from finite element analysis. A pre-processor, which transforms data from ADAMS or DADS to the AutoDyn7 format, has been developed. A post-processor has also been developed using a Unix graphic environment. Finally, an IP (Intermediate Processor) has been developed to link the MSC/NASTRAN68 or ANSYS5.0 to AutoDyn7^{(52),(53)}.

Special purpose modules for automobiles have been developed to analyze vehicle dynamic characteristics with high efficiency and precision. These special purpose modules have been designed for roads, tires⁽⁵⁴⁾, roll stabilizer bars, leaf springs, bushings, steering linkages, brakes, power trains⁽⁵⁵⁾, contacts⁽⁵⁶⁾, handling evaluations, etc. The road module generates road surface profiles in a spatial domain using a power spectral density function. The derived road surfaces conform to ISO (International Organization for Stan-

dardization) standards as well as classifications proposed by the MIRA (Motor Industry Research Association). A precise model of tire-road interaction is required to analyze dynamic vehicle behavior. Thus, more precise tire modules have been developed based on the theories used in the DADS and ADAMS tire modules⁽⁵⁴⁾.

A mathematical model of the roll stabilizer bar has been also generated to calculate the roll stabilizer bar forces, including the bushing effect. A mathematical leaf spring model has been developed using its shape and material properties. The shape of the leaf spring, the stiffness matrix, and hysteretic data obtained from experimental tests are required to use this module.

After reviewing several standards for ride quality, a ride quality estimation module was developed for the AutoDyn7 program. All proposed ride quality criteria were included. To evaluate performance of the AutoDyn7 program, vehicle modeling and stability analyses are performed under various operating conditions.

4. Comparisons with Multibody Dynamics Research Overseas

In order to compare Korean multibody research to overseas multibody research, recent conferences in Asia, the U.S.A. and Europe will now be summarized.

4.1 U.S.A.

1) The 6th U.S. National Congress on Computational Mechanics (2001)

The Sixth U.S. National Congress on Computational Mechanics (USNCCM VI) was held in Dearborn, Michigan from July 31 to August 4, 2001. At this conference, two multibody dynamics groups were organized. Five sessions were held for the computational multibody dynamics group, and two sessions were offered for the vehicle dynamics and tire modeling group. Forty papers were presented altogether for group I. The session title and the number of papers presented are shown in Table 1. Twenty-nine papers were presented in the field of computational multibody dynamics. Eleven papers were presented in the field of vehicle dynamics and modeling (i.e., Group II). One paper⁽⁵⁷⁾ was presented from Korean researcher in this workshop.

2) 2001 ASME DETC (3rd Symposium on MBD and Vibration)

The 3rd Symposium on Multibody Dynamics and Vibration was held as a special symposium of the 18th Biennial Conference on Mechanical Vibration and Noise at the 2001 ASME International Design Engineering Technical Conference, in Pittsburgh, Pennsylvania from September 9 to 12, 2001. This symposium

Table 1 Papers in group I at USNCCM VI (Computational multibody dynamics)

Group	Topics	No. of Papers
I	Methods and algorithms	6
II	Flexible / stiff systems	5
III	Controls and Locomotion	6
IV	Vehicle dynamics	6
V	Multibody systems	6

Table 2 Papers at multibody symposium in 2001 ASME DETC

Session No.	Session Titles	No. of Papers
1	Vehicle Applications	5
2, 10	Flexible Multibody Dynamics I, II	10
3	Mathematical and Numerical Methods	4
4	Control of Multibody Systems I, II	10
5	Impact and Intermittent Motion	5
6, 11	Multibody Formulations and Algorithms I, II	9
7	Finite Element Applications	5
9	Vibration Problems	4
12	Applications	5

sium was held in honor of the late Richard Schwertasek of DLR Germany. Fifty-seven papers dealing with various subjects were presented at 12 sessions.

The session titles and the number of papers presented are shown in Table 2. Along with finite element applications, flexible multibody dynamics seemed to be the most interesting research subject. This symposium differed from previous ASME multibody symposia in that several Japanese researchers attended. It seems MBD research is becoming popular in Japan. Many papers were also presented from Korean researchers⁽⁵⁸⁾⁻⁽⁶²⁾ and Japanese researchers⁽⁶³⁾⁻⁽⁶⁹⁾.

4.2 Europe

1) NATO's ARW (Advanced Research Workshop) 2000

NATO's Advanced Research Workshop was held in Pultusk, Poland, from July 2 to 7, 2000. The workshop topic was the computational aspects of nonlinear structural systems with large rigid body motion. Computational methods to deal with nonlinear structures experiencing large rigid body motion have been developing for a decade in the finite element community though flexible multibody systems with nonlinear deformations have garnered more attention in MBD society. Although these two different scientific communities have been trying to solve the same problems, they have interacted little. The NATO ARW workshop provided an opportunity for

Table 3 Papers at NATO_ARW (2000)

Group No.	Lecture Subjects	No. of Lectures
1	Flexible Multibody Systems	3
2	Finite Elements Procedures for Structural Systems with Large Rotations	3
3	Numerical Integration Methods for Rigid and Flexible Systems	4
4	Advanced Methods in Systems with Large Rigid Body Motion	4

these two communities to discuss common research interests together for the first time. Prof. Ted Belytschko, Prof. Michael Crisfield, Prof. Michel Geradin, and Prof. Edward Haug collaborated to organize this workshop. About 50 people from 17 countries attended and 14 lectures and 20 other presentations were given during the workshop. Table 3 shows the various lecture subjects as well as the number of lectures presented under each one. Two papers^{(70),(71)} were presented from Korean researchers in this workshop.

2) EUROMECH 427(2001)

Euromech, the European mechanics society, held colloquium 427, which focused on computational techniques and applications in nonlinear dynamics of structures and multibody systems, at the Laboratoire de Mécanique et Technologie in Cachan, France from September 24 to 27, 2001. Seventy-five papers discussing computational techniques, theoretical formulations in structural and multibody dynamics, and engineering applications were presented. At this colloquium, the finite element and flexible multibody communities again gathered to share their expertise, as they had at NATO's ARW 2000. Two papers^{(72),(73)} were presented from Korean researchers in this workshop.

3) NATO's ASI(Advanced Scientific Institute) 2002

NATO's ASI workshop was held at the Czech Technical University, Prague, Czech Republic from June 23 to July 3, 2002. The workshop topic was Virtual Nonlinear Multibody Systems. The related topics were as follows; data model from CAD to multibody dynamics model, parameter identification of multibody systems, optimal design, dynamic strength analysis, contact and impact problems, extension to control and mechatronics, nonholonomic systems, integration schemes, real-time simulation and animation, and challenging applications such as biomechanics, etc. The contents of invited lectures covered formulation and modeling contact problems, wave propagation, ANCF(absolute nodal coordinate formulation) of large deformation, unilateral constraints, model reduction techniques, impacts, non-

linear control, virtual proving ground, graph theory, geometrical interpretation, and optimization of passive and active dynamic systems. Two papers^{(73),(74)} are presented from Korean researchers in this workshop.

4.3 Asia

As was seen in previous sections, European and American researchers have periodically held joint conferences to explore new research areas. However, in Asian, no conference associated with multibody dynamics was held until 2002. In July 2002, the first ACMD(Asian Conference on Multibody Dynamics) meeting convened successfully in Iwaki, Japan. In August 2004, the second ACMD meeting will be convened in Seoul, Korea.

Several selected papers⁽⁷⁶⁾⁻⁽⁸⁶⁾ written by Korean MBD researchers were recently published in several international journals.

5. Concluding Remarks

1) Research trends

Until the 1990s, research on structural dynamics and multibody dynamics proceeded separately. But, when large deformation is considered in the context of flexible multibody dynamics, absolute nodal coordinate formulations are employed, thus narrowing the gap between structural dynamics and flexible multibody dynamics(as shown in Fig.1). Currently, these two fields are using the same applications, though their derivations and governing equations differ greatly.

In Korea, multibody dynamics people dominate flexible multibody dynamics. Up to this point, their connection to structural researchers has been confined to the adaptation of integration schemes. The contributions of multibody researchers in Korea industry are continuing to grow.

2) Future of Korean multibody research

Before 2001, most Korean funds for research in multibody dynamics were linked to the automobile industries, whose primary research interests included kinematic analysis, suspension system design, and vehicle dynamic analysis for ride, handling, and NVH (noise, vibration, and harshness). Recently, however, they have been trying to invest more money in concept vehicles (i.e., electric vehicle or hybrid vehicles). Also, they are becoming more interested in the development of human safety devices (i.e., airbags, side airbags, pre-tensioners, and air curtains). Consequently, it is becoming more difficult to obtain research funds for multibody dynamics from automotive companies.

As their incomes and living standards up, the Korean people and their government are becoming

Fig. 1 Multibody dynamics and structural dynamics

more interested in health and daily life issues. Thus, research related to human welfare and accident prevention should receive big increase in funding in the near future.

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