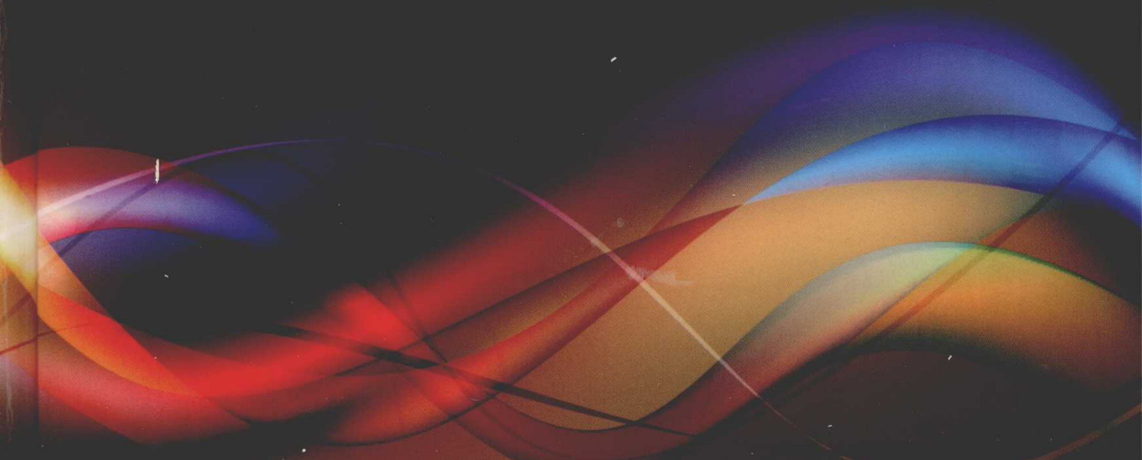
From Waves in Complex Systems to Dynamics of Generalized Continua

Tributes to Professor Yih-Hsing Pao on His 80th Birthday



Editors

Kolumban Hutter · Tsung-Tsong Wu · Yi-Chung Shu

World Scientific

From Waves in Complex Systems to Dynamics of Generalized Continua

Tributes to Professor Yih-Hsing Pao on His 80th Birthday

Editors

Kolumban Hutter (Federal Institute of Technology, Zurich, Switzerland)
Tsung-Tsong Wu (National Taiwan University, Taiwan)
Yi-Chung Shu (National Taiwan University, Taiwan)

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

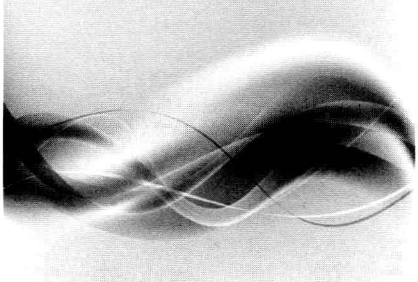
British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

FROM WAVES IN COMPLEX SYSTEMS TO DYNAMICS OF GENERALIZED CONTINUA
Tributes to Professor Yih-Hsing Pao on His 80th Birthday

ISBN-13 978-981-4340-71-7
ISBN-10 981-4340-71-5

Printed in Singapore by World Scientific Printers.

From Waves in Complex Systems
to
Dynamics of Generalized Continua



Tributes to Professor Yih-Hsing Pao
on His 80th Birthday

PREFACE

This book has been assembled from contributions dedicated to Professor Yih-Hsing Pao on the occasion of His 80th birthday, held at the **International Symposium on Engineering Mechanics** on 21/22 May 2010 and organized by the Institute of Applied Mechanics, National Taiwan University, Taipei. It concentrates on reviews and new developments in the fields of **waves in complex systems** and **dynamics of generalized continua**, the two classes of subjects, embracing the more than 50 years of active research to which Professor Pao dedicated his scientific efforts in the field of Applied Mechanics. His scientific achievements and his leading role played as a University teacher and internationally as an educator and researcher are reviewed in the preliminary items of this book in the Laudatio.

The fifteen contributions, which are collected in this book are divided into four groups typified as

- Waves,
- Numerical Methods and Time Series Analyses,
- Continuum Mechanical Theories, and
- Wind Energy Techniques.

Waves are analyzed in the context of Lamb waves in phononic band gap structures and as early time responses in trusses and frames, using the reverberation-ray matrix technique. Wave theory is also applied to surface wave nonlinearities for fatigued steel and as acousto-elastic Lamb waves in implications to structural health monitoring.

Time series analyses are treated by an adaptive data analysis method via a novel so-called Hilbert-Huang Transformation (HHT), which is particularly apt in the characterization of non-stationary statistical processes in a great variety of data through measured digital quantities.

In the subject of numerical **mathematics**, computational fluid dynamics is illustrated with the so-called Unified Coordinates (UC); these are generalizations of the Euler-Lagrange Algorithms (ELA), by which initial boundary value problems can be more effectively solved than with the classical ELAs, since the UCs are optimally and automatically generating boundary adjusted meshes. Moreover, in the fields of seismology and exploration geophysics, imperfectly partitioned ambient wave fields allow retrieval of the Green's function and, thus, yield exact determination of travel times, attenuations, specific intensities and scattering strengths in complex wave fields. A contribution, which applies optimization techniques, shows their use in structural elements, which minimize their size on the basis of periodic micro-structural elements, and inverse techniques are applied to problems in optical sciences.

Methods of advanced continuum-thermo-mechanics are applied to such complex systems as lava flows, in which the aggregation states arise as hot fluids, temperate solid-fluid mixtures at the solidification temperature and as cold solids separated by phase change surfaces and nourished by mass transports across these surfaces, as ternary bio-fluid mixtures and as acoustic and electromagnetic meta-materials, and in electro-magneto-mechanical coupled fields with various postulations of electro-magnetic interaction forces, couples and stress tensors.

Wind energy is, finally, tackled by studying, how nonlinear vibro-wind energy generation competes with its rotational counterpart and how off-shore wind energy can be produced below the costs of coal electricity.

The articles either review a topic or present new developments; but both appeal to experts as well as researchers and practitioners alike.

The editors express their heartfelt thanks to the distinguished international team of contributors whose scientific efforts unite to form this book. They also express thanks to Professor C. C Chang, chairperson of the Institute of Applied Mechanics at National Taiwan University and his staff, in particular Chi-Wei Liu for organizing the conference and to Fong Kiaw Wong at World Scientific Publishing Company for the assistance in editing this book.

Zurich, Switzerland and Taipei, Taiwan, 22. May 2010

K. Hutter, T. T. Wu and Y. C. Shu

CONTRIBUTORS

W. Q. Chen
Zhejiang University, China
chenwq@zju.edu.cn

G. D. Cheng
Dalian University of Technology, China
chenggd@dlut.edu.cn

M. Hirao
The University of Tokyo, Japan
hirao@me.es.osaka-u.ac.jp

N. E. Huang
National Central University, Taiwan
norden@ncu.edu.tw

K. Hutter
Laboratory of Hydraulics, Hydrology and Glaciology, Federal Institute of Technology, Zurich, Switzerland
hutter@vaw.baug.ethz.ch

W. H. Hui
Hong Kong University of Science and Technology, Hong Kong
whhui@ust.hk

J. E. Michaels
Georgia Institute of Technology, U.S.A.
jennifer.michaels@ece.gatech.edu

F. Moon
Cornell University, U.S.A
fcm3@cornell.edu

V. C. Mow
Columbia University, U.S.A
vcm1@columbia.edu

W. W. Symes
Rice University, U.S.A
symes@caam.rice.edu

V. V. Varadan
University of Arkansas, U.S.A
vvvesm@uark.edu

T. T. Wu
National Taiwan University, Taiwan
wutt@spring.iam.ntu.edu.tw

R. L. Weaver
University of Illinois
at Urbana-Champaign U.S.A
r-weaver@illinois.edu

C. S. Yeh
National Taiwan University, Taiwan
csyeh@spring.iam.ntu.edu.tw

X. J. Zheng
Lanzhou University, China
xjzheng@lzu.edu.cn

Conference participants at the entrance of the Institute of Applied Mechanics, National Taiwan University, Taipei, with the jubilee, Professor Y.-H. Pao (seated in the middle, front row)

LAUDATIO FOR PROFESSOR YIH-HSING PAO ON THE OCCASION OF THE INTERNATIONAL SYMPOSIUM ON ENGINEERING MECHANICS 2010, ON THE OCCASION OF HIS 80TH BIRTHDAY (21/22 May 2010)

Kolumban Hutter

Retired Professor of Mechanics, Darmstadt University of Technology, Germany
NOW: c/o Laboratory of Hydraulics, Hydrology and Glaciology
Swiss Federal Institute of Technology, Zurich, Switzerland
E-mail: hutter@vaw.baug.ethz.ch

Dear Professor Pao, dear Mrs Pao,

Respected representatives of the National Taiwan University (NTU) and other Universities, of governmental and scientific agencies of Taiwan and abroad,

Dear Academicians, dear scientists and Professors from Academies and Universities worldwide,

Dear guests and friends of Professor Pao

We have come together here to celebrate Professor Pao on the occasion of his 80th birthday – it was on 19th January 2010 – and to look back and contemplate about him as a personality, a scientist and simply as a human being. We have also come together to pay tribute to a superior, a colleague and a friend with whom some of us have had extensive work interactions, scientific discussions, disagreements, long working sessions in seminar rooms, intellectually, always as equals, but hard and subject oriented and not person oriented, focused on every detail until intellectual agreement was reached. When experiencing this for the first time in 1969 in seminars together with the late Steve Thau, this was for me, the young Swiss student a unique experience for which I first had to take breath to understand that objective scientific arguments could be separated from professional seniority or superiority. At that time, this was not at all so in Swiss academic circles, but I learned quickly! This, however, does not mean that a clear superior-subordinate relationship would not have been respected. I addressed him as 'Professor Pao' and he responded as 'Yes Kolumban!', and this is essentially still so now. However, the creation of absolute unquestioned equality of scientific arguing was my first experience of an attitude of Professor Pao, which I had never experienced before and am still sometimes missing in Europe today.

There is a further early incidence in my academic education which demonstrated Professor Pao's generosity. During the first summer break as a student in the Department of Theoretical and Applied Mechanics at Cornell University, I had a research assistantship with the duty to develop finite difference software on elastic waves in a layered half plane as a subject of my Master of Science thesis. This work dragged on in the following semester with no success. In that fall semester 1969 Professors Pao and Rand had organized a reading seminar on Cole's new book on 'Perturbation Theory'. One chapter dealt with pre-stressed cables with small bending rigidity. We all know the result: Bending effects are strong in the vicinity of built-in supports due to the small flexural stiffness associated with the highest derivative arising in the differential equation, a problem of matched asymptotics. This problem hit me immediately with high heart beating. A year or so before in Switzerland, I was involved with the construction of a concrete bridge with box cross section and skew supports. We had computed the torsional response by use of the Saint Venant theory, but measurements of the stress distribution in the supports of the realized bridge revealed large deviations from the computed twisting moment along the bridge axis, whilst agreement distant from the supports was good. My heart beating in the seminar room at Cornell's Thurston Hall was caused by my immediate recognition that warping torsion due to the cantilever pedestrian paths on each side of the box cross section of the bridge was ignored; it corresponded to the bending effects of the pre-stressed cable in Cole's book, whilst Saint Venant torsion was the analogue of the tension-string effects in the cable.

I went home that Friday in fall 1969, worked day and night through the weekend and presented Professor Pao a drafted manuscript on Monday, asking – but being very scared – whether he would accept this as a basis for a Master's Thesis. He did; the Master's Thesis is from 1970 and the work became my first paper in the Int. J. Solids and Structures in 1971. I was scared because I had failed with the layered media problem and weigh Professor Pao's decision at that time as generosity, because he measured the success and forgot the failing precursor. My experience in Switzerland years before was the opposite.

I have above illustrated *objective professional judgment* and *generosity* as two outstanding features which Professor Pao employs in reaching optimal scientific advancement. *Endurance* in pursuing a chosen approach in reaching intended goals and *vision* for the longer range development into the future of the field of Applied Mechanics are yet other ones. He also believes that first rank achievements, such as the foundation of the Institute of Applied Mechanics at National Taiwan University (NTU), which he founded single-handed and which is based on his long range vision and firm belief: Namely, that Applied Mechanics has important developments to offer to future technology both in education and industrial development of Taiwan on a global scale. He did this contrary to today's army of deans and presidents of Engineering Schools and Universities who closed Departments of Theoretical and Applied Mechanics or Departments of General Engineering Sciences. Such educational units disappeared by and large on the entire Globe. In Germany, the Department of Mechanics at Darmstadt University and the Department of Physical Engineering Sciences at the Technical University in Berlin have been closed. The professors were distributed to more professional engineering departments, and at their retirement were not or have been differently replaced by representatives of professional specialties. In the United Kingdom the Department of Theoretical and Applied Mechanics at Nottingham has been closed, as have the Departments of Theoretical and Applied Mechanics at Cornell University and the University of Illinois at

Urbana-Champaign in the US. In Darmstadt, four Professors now teach statics, dynamics and strength of materials to about 3000 students. (When I was there, we were first 12 and then 8 professors.) There is hardly any time left for specialized courses to form accordingly specialized pupils. Professor Pao's 'endurance and vision' during the foundation period of the Institute of Applied Mechanics at NTU have been very efficient supports for the creation of the institute, and the Institute of Applied Mechanics has already and may further prove to be very valuable for forefront activity not only in the industrial development of Taiwan.

What are Professor Pao's research achievements and how did he pursue research to get where he is now?

There seems to be one main theme. This is '*Waves in complex continuous systems*'. This theme is embellished with variations on '*Dynamics of generalized continua*'. Waves became already the main focus when our jubilee started as a Ph. D. student under the supervision of Professor Raymond D. Mindlin, the American born Russian professor of civil engineering at Columbia University, who is most famous for his work on the derivation of the dynamical plate equations by employing a variational formulation (the Principle of Weighted Residuals) and using Cauchy series expansion of the displacement field in the direction perpendicular to the plate reference plane. He is not only known for his applied work on vibrations of elastic plates, but has also done fundamental work in early Cosserat theories, in vibrations of piezoelectric plates, in which polarization gradients were introduced (for the first time?) to describe deformation-induced birefringence. The graduate student Yih-Hsing Pao was exposed to this environment of fundamental applied physics, in which plates were two-dimensional continua with Cosserat structure, rather than just elements of structural engineering, which could also be loaded by electromagnetic forces, which were subjected to electrical and magnetic dipoles, and when transparent and deformable, could change the polarization of the light. The point I want to make is, that the young engineer Y.-H. Pao wrote his first paper on 'Dispersion of Flexural Waves in an Elastic, Circular

Cylinder' with his advisor, Professor Mindlin, on a classical subject of Applied Dynamics, being immersed in a non-classical work environment. He was exposed to a wealth of other subjects of Applied Physics, where expert knowledge of engineers could be used with tremendous advantage.

It is quite natural to look at Professor Pao's early work in the field of scattering of elastic waves from this point of view. Flexural waves in circular cylinders are the beam or shaft analogue of plates, and circular cylinders are bounded by the simplest quadratic surface. Scattering of elastic waves by spherical and elliptical obstacles and parabolic cylinders involves more complex quadratic surfaces and makes a fantastic playground to study the mathematics of spherical harmonics, Mathieu and parabolic cylinder functions. This was work done with C. C. Mow (1963) and S. A. Thau (1966/67). Also in the sixties, work with K. F. Graff on the influence of couple-stresses on wave reflection and scattering by a spherical cavity (1967) shows Mindlin's tangible influence on dynamics of generalized continua. However, elastodynamics with waves, vibrations, focusing on scattering, diffraction, acoustoelasticity, residual stresses, layered media, generalized ray theory, hyperbolic heat conduction equation, ultrasonic waves and non-destructive testing of materials continued to be Professor Pao's main research activities. Collaborators through the years on these subjects were, among others, R. Gayewski, W. Sachse, V. K. and V. Varadan, F. Ziegler, U. Gamer, T. T. Wu, M. Hirao and Y. S. Wang. Most of these subjects were initiated and formulated in their elements already in the late sixties and early seventies. I participated in 1970-1972 with Professors W. Sachse and J. T. Jenkins in long work-seminars on ultrasonic waves and non-destructive testing. In the summer of 1971 Professors Jenkins, Pao and Sachse and two graduate students, D. K. Banerjee and myself also wrestled with the formulation of a thermodynamic theory of solids close to absolute zero. A hyperbolic heat equation was a necessity, and it turned out that a linearized theory for the coldness – the inverse of the absolute temperature (not the temperature itself) – was the optimal variable for a linearized hyperbolic heat conduction equation. The work merged into D. K. Banerjee's Ph. D dissertation and two papers on thermoelastic waves in dielectric and anisotropic solids. (As a side remark: Dr. I. Luca from Bucharest, Romania who was 2.5 years at Academia Sinica from 2007 to 2009 and worked there on debris flow, continued that work in the 80s as her Ph. D. dissertation under the supervision of Prof Soos in the Mathematics Department of the University of Bucharest).

Waves in plates became the center of activity again in the late seventies and eighties in work with R. L. Weaver and W. J. Parzygnat as waves emerging from point sources and resonating in non-linear vibrations, as propagations of elastic pulses and as inverse source problems with F. Santosa, W. W. Symes, A. N. Ceranoglu and J. E. Michaels. In my opinion, Professor Pao's activity truly deserving the qualification 'waves *in complex systems*' is work on waves in trusses and frames, done in the late nineties to present. The problem of steady vibration of trusses and frames as linear elastic systems is today a standard linear eigenvalue problem. Much more difficult is the analysis of wave propagation in the transient regime (the early time behavior). This research led to the *method of reverberation-ray matrices*, an alternative to the method of transfer matrices, in which a wave arriving at a nodal point of an element of the truss or frame, is distributed among the elements at the nodal point and then propagated in each element to the neighboring nodal points. Work on this subject has been done with D. C. Keh, S. M. Howard, X. Y. Su, J. Y. Tian and W.Q. Chen and is presently on an advanced level to reach commercial exploitation.

Back to the sixties and early seventies, when a brilliant student, F. C. Moon, performed experiments on buckling of magnetoelastic cantilever plates! The early work of F. C. Moon and Professor Pao was also on waves, but the paper 'Magnetoelastic Buckling of a Thin Plate' (1968) was the trigger of a whole surge of Ph. D. dissertations and research articles, and this work is still under way. A fascination of the problem was that electromagnetic forces could generate a quasistatic mechanical instability; the disappointment was that the buckling load predicted by the theory was far off from its measured counterpart in the experiment. The second paper by F. C. Moon and Professor Pao on the subject 'Vibration and Dynamic Instability of a Beam-Plate in a Transverse Magnetic Field' did not fully rectify the discrepancy. A thorough study of the foundations of electro-magneto-mechanics was needed, a theory of

Electrodynamics of Deformable Continua with the flexibility that an arbitrary class of constitutive behavior could be postulated and accordingly reduced to be in conformity with the second law of thermodynamics. A beautiful book by the MIT Professors P. Penfield and H. A. Haus 'Electrodynamics of Moving Media' (1967) led us to the complexities of the electric and magnetic force postulates. They were not the same, depending upon, whether magnetization was constructed by a dipole of magnetic monopoles or an electric current in a closed loop. Another beautiful book by W.F. Brown Jr. 'Magnetolelastic Interactions' (1966) showed us that the separation of electromagnetic short and long range effects could not be established in a unique way. This result says that the electromagnetic body forces (and couples) are not unique and therefore neither are the stresses. This also means that the definition of a magnetoelastic material is subtle. Moreover, since in an elastic material the stress tensor is given by the derivative of the Helmholtz free energy with respect to the strain tensor, two different formulations of magnetoelasticity have only a chance of furnishing the same solution for observables (e.g., the displacement distribution), if the free energies in the two formulations are related to one another in the correct manner.

This discussion shows that the answer to the question whether a certain electromagnetic force postulate is correct, is at last a problem of thermodynamics. Moreover, its discussion in isolation without corresponding stress postulates is futile. The papers by Pao and Yeh 'A Linear Theory of Soft Ferromagnetic Elastic Solids' (1973) and of Pao and Hutter 'Electrodynamics for Moving Elastic Solids and Viscous Fluids' (1974) are concerned with a proper embedding of the thermomechanical and electrodynamic equations in an entropy principle plus a systematic derivation of magnetic body forces and body couples from a dipole model. This latter topic was subsequently deepened by Professor Pao in his famous 1978-article 'Electromagnetic Forces in Deformable Continua', which appeared in *Mechanics Today*. This work has been continued in the last 32 years by many researchers; the final answer is still not given. The problem with the magnetic force models is reviewed in this book by X. Zheng and K. Jin, however, without touching the question of thermodynamic consistency. It is my belief that disagreements between theoretical results and experimental findings which still exist (see X. Zheng & K. Jin, this volume) need a thermodynamic setting to be resolved. The book by K. Hutter, A.A.F. van de Ven 'Field Matter Interaction in Thermoelastic Solids' (1978), in the second edition by K. Hutter, A.A.F. van de Ven and A. Ursescu as 'Field Matter Interaction in Thermoelastic Solids and Viscous Fluids', Springer Verlag (2006) provides a hint.

Let us finish this review with yet another hobby horse of Professor Pao's scientific activities: Variational Principles of Thermomechanics of Continuous Systems. [Professor Pao has long fought to get his work with L. S. Wang published, now, as I am told, in press in the Int. J. of Engr. Sci.] Publishing novel ideas in this topic is almost certainly bound to be condemned to fail. Why is this so? In my opinion, it probably goes back to several centuries of competing relations between the French and the Britons. On an intellectual level the Britons (and today also the Americans) take forces as the fundamental entities to rein the physical world. Geometry is simply the space in which forces live. The French take work or better the power of working as the fundamental entity. For them, the two elements 'force' and 'trajectory', which I now identify with 'geometry', are equal partners. Geometry reins our physical world as much as do forces. This is d'Alembert's Principle: force and geometry are combined as equal partners to define the work which reins the world. Note, after all, the French beheaded the king and founded their democracy. The Britons still have a Queen, and a further King certainly in less than 20 years.

Professor Pao might want to be a king, but his teacher, Professor Mindlin, showed him, how two-dimensional plate equations are obtained from three-dimensional theory. The vehicle to do this is the Principle of Weighted Residuals, essentially nothing else than the power of working, equality between forces (the momentum equations) and geometry (variations of the dual geometric field). It is a fairly trivial step to extend this to other fields, e.g. the energy equation (~force) and variation of temperature (~geometry) and eventually any other quantity with dual deformation field (angular momentum, angular velocity, see the article of P. Germain in SIAM J. Appl. Math., 1973).

This approach is simple and so natural that many scientists treat it as intellectually almost empty. There is no room to make a big fuss about such a natural thing, and this is taken by referees to claim that nothing is new in such a formulation and to reject such papers. The mechanics people in the western world (modulo the French) are "Britons" and will likely reject papers on such variational principles, claiming there is nothing to them. Perhaps you should formulate your variational principles in a setting of general relativity. (Beam theories in a covariant setting of the theory of general relativity do exist!) I am joking now, but if you do so, you might have a chance to get a theoretical physicist as a referee. Physicists know very well since Einstein that the curvature of the space is made by the mass distribution which determines the forces. Here, geometry and forces are true brother and sister.

I nevertheless believe – and I now return to Professor Pao's activities on the Principle of Virtual Power – that this is useful as an alternative to the classical balance law approach. However, success is more likely, if it is applied in the context of generalized continua. The role of the 'forces' is then played by the evolution equations of the subgrid field variables and the 'geometry' is described by dual fields, which need to be invented together with the mathematical properties of the operations which generate a scalar field, representing the 'power of working'. It is obvious that from a viewpoint of inventing field equations including constitutive relations and boundary (jump) condition, it may be easier to guess scalars, rather than tensors. The apparent triviality of the method is then hidden behind the complexity of the physics.

Mention should also be made about Professor Pao's handling of his blindness, due to retinitis pigmentosa, the tunnel vision which started in the eighties and progressed to complete blindness in the late nineties. Apart from his negligence to learn Braillie, it is absolutely amazing and deserves our highest respect and admiration, how he keeps his spirit and intellectual level. This allows him not only to follow forefront research but also to inspire and take part in actual research activity. I have never seen him presenting a talk at a conference since complete blindness, but I am told that it is a well organized event to see how he guides the audience in a GPS manner through his densely filled transparencies, made by one of his aids. Of course, all of this is only possible, because the faculty and staff members of the Institute of Applied Mechanics at the National Taiwan University provide admirable support to an extent