Improved Models for Impact of Viscoplastic Bodies

by

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A thesis submitted in fulfillment of the requirements for the degree of
Doctor of Philosophy

School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS

2018

ACKNOWLEDGEMENTS

Alhamdulillah, all praises to Allah for the strengths and His blessing in completing this thesis. First of all, I am deeply indebted to my supervisor Assoc. Prof. Dr. Khairul Azwan Ismail whose help, stimulating suggestions, knowledge, experience and encouragement that helped me in all times of study. He inspired me greatly to work in this project.

I also wish to express my gratitude to my co-supervisor, Dr Fauziah Mat who has given her support, motivation, constructive comments and suggestions that have contributed to the success of this research. Not forgotten, a special appreciation to my mentor, Dr Afendi Rojan, who was abundantly helpful and offered invaluable assistance and support.

I would also thank to Ministry of Higher Education and Universiti Malaysia Perlis for the financial support for this study under Skim Latihan Tenaga Pengajar Akademik (SLTPA). Sincere thanks to Department of Mechanical Engineering, Faculty of Engineering Technology UniMAP especially to Dr Azwan for the supports of the equipment. Not forgotten, special thanks to the School of Manufacturing Engineering UniMAP, a place where I spent most of my times since the last 4 years to complete this study. In addition, I would also like to express my gratitude to Mr Nabil, Mr Nazmi, Mr Rashid, Mr Hafiz and all my friends especially postgraduate students from School of Manufacturing Engineering for the joy and pain as well as continuous moral supports in completing this study.

Last but not least, my deepest gratitude goes to my beloved parents, Ahmad and Masuri, my mother and father in law, Yasin and Long, my sisters, Masniezar and Masri, my brothers, Hairul and Faizal, and also for all of my family for their loves, prayers and encouragement. Also a special thanks to my wife, Yuziana and my children Fariesh, Fariesya and my 12 days-newborn for their endless love and for being my greatest motivation in completing this study. To those who directly and indirectly contributed to this study, your kindness means a lot to me. May God bless you and grant you happiness and success in every journey you take.

Thank you very much.

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LIST OF ABBREVIATIONS

ABMA	American Bearing Manufacturers Association
COR	Coefficient of restitution
DAQ	Data acquisition
FE	Finite element
FEA	Finite element analysis
FIMS	Fastec InLine Monitoring System
fps	Frame per second
ITF	International Tennis Federation
JIS	Japanese Industrial Standards
MLB	Major League Baseball
ODE	Ordinary differential equation
R&A	The Royal and Ancient Golf Club of St Andrews
USGA	United States Golf Association
2D	Two-dimensions
3D	Three-dimensions

LIST OF SYMBOLS

a	Acceleration at the center of mass of the ball
a_1	Deformation of spring (see z)
a_2	Velocity of spring (see $\dot{z}$)
A	Cross sectional area of ball
c	Damping constant of dashpot
c_p	Speed for plastic stress wave
c_0	Speed for elastic stress wave
C	Intersection point at y-axis
C_D	Drag coefficient
C_1	Contact point of body 1
C_2	Contact point of body 2
dh	Change of distance between the center of ball
dt	Change of time
dz	Deformation of the ball from the center of mass
e	Coefficient of restitution
E	Elastic modulus
E_p	Slope of stress-strain curve in plastic region
E_1	Elastic modulus of body 1 (impactor)
E_2	Elastic modulus of body 2 (target)
E^*	Effective elastic modulus
f	Frequency of ball during impact
f_n	Natural frequency of dynamometer
F	Contact force
F_c	Force at maximum compression phase
F_m	Maximum contact force
F_x	Tangential force in x-axis
F_y	Tangential force in y-axis

F_z	Normal force in *z*-axis
G_1	Center of mass of body 1
G_2	Center of mass of body 2
g	Acceleration due to gravity
h	Distance from datum
h_0	Initial height of the ball at time zero
K_h	Hertzian contact stiffness
K_y	Spring constant
m	Mass
M	Line slope
m_1	Mass of body 1
m_2	Mass of body 2
m^*	Effective mass
n	Nonlinear power exponent
p	Impulse
p_c	Normal impulse for compression phase
p_r	Normal impulse for restitution phase
R	Radius of body
r_1	Position vector from G_1 to C_1
r_2	Position vector from G_2 to C_2
S_y	Yield strength of the softer body
t	Time
t_c	Transition time from compression to restitution phase
t_f	Time at the end of restitution phase
t_y	Time when the deformation of spring reaches yielding point
v_{avg}	Average velocity
v_f	Final velocity
v_i	Initial velocity
v_r	Rebound velocity

v_w	Wind velocity
v_y	Yield velocity of material
v_D	Ball velocity with considering drag effect
v_R	Relative velocity due to air drag
v_T	Impact velocity calculated by energy balance between kinetic and potential energy
v_0	Initial relative velocity
v_1	Initial velocity of body 1
v_2	Initial velocity of body 2
W	Weight of ball
W_c	Work done during compression phase
W_r	Work done during restitution phase
x	Ball's displacement
X	Variable at *x*-axis
$\dot{x}$	Velocity with considering the effect of air drag
y	Relative displacement of dashpot
Y	Variable at *y*-axis
$\dot{y}$	Velocity of dashpot
z	Deformation of spring
z_f	Final deformation of spring
z_m	Maximum spring deformation
z_x	Deformation of spring when the value of F is dropped to $F = F_y$
z_y	Deformation of spring at yielding point
$\dot{z}$	Velocity of spring
$\dot{z}_y$	Velocity of spring at yielding point
α	Deformation of the body
α_m	Maximum deformation of the body
$\dot{\alpha}$	Velocity of the body
δ	Deformation length
δ_c	Deformation at maximum compression phase

δ_f	Final deformation
$\delta_{\max}$	Maximum deformation
δ_p	Permanent deformation after separation
$\dot{\delta}$	Rate of deformation
ζ	Damping factor
κ	Stiffness of spring element
θ	Angle between velocity vector and normal line
σ_y	Yield stress
σ_{y1}	Yield stress of body 1
σ_{y2}	Yield stress of body 2
ρ	Mass density
ρ_A	Air density
ν	Poisson's Ratio
ν_1	Poisson's ratio of body 1
ν_2	Poisson's ratio of body 2
ω_d	Damped constant
ω_0	Undamped constant
γ	Plastic loss factor

Model Penambahbaikan Kesan Hentaman Terhadap Jasad Viskoplastik

ABSTRAK

Hentaman antara dua jasad adalah fenomena kompleks yang sering berlaku dalam pelbagai bidang seperti sukan, automotif, geologi dan sebagainya. Sehingga kini, tugas penambahbaikan model bagi kesan hentaman lebih mencabar kerana teori konstitutif yang sedia ada digunakan dalam mekanik hentaman adalah kurang tepat. Kaedah dedenyut dan momentum telah digunakan sebagai prinsip am untuk menyelesaikan masalah dinamik sebelum ini. Kemudian, model kesan hentaman telah digabungkan dengan menggunakan parameter yang diwakili oleh elemen spring dan/atau daspot di titik sentuhan yang kecil dalam kawasan sentuhan. Melalui kaedah ini, mekanik sentuhan yang berlaku semasa hentaman dalam tempoh yang singkat dapat dikira. Model hentaman ini mengambil kira sifat konstitutif bahan seperti elastik, viskoelastik, elastoplastik atau viskoplastik seperti yang terkandung dalam undang-undang sentuhan pada kawasan termampat yang kecil. Pada kelajuan hentaman yang sangat rendah, model elastik berdasarkan teori sentuhan Hertz dan model viskoelastik Hunt & Crossley dapat menentukan tindak balas hentaman dengan tepat. Namun begitu, pada halaju hentaman yang sederhana atau tinggi, sebahagian besar daripada tenaga kinetik awal telah hilang akibat canggaan plastik, penyebaran gelombang tekanan, bunyi, haba dan kesan-kesan lain. Model elastoplastik boleh digunakan untuk meramal canggaan plastik pada jasad yang dihentam tetapi kesan penyebaran gelombang tekanan tidak dipertimbangkan dalam model ini. Permasalahan ini telah ditangani dengan menggunakan model viskoplastik yang dapat meramalkan tindak balas hentaman dengan mengambil kira canggaan elastik dan plastik serta mengambil kira tenaga yang hilang akibat penyebaran gelombang tekanan. Oleh yang demikian, kajian ini mencadangkan dua model viskoplastik untuk hentaman yang dibangunkan melalui penambahbaikan model viskoplastik terdahulu iaitu Model Yigit dan Model Ismail & Stronge. Model yang dicadangkan ini merupakan kaedah alternatif untuk meramal tindak balas hentaman dengan menggunakan elemen spring secara linear atau menggabungkan elemen spring secara linear dan tidak linear semasa fasa rehat. Selain itu, tindak balas hentaman untuk beberapa jenis bola telah diukur melalui eksperimen ujian hentaman dan analisis unsur terhingga. Dalam eksperimen, pelbagai ujian yang telah dilaksanakan bertujuan untuk memastikan ketepatan pengiraan daya dan halaju bagi hentaman pelbagai jenis bola sukan. Selain itu, model unsur terhingga yang tepat telah dibangunkan dan telah disahkan dengan model unsur terhingga sebelumnya. Dapatan kajian menunjukkan tindak balas hentaman yang diperoleh daripada model-model yang dicadangkan juga telah disahkan melalui eksperimen dan analisis unsur terhingga. Model yang dicadangkan ini dapat menganggar nilai daya maksimum dengan ralat kurang daripada 20 % dan nilai masa pelanggaran dengan ralat kurang daripada 11 %. Model yang dicadangkan ini juga berjaya meningkatkan ketepatan tindak balas hentaman iaitu hentaman normal antara dua komponen yang padat terutamanya untuk kes hentaman elastik. Model yang dicadangkan ini menghasilkan kehilangan tenaga yang paling kecil berbanding model-model terdahulu. Maka, pengiraan daya dan canggaan dapat dikira dengan tepat berbanding model-model viskoplastik yang lain. Selain itu, model unsur terhingga juga telah digunakan untuk mendapatkan tindak balas hentaman bagi bahan, saiz dan halaju hentaman jasad yang berbeza. Secara keseluruhannya, model viskoplastik untuk hentaman yang baru telah dibangunkan dan tindak balas hentaman antara dua komponen telah dikemukakan.

Improved Model for Impact of Viscoplastic Bodies

ABSTRACT

Impact between two bodies is a complex phenomenon commonly occurs in many areas such as sports, automotive, geology and many more. Until now, modeling an impact is still a challenging task due to inherent imprecision of constitutive laws for the impact mechanics. Previously, impulse-momentum method was used as general principle to solve this dynamic problem. Then, impact is modeled by employing a lumped-parameter, which is represented by the spring and/or dashpot elements as a compliance at a small contact region around the point of contact. Through this method, the mechanics of contact during a short interval of impact event can be calculated. Formulation of the model using elastic, viscoelastic, elastoplastic or viscoplastic constitutive material behavior is employed as a contact law for the compliance at the small deforming region. At a very low impact velocity, an elastic model based on Hertz contact theory and the viscoelastic Hunt & Crossley model have accurately predicted impact responses. However, at higher impact velocities, a significant part of the initial kinetic energy is dissipated due to plastic deformation, stress wave propagation, sound, heat and other effects. An elastoplastic impact model can be used to predict the elastic-plastic deformation of the impacted bodies, however the effect of stress wave propagation is not considered in this model. This problem has been addressed by adopting a viscoplastic model that can predict the impact response which encompasses both elastic and plastic deformation and also considers the energy dissipated due to wave propagation. This study proposes two viscoplastic impact models that were developed from modification of previous viscoplastic models; Yigit and Ismail & Stronge models. The proposed model provides an alternative method to predict the impact responses by employing a linear spring element or combining a linear and nonlinear spring element in restitution phase of the compliance. The impact responses for several types of balls have been also studied by drop test experiments and finite element analysis. In experiment, various tests have been conducted to ensure accurate measurements of force and velocity for drops of different sports balls. On the other hand, an accurate finite element model (FE model) was developed and it was validated with previous FE model. As a result, the impact responses obtained from the proposed models have been validated with both experiment and FE analysis. In general, the proposed models can predict the maximum force and contact time with percentage error of less than 20 % and 11 % respectively. The proposed model was successfully improved the accuracy of impact response prediction for normal impact between two compact bodies. For the case of elastic impact, the proposed model gives the smallest energy loss of any of these previous models. Thus, it provides good estimation of contact forces and deformations, compared to the other viscoplastic models. Besides that, the impact responses for impact of different materials, sizes and impact velocities of the body have been obtained from the FE analysis. In overall, new developments for viscoplastic impact model and impact responses for colliding bodies were presented.

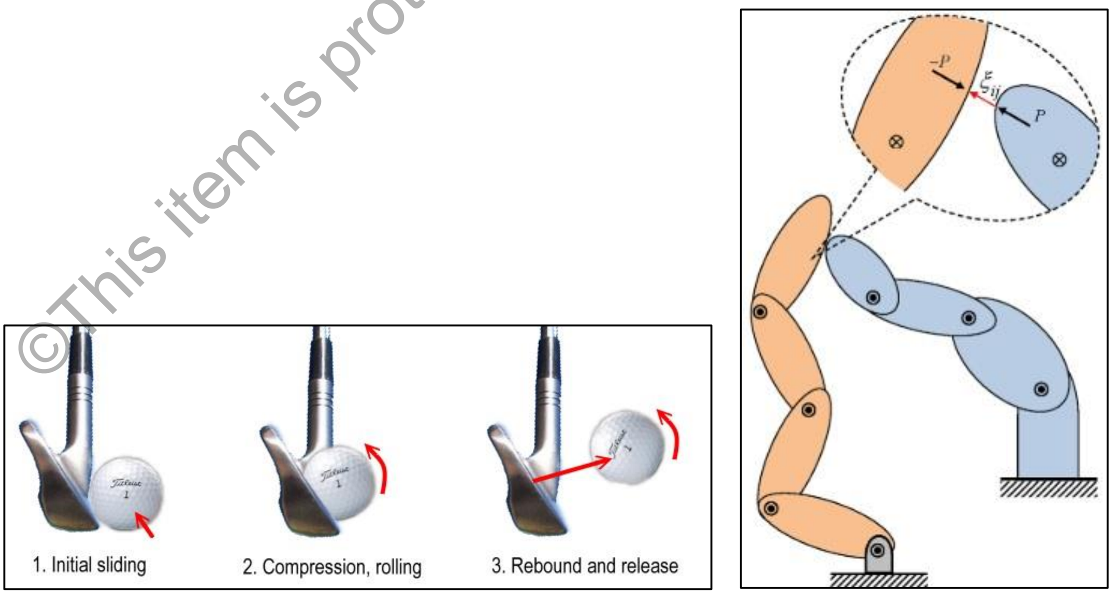
CHAPTER 1: INTRODUCTION

1.1 Background of study

Impact is a complicated phenomenon that occurs when two or more bodies collide at a short time period. During impact, the bodies experience a high force level at very brief duration, while energy is rapidly dissipated and high acceleration and deceleration occurred (Gilardi & Sharf, 2002). The simplest impact application can be shown by human's daily routine, such as knocking a door, drop rubbish into a dustbin and many more. Moreover, impact frequently happened in sports and engineering application, from hitting a ball in a game until crashworthiness of automotive application.

Impulse-momentum method is a conventional method that can be used to measure the impact responses at the end of an impact event. However, this method has several drawbacks, and the most significant is this method unable to predict the impact responses during impact (Gharib & Hurmuzlu, 2012). To overcome this problem, numerous impact models have been introduced by previous researchers (Brake, 2015; Li, Quan, Tang, Li, & Deng, 2017; Thornton, Cummins, & Cleary, 2017). In general, elastic, viscoelastic, elastoplastic and viscoplastic constitutive material behaviors are employed as contact laws in order to form the impact models. Through impact model, the impact responses of the contact bodies during and after collision can be calculated based on their initial parameters. For example, the results of force, deformation, energy loss, impact duration and velocity of the impacted bodies can be measured at any time during impact.

Impact models are widely used to solve the problems in sports engineering (Cross, 2014; Goodwill & Haake, 2001), geology (Ashayer, 2007; Imre, Räbsamen, & Springman, 2008), coal gasification industry (Gibson, Gopalan, Pisupati, & Shadle, 2013), automotive (Batista, 2006), robotic (Vasilopoulos, Paraskevas, & Papadopoulos, 2014) and many more. For example, Figure 1.1 shows example of impact applications where impact models are always utilized in order to obtain the impact responses. Previously, extensive studies have been reported on development and modification of the impact models. However, these impact models have their own limitation and the solution in impact models are not usually straightforward. To address this concern, many researchers are still putting their efforts to develop and modify the impact models in order to improve the current impact models (Argatov, Kachanov, & Mishuris, 2017; Christoforou & Yigit, 2016; Thornton, Cummins, & Cleary, 2017; Yu & Tafti, 2016; Zhang et al., 2016).



(a) (b)

Figure 1.1: Example of impact phenomena where impact models are widely utilized: (a) impact between a golf ball and club head and (b) impact in multibody system (Dave, 2017; Khulief, 2013).

In general, the present study proposes two modified impact models based on viscoplastic constitutive behavior for normal impact between two bodies. The proposed models are compared with previous impact models, experimental and finite element results throughout this thesis.

1.2 Problem statements

According to Brogliato (2016), there are four types of initial impact velocities. Very low and low impact velocities occurred within 0-1 m/s and 1-10 m/s of initial impact velocities, respectively. In addition, high and hyper impact velocities occurred within 10-1000 m/s and 1000-10000 m/s of initial impact velocities, respectively.

In cases where impacts are elastic in nature (i.e. at very low impact velocity and no plastic deformation), an elastic model based on Hertz contact theory and the viscoelastic Hunt & Crossley model have accurately predicted the impact response (Hertz, 1896; Hunt & Crossley, 1975). However, these models are not adequate for most impacts in practice (at higher impact velocities), as a significant part of initial kinetic energy is dissipated due to plastic deformation, wave propagation, and other effects. Therefore, elastoplastic impact models have been developed to account for energy dissipation during impact in both elastic and plastic deformation. However, the effect of stress wave propagation is not considered in this model.

These problems have been addressed by adopting a viscoplastic impact model that can predict the impact response which encompasses both elastic and plastic deformation and also considers the energy dissipated due to wave propagation. Currently, the available viscoplastic model is only valid for low and high impact velocities (Yigit, Christoforou, & Majeed, 2011). Yet, this impact model is not suitable for very low impact velocity as the result of force-deformation relation is inaccurately predicted in this case. Besides that, the works to improve the viscoplastic impact model are still less reported in the previous studies. In general, the research problems can be summarized as follows.

i. Although there are numerous impact models developed in literatures, the choice of an adequate impact model for a certain problem is still an important issue to be considered.

ii. The development of impact models for viscoplastic bodies are still limited in the previous studies.

iii. The available viscoplastic impact models unable to predict accurate impact responses for the case of elastic impact.

1.3 Objectives

The main objective of this research is to develop mathematical impact models for colliding bodies based on viscoplastic constitutive behavior. To achieve the main objective, the sub-objectives are performed as follows.

i. To measure impact responses of colliding bodies by performing drop test experiment.

ii. To validate impact responses from the proposed impact models with experiment, finite element analysis and previous impact models.

iii. To perform parametric studies using validated finite element model for impact of balls at higher impact velocities.

1.4 Scopes

i. Throughout this study, the impact is represented by a collision between several types of ball (sports balls and metallic balls) with a hard body (metal). Moreover, these bodies collide in a normal impact configuration. Thus, the results are only considered in normal direction and the results in the tangential direction can be ignored. In addition, the impact is configured with no initial spin on the balls.

ii. Two mathematical impact models are developed by modification on the previous models. These models are developed based on the viscoplastic constitutive behavior that can be solved analytically or numerically.

iii. In experiment, the ball is dropped on the impacted plate from 10 cm to 110 cm of initial height, which is equivalent to 1.401 m/s and 4.646 m/s of initial velocity, respectively. A high speed camera is used to capture the motion of the balls during impact. Moreover, the force-time curves during impact are measured by a dynamometer located at the bottom of impacted plate. It should be noted that these devices have their own limitations and it is discussed further in Chapters 3 and 5.