

**INVESTIGATION OF DYNAMICS  
PROPERTIES OF DISSIMILAR MATERIALS  
JOINTS PRODUCED BY FRICTION STIR  
WELDING**

**SITI NORAZILA BINTI ZAHARI**

**Master of Science**

**UNIVERSITI MALAYSIA PAHANG**



### **SUPERVISOR'S DECLARATION**

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

---

(Supervisor's Signature)

Full Name : Mohd Shahrir Bin Mohd Sani

Position : Senior Lecturer

Date : 15<sup>th</sup> July 2017

---

(Co-supervisor's Signature)

Full Name : Mahadzir Bin Ishak

Position : Associate Professor

Date : 15<sup>th</sup> July 2017



### **STUDENT'S DECLARATION**

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

---

(Student's Signature)

Full Name : SITI NORAZILA BINTI ZAHARI

ID Number : MMM15001

Date : 15<sup>th</sup> July 2017

**INVESTIGATION OF DYNAMICS PROPERTIES OF DISSIMILAR MATERIALS  
PRODUCED BY FRICTION STIR WELDING**

**SITI NORAZILA BINTI ZAHARI**

Thesis submitted in fulfilment of the requirements  
for the award of the degree of  
**Master of Science**

Faculty of Mechanical Engineering  
**UNIVERSITI MALAYSIA PAHANG**

**JULY 2017**

## **ACKNOWLEDGEMENTS**

All praise belongs to Allah alone, and blessings and peace be upon the final Prophet Muhammad. I thank Allah the Almighty for making my dreams come true. Finally I have completed my thesis for master's degree.

I would like to express my sincere gratitude to my main supervisor, Dr. Mohd Shahrir bin Mohd Sani, for his support, encouragement and supervision throughout the period of this study, which has enabled me to complete my work successfully. I am sincerely thankful for his valuable guidance and contributions towards improving my understanding and giving practical ideas for the testing and analysis. I also would like to thank Assoc. Prof. Dr. Mahadzir bin Ishak as my co-supervisor for his suggestions and cooperation throughout the study.

I am also grateful towards the members of the Advanced Structural Integrity & Vibration Research (ASiVR) focus group for their willingness to exchange knowledge with me besides encouraging me during my study.

My deepest appreciation goes to my beloved parents for all the constant encouragement, care and love, supporting me in every step of the journey. Special thanks to my siblings who were always there for me. Not to forget, a big appreciation to all my friends who are involved either directly or indirectly in helping me to complete the study.

I would like to greatly thank the Ministry of Higher Education (MOHE) and Universiti Malaysia Pahang (UMP) for all the support throughout the period of me completing this study.

May ALLAH bless all of you. Thank you all.

## **TABLE OF CONTENT**

### **DECLARATION**

### **TITLE PAGE**

<b>ACKNOWLEDGEMENTS</b>	ii
-------------------------	----

<b>ABSTRAK</b>	iii
----------------	-----

<b>ABSTRACT</b>	iv
-----------------	----

<b>TABLE OF CONTENT</b>	v
-------------------------	---

<b>LIST OF TABLES</b>	viii
-----------------------	------

<b>LIST OF FIGURES</b>	x
------------------------	---

<b>LIST OF SYMBOLS</b>	xii
------------------------	-----

<b>LIST OF ABBREVIATIONS</b>	xiv
------------------------------	-----

<b>CHAPTER 1 INTRODUCTION</b>	1
-------------------------------	---

1.1 Introduction	1
------------------	---

1.2 Background of Study	2
-------------------------	---

1.3 Significance of Study	4
---------------------------	---

1.4 Problem Statements	4
------------------------	---

1.5 Objectives	5
----------------	---

1.6 Scopes	5
------------	---

1.7 Organization of Thesis	6
----------------------------	---

<b>CHAPTER 2 LITERATURE REVIEW</b>	8
------------------------------------	---

2.1 Welding Technologies in Industry	8
--------------------------------------	---

2.1.1 Friction Stir Welding	9
-----------------------------	---

2.2	Basic Theory of Vibration	11
2.3	Mechanical System – Single Degree of Freedom (SDOF)	13
2.3.1	Undamped and Viscously Damped System	13
2.3.2	Frequency Response	16
2.4	Mechanical System – Multi Degrees of Freedom	18
2.4.1	Eigenvalues, Eigenvectors and Damping Formulation	19
2.5	Finite Element Method (FEM)	21
2.5.1	Review of Structural Joint Modelling	22
2.6	Experimental Modal Analysis	25
2.7	Finite Element Model Analysis and Updating	28
2.7.1	Normal Mode Analysis (SOL 103)	28
2.7.2	Finite Element Model Updating	33
2.8	Summary	40
<b>CHAPTER 3 METHODOLOGY</b>		<b>42</b>
3.1	Introduction	42
3.2	Preparation of Materials	45
3.3	First Stage - Selection of the Ideal Specimen	49
3.3.1	Finite Element Modelling and Analysis	49
3.3.2	Impact Hammer Test	51
3.3.3	Correlation between FEA and EMA Results	55
3.4	Second Stage – Selection of Reliable FSW Joint Modelling	55
3.4.1	Joint Modelling and Analysis	56
3.4.2	Correlation between FEA and EMA Results	60
3.4.3	FE Model Updating	61
3.5	Summary	63

<b>CHAPTER 4 RESULTS AND DISCUSSION</b>	<b>64</b>
4.1    Introduction	64
4.2    Selection of Ideal Specimen	64
4.2.1    Finite Element Analysis of Equivalence Model	65
4.2.2    Impact hammer test	66
4.2.3    FE and Experimental Data Correlation	75
4.3    Selection of Reliable FSW Joints Model for Ideal Specimen	75
4.3.1    Finite Element Analysis Data for Three Joint Modelling Strategies	76
4.3.2    Correlation on FEA of Three Modelling Joints Strategies and EMA Results	77
4.3.3    Model Updating	79
4.4    Summary	93
<b>CHAPTER 5 CONCLUSION</b>	<b>94</b>
5.1    Introduction	94
5.2    Conclusion of the Study	94
5.3    Contribution of the Research	95
5.4    Recommendation for Future Work	96
<b>REFERENCES</b>	<b>97</b>
<b>APPENDIX A</b>	<b>103</b>

## LIST OF TABLES

Table 3.1	Material properties	46
Table 3.2	Welding parameters	49
Table 3.3	Information of impact hammer and accelerometer used in experimental modal testing	55
Table 3.4	Types of rigid elements and their descriptions	56
Table 3.5	Properties of CBAR	59
Table 3.6	Properties of CWELD	60
Table 3.7	Parameters that undergo the sensitivity analysis	62
Table 4.1	Coherence of Specimen E and I (Mag, dB vs Freq, Hz)	67
Table 4.2	FRFs on specimen E and I (Mag, dB vs Freq, Hz)	68
Table 4.3	Natural frequencies of nine specimens	70
Table 4.4	Percentage of error between FEA and EMA for nine specimens	75
Table 4.5	Natural frequencies of three types of joint modelling (FEA)	76
Table 4.6	Finite element mode shapes of FSW welded plate model using different approaches of joint modelling elements	77
Table 4.7	Percentage of error between EMA and FEA for three types of joint modelling	78
Table 4.8	Experimental and finite element mode shapes of FSW welded structure model with different modelling strategies	79
Table 4.9	Sensitivity analysis for five parameters	81
Table 4.10	Percentage of error between FEA and EMA after updating (Case 1)	82
Table 4.11	Sensitivity analysis for Case 1	82
Table 4.12	Percentage of error between FEA and EMA after updating using three updating parameters (Case 2)	83
Table 4.13	Sensitivity analysis for Case 2	83
Table 4.14	Percentage of error between FEA and EMA after updating using three updating parameters (Case 3)	83
Table 4.15	Sensitivity analysis for Case 3	84
Table 4.16	Percentage of error between FEA and EMA after updating using three updating parameters (Case 4)	84
Table 4.17	Sensitivity analysis for Case 4	84
Table 4.18	Percentage of error between FEA and EMA after updating using three updating parameters (Case 5)	85
Table 4.19	Sensitivity analysis for Case 5	85

Table 4.20	Percentage of error between FEA and EMA after updating using two updating parameters (Case 6)	85
Table 4.21	Sensitivity analysis for Case 6	86
Table 4.22	Percentage of error between FEA and EMA after updating using two updating parameters (Case 7)	86
Table 4.23	Sensitivity analysis for Case 7	86
Table 4.24	Percentage of error between FEA and EMA after updating using two updating parameters (Case 8)	87
Table 4.25	Sensitivity analysis for Case 8	87
Table 4.26	Percentage of error between FEA and EMA after updating using two updating parameters (Case 9)	87
Table 4.27	Sensitivity analysis for Case 9	88
Table 4.28	Percentage of error between FEA and EMA after updating using two updating parameters (Case 10)	88
Table 4.29	Sensitivity analysis for Case 10	88
Table 4.30	Percentage of error between FEA and EMA after updating using two updating parameters (Case 11)	89
Table 4.31	Sensitivity analysis for Case 11	89
Table 4.32	Updated values of parameters	92

## LIST OF FIGURES

Figure 2.1	Types of welding processes	8
Figure 2.2	FSW process	9
Figure 2.3	Single degree of freedom	13
Figure 2.4	Multi degrees of freedom	18
Figure 2.5	Impact hammer	26
Figure 2.6	Accelerometer	26
Figure 2.7	Data acquisition (DAQ)	27
Figure 2.8	Roving accelerometer method	28
Figure 2.9	Types of error in FE modelling	34
Figure 2.10	Overview of model updating	35
Figure 2.11	SOL 200 Optimization process	40
Figure 3.1	Flow chart of the study	44
Figure 3.2	Application of FSW in aircraft (substructures),	45
Figure 3.3	FSW welded structure	45
Figure 3.4	Surface finishing process	46
Figure 3.5	Butt joint	47
Figure 3.6	Welding tool	47
Figure 3.7	Backing plate and parallel bar	48
Figure 3.8	Milling machine	48
Figure 3.9	FE model of two plates	50
Figure 3.10	Equivalence nodes	51
Figure 3.11	Worst response with unsuitable hammer tip	52
Figure 3.12	Types of impact hammer tips	52
Figure 3.13	Impact hammer test specimenup	53
Figure 3.14	Experimental model built in post processing software	54
Figure 3.15	RBE2 element	57
Figure 3.16	CBAR element in Nastran	58
Figure 3.17	CBAR element for FSW welded structure	58
Figure 3.18	CWELD element in FE model	59
Figure 4.1	Natural frequencies and mode shapes for equivalence model	65
Figure 4.2	Specimen welded from various parameters (A to I).	69
Figure 4.3	Mode shapes for specimen A	70
Figure 4.4	Mode shapes for specimen B	71

Figure 4.5	Mode shapes for specimen C	71
Figure 4.6	Mode shapes for specimen D	72
Figure 4.7	Mode shapes of specimen E	72
Figure 4.8	Mode shapes of specimen F	73
Figure 4.9	Mode shapes of specimen G	73
Figure 4.10	Mode shapes of specimen H	74
Figure 4.11	Mode shapes of specimen I	74
Figure 4.12	Summary of cases.	90
Figure 4.13	Parameters changes of the welded structure (Case 1)	90
Figure 4.14	Parameters changes of the welded structure (Case 2)	91
Figure 4.15	Parameters changes of the welded structure (Case 3)	91
Figure 4.16	Parameters changes of the welded structure (Case 6)	92

## LIST OF SYMBOLS

$m$	Mass
$k$	Springs coefficient
$c$	Damping coefficient
$c_c$	Critical damping coefficient
$a$	Amplitude
$t$	Time
$\ddot{x}, \ddot{v}, \ddot{u}$	Acceleration
$\dot{x}, \dot{v}, \dot{u}$	Velocity
$x, v, u$	Displacement
$f(t)$	External force
$\omega$	Excitation frequency
$\omega_n, f$	Natural frequency
$x_o$	Initial displacement
$v_o$	Initial velocity
$X, \alpha, \beta$	Non-zero constant
$X_1, X_2$	Arbitrary constant determined by initial conditions
$\xi$	Damping ratio
$f_o$	Forcing excitation amplitude
$x_h$	Homogeneous response
$x_p$	Particular response
$H(i\omega)$	Complex frequency response function
$\theta$	Phase angle
$\{\varphi\}$	Design parameters
<b>M</b>	Mass matrix
<b>K</b>	Stiffness matrix
<b>C</b>	Damping matrix
<b>A</b>	Square matrix
<b>I</b>	Identity matrix

$   $	Determinant
$\lambda$	Eigenvalue
$\lambda_i$	Initial eigenvalue
$\lambda_j^{\text{exp}}$	Experimental eigenvalue
$\phi$	Eigenvector
$w_i$	Weighting coefficient
$J$	Objective function
$\hat{z}_m$	Vector of measurement data
$\hat{z}_j$	Vector of analytical output at $j$ -th iteration
$\hat{\theta}$	Vector of structural parameters
$S_j$	Sensitivity matrix at $j$ -th iteration

## **LIST OF ABBREVIATIONS**

SDOF	Single degree of freedom
MDOF	Multi degree of freedom
DOFs	Degree of freedoms
FE	Finite element
FEM	Finite element method
FEA	Finite element analysis
TWI	The Welding Institute
FSW	Friction stir welding
FRF	Frequency response function
MAC	Modal assurance criterion
CWELD	Spot weld element connector
PWELD	Spot weld element connector property
CBAR	One dimensional beam element - bar
NI-DAQ	National Instrument – Data acquisition system

**INVESTIGATION OF DYNAMICS PROPERTIES OF DISSIMILAR MATERIALS  
PRODUCED BY FRICTION STIR WELDING**

**SITI NORAZILA BINTI ZAHARI**

Thesis submitted in fulfilment of the requirements  
for the award of the degree of  
**Master of Science**

Faculty of Mechanical Engineering  
**UNIVERSITI MALAYSIA PAHANG**

**JULY 2017**

## **ABSTRAK**

Kebiasaannya, aplikasi model unsur terhingga (FE) meluas digunakan dalam meramalkan tindak balas keseluruhan struktur kompleks dengan memerlukan asas pengkomputeran yang tinggi. Dalam usaha untuk mengurangkan masalah penggunaan pengkomputeran yang tinggi, model FE cenderung untuk dibina dengan mengurangkan butiran dengan menggunakan andaian tertentu atau meringkaskan model dengan mengabaikan ciri-ciri tempatan seperti penyambungan. Malangnya, perkembangan ini akan menyebabkan ketidaktepatan model FE terutamanya disebabkan oleh beberapa kesilapan diperkenalkan semasa pembinaan model FE. Oleh itu, pembangunan model FE yang tepat menjadi lebih penting bagi jangkaan dinamik struktur kompleks dengan sambungan dan juga untuk analisis lanjut. Kajian ini akan memberi tumpuan kepada kesilapan tatarajah, yang mana adalah ciri-ciri 'kunci' dalam struktur dikenali sebagai permodelan sambungan yang ketara mempengaruhi sifat dinamik model. Kimpalan geseran kacau (FSW) dengan struktur 'butt joint' dipilih untuk projek ini kerana aplikasinya digunakan sangat meluas dalam industri. Terdapat dua peringkat utama yang terlibat dalam menyiapkan kajian; pemilihan spesimen yang FSW dan strategi pemodelan sambungan yang betul untuk struktur FSW. Untuk peringkat pertama, sembilan specimen spesimen yang mengandungi siri aloy aluminium; AA7075 dan AA6061 telah direka menggunakan pelbagai jenis parameter kimpalan FSW. Dalam usaha untuk mencari specimen yang paling optimum bagi struktur FSW, model unsur terhingga teknik menggunakan kespecimenaraan telah dibangunkan dan analisis mod biasa di MSC Nastran / Patran (SOL 103) yang dilakukan untuk mendapatkan parameter modal (frekuensi tabii dan bentuk mod). Kemudian, korelasi antara keputusan FEA dan EMA disediakan telah dibuat dan spesimen yang sesuai telah dipilih. Peringkat kedua bermula dengan membina tiga jenis pemodelan bersama dalam model FE struktur FSW. Menghubungkan unsur-unsur yang terlibat dalam kajian ini ialah unsur badan tegar Jenis 2 (RBE2), elemen bar (CBAR) dan tempat penyambung unsur kimpalan (CWELD). SOL 103 telah dijalankan ke atas tiga model dan korelasi antara data ramalan modal dan keputusan ujian untuk spesimen yang sesuai dipilih dalam peringkat pertama (specimen E) telah dibuat. Berdasarkan keputusan yang diperolehi, ia menunjukkan bahawa elemen CWELD menunjukkan peratusan ralat lebih rendah iaitu 5.13% berbanding dengan kedua-dua unsur-unsur lain. Elemen CWELD telah dipilih untuk mewakili model kimpalan untuk sendi FSW kerana ramalan tepatnya bentuk mod selain mengandungi parameter pengemaskinian untuk pemodelan kimpalan berbanding model kimpalan lain. Selepas mengemaskini model telah dilakukan, kesimpulan mendapati bahawa parameter mengemaskini paling sensitif adalah E7075, diikuti oleh E6061 dan v<sub>7075</sub>. Specimenelah menunaikan tatacara contoh mengemaskini menggunakan parameter mengemaskini terpilih, ralat purata frekuensi semula jadi untuk model CWELD dikurangkan kepada 4.47 % iaitu 0.66% lebih rendah berbanding sebelum melaksanakan pengemaskinian model.

## ABSTRACT

The finite element (FE) model is broadly used in predicting the overall response of a complex structure with the requirement of highly computational effort. In order to reduce computational problem, FE model tends to be developed by reducing the details using certain assumptions or model simplification by neglecting the local features such as joint. Unfortunately, these developments will result to the inaccuracy of FE model mainly due to some errors introduced during the construction of FE model. Therefore, the development of an accurate FE model of local features becomes more significant for predictions of dynamic behaviours of complex structure with joint and also for further analysis. This study will be focused on the configuration errors, which are the ‘key’ features in structure known as joints modelling which significantly influence dynamic properties of the model. Friction stir welding (FSW) with butt joint configuration joints structure was chosen in this project due to its ability to join similar and dissimilar materials and its growing application in the industries. There are two main stages involved in completing the study; selection of ideal specimen of FSW and reliable joint modelling strategies for FSW structure. For the first stage, nine specimens of specimens containing series of aluminium alloy; AA7075 and AA6061 were fabricated using various types of FSW welding parameters. In order to find the most optimum specimen of FSW plate, the finite element model using equivalence technique was developed and normal mode analysis in MSC Nastran/Patran (SOL 103) was performed to extract the modal parameters (natural frequency and mode shapes). Then, the correlation between FEA and EMA results provided was made and the ideal specimen was chosen. The second stage was started by constructing three types of joint modelling in FE model of FSW structure. Connecting elements that were engaged in this study are rigid body element Type 2 (RBE2), bar element (CBAR) and spot weld element connector (CWELD). SOL 103 was performed on the three models and correlation between prediction modal data and test results for the ideal specimen chosen in the first stage (specimen E) was made. Based on the results obtained, it demonstrates that CWELD element showed lower percentage of error which is 5.13 % compared to the other two elements. CWELD elements were chosen to represent weld model for FSW joints due to its accurate prediction of mode shapes besides containing an updating parameter for weld modelling compared to other weld modelling. After model updating was performed, it was also concluded that the most sensitive updating parameters are E7075, followed by E6061 and v7075. In performing the model updating by using these selected updating parameters, the average error of the natural frequencies for CWELD model reduced to 4.47 % which is 0.66% lower than before performing the model updating.

## REFERENCES

- Abdullah, N. A. Z., Sani, M. S. M., Rahman, M. M. & Zaman, I. 2015. A review on model updating in structural dynamics. *IOP Conference Series: Materials Science and Engineering*, 100, 012015.
- Abu Husain, N., Khodaparast, H. H., Snaylam, A., James, S., Dearden, G. & Ouyang, H. 2010. Finite-element modelling and updating of laser spot weld joints in a top-hat structure for dynamic analysis. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 224, 851-861.
- Abu Hussain, N. 2010. FE modelling and model updating of laser weld joints. University of Liverpool.
- Allemang, R. J. 2003. The modal assurance criterion—twenty years of use and abuse. *Sound and vibration*, 37, 14-23.
- Alvarez, R. D. A., Ferguson, N. & Mace, B. 2014. A robust spot weld model for structural vibration analysis. *Finite Elements in Analysis and Design*, 89, 1-7.
- Arbegast, W. J. 2006. Friction stir welding after a decade of development. *Welding journal*, 85, 28-35.
- Avitabile, P. 2001. Experimental modal analysis. *Sound and vibration*, 35, 20-31.
- Beards, C. 1996. Structural vibration: analysis and damping, Butterworth-Heinemann.
- Berman, A. 1979. Mass matrix correction using an incomplete specimen of measured modes. *AIAA journal*, 17, 1147-1148.
- Bottega, W. J. 2014. Engineering vibrations, CRC Press.
- Brownjohn, J. M. & Xia, P.-Q. 2000. Dynamic assessment of curved cable-stayed bridge by model updating. *Journal of Structural Engineering*, 126, 252-260.
- Bruël, K. 2013. Structural testing: Mechanical mobility measurements.
- Cai, L. W. 2016. Fundamentals of Mechanical Vibrations, Wiley.
- Chen, G. 2001. FE model validation for structural dynamics, University of London.
- Chen, W. & Deng, X. 2000. Performance of shell elements in modeling spot-welded joints. *Finite elements in analysis and design*, 35, 41-57.
- Collins, J. D., Hart, G. C., Haselman, T. K. & Kennedy, B. 1974. Statistical Identification of Structures. *AIAA Journal*, 12, 185-190.
- De Silva, C. W. 2006. Vibration: fundamentals and practice, CRC press.
- Deng, X., Chen, W. & Shi, G. 2000. Three-dimensional finite element analysis of the mechanical behavior of spot welds. *Finite Elements in Analysis and Design*, 35, 17-39.
- Dorbane, A., Mansoor, B., Ayoub, G., Shunmugasamy, V. C. & Imad, A. 2016. Mechanical, microstructural and fracture properties of dissimilar welds produced by friction stir welding of AZ31B and Al6061. *Materials Science and Engineering: A*, 651, 720-733.

- Dostrovsky, S. 1975. Early vibration theory: Physics and music in the seventeenth century. *Archive for History of Exact Sciences*, 14, 169-218.
- Doude, H., Schneider, J., Patton, B., Stafford, S., Waters, T. & Varner, C. 2015. Optimizing weld quality of a friction stir welded aluminum alloy. *Journal of Materials Processing Technology*, 222, 188-196.
- Dracup, B. J. & Arbegast, W. J. 2004. Friction stir welding as a rivet replacement technology. Google Patents.
- Dukkipati, V. R. A. O. & Srinivas, J. 2012. *Textbook of Mechanical Vibrations*, PHI Learning.
- Ewins, D. J. 2000. *Modal testing: theory, practice and application*, Research studies press Baldock.
- Fang, J., Hoff, C., Holman, B., Mueller, F. & Wallerstein, D. Weld modelling with MSC. Nastran. Second MSC Worldwide Automotive User Conference, Dearborn, MI, USA, 2000.
- Fox, R. & Kapoor, M. 1968. Rates of change of eigenvalues and eigenvectors. *AIAA journal*, 6, 2426-2429.
- Friswell, M. & Mottershead, J. E. 1995. *Finite element model updating in structural dynamics*, Springer Science & Business Media.
- Fu, B., Qin, G., Li, F., Meng, X., Zhang, J. & Wu, C. 2015. Friction stir welding process of dissimilar metals of 6061-T6 aluminum alloy to AZ31B magnesium alloy. *Journal of Materials Processing Technology*, 218, 38-47.
- Fu, Z.-F. & He, J. 2001. *Modal analysis*, Butterworth-Heinemann.
- Gaul, L. & Nitsche, R. 2001. The role of friction in mechanical joints. *Applied Mechanics Reviews*, 54, 93-106.
- Gibson, B., Lammlein, D., Prater, T., Longhurst, W., Cox, C., Ballun, M., Dharmaraj, K., Cook, G. & Strauss, A. 2014. Friction stir welding: process, automation, and control. *Journal of Manufacturing Processes*, 16, 56-73.
- Gladwell, G. & Ahmadian, H. 1995. Generic element matrices suitable for finite element model updating. *Mechanical Systems and Signal Processing*, 9, 601-614.
- Grafe, H. 1999. Model updating of large structural dynamics models using measured response functions. University of London.
- Guo, J., Chen, H., Sun, C., Bi, G., Sun, Z. & Wei, J. 2014. Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters. *Materials & Design*, 56, 185-192.
- Heiserer, D., Charging, M. & Sielaft, J. High performance, process oriented, weld spot approach. First MSC Worldwide Automotive User Conference, Munich, Germany, 1999.
- Infante, V., Braga, D., Duarte, F., Moreira, P., de Freitas, M. & de Castro, P. 2016. Study of the fatigue behaviour of dissimilar aluminium joints produced by friction stir welding. *International Journal of Fatigue*, 82, 310-316.

- Inman, D. J. 2001. Engineering Vibration, Prentice Hall.
- Iranzad, M. & Ahmadian, H. 2012. Identification of nonlinear bolted lap joint models. *Computers & Structures*, 96–97, 1-8.
- Jia, Y. & Bai, Y. 2016. Experimental study on the mechanical properties of AZ31B-H24 magnesium alloy sheets under various loading conditions. *International Journal of Fracture*, 197, 25-48.
- Jung, H. 1992. Structural dynamic model updating using eigensensitivity analysis. University of London.
- Kallee, S. 2006. NZ fabricators begin to use friction stir welding to produce aluminum components and panels. *New Zealand Engineering News* (2006, August) TWI [http://www.twi.co.uk/technical-knowledge/published-papers/nz-fabricators-begin-to-use-friction-stir-welding-to-produce-aluminium-components-and-panels-august-2006/\[06.12.12\]](http://www.twi.co.uk/technical-knowledge/published-papers/nz-fabricators-begin-to-use-friction-stir-welding-to-produce-aluminium-components-and-panels-august-2006/[06.12.12]).
- Kasai, H., Morisada, Y. & Fujii, H. 2015. Dissimilar FSW of immiscible materials: steel/magnesium. *Materials Science and Engineering: A*, 624, 250-255.
- Kelly, S. G. 2012. Mechanical vibrations: theory and applications, Cengage Learning.
- Kim, G.-H. & Park, Y.-S. 2004. An improved updating parameter selection method and finite element model update using multiobjective optimisation technique. *Mechanical Systems and Signal Processing*, 18, 59-78.
- Kuratani, F., Okuyama, M., Yamauchi, T. & Washior, S. 2010. Finite element modeling of spot welds for vibration analysis.
- Li, L., Hu, Y. & Wang, X. 2014. Direct way of computing the variability of modal assurance criteria. *Mechanics Research Communications*, 55, 53-58.
- Lin, R. M. & Ewins, D. J. 1994. Analytical model improvement using frequency response functions. *Mechanical Systems and Signal Processing*, 8, 437-458.
- Lohwasser, D. & Chen, Z. 2009. Friction stir welding: From basics to applications, United Kingdom, Woodhead Publishing Limited.
- Maia, N. & Silva, J. 2001. Modal analysis identification techniques. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 359, 29-40.
- Maia, N. M. M. & e Silva, J. M. M. 1997. Theoretical and experimental modal analysis, Research Studies Press.
- Mares, C., Friswell, M. & Mottershead, J. 2002. Model updating using robust estimation. *Mechanical Systems and Signal Processing*, 16, 169-183.
- Masoudian, A., Tahaei, A., Shakiba, A., Sharifianjazi, F. & Mohandesi, J. A. 2014. Microstructure and mechanical properties of friction stir weld of dissimilar AZ31-O magnesium alloy to 6061-T6 aluminum alloy. *Transactions of Nonferrous Metals Society of China*, 24, 1317-1322.

- Mishra, R. S. & Ma, Z. 2005. Friction stir welding and processing. Materials Science and Engineering: R: Reports, 50, 1-78.
- Modak, S. V., Kundra, T. K. & Nakra, B. C. 2002. Comparative study of model updating methods using simulated experimental data. Computers & Structures, 80, 437-447.
- Moore, G. J. 1994. MSC/NASTRAN design sensitivity and optimization: user's guide, version 68, MacNeal-Schwendler Corporation.
- Motterhead, J. & Friswell, M. 1993. Model updating in structural dynamics: a survey. Journal of sound and vibration, 167, 347-375.
- Motterhead, J., Mares, C., Friswell, M. & James, S. 2000. Selection and updating of parameters for an aluminium space-frame model. Mechanical Systems and Signal Processing, 14, 923-944.
- Motterhead, J. E., Link, M. & Friswell, M. I. 2011. The sensitivity method in finite element model updating: a tutorial. Mechanical Systems and Signal Processing, 25, 2275-2296.
- Nandan, R., DebRoy, T. & Bhadeshia, H. 2008. Recent advances in friction-stir welding—process, weldment structure and properties. Progress in Materials Science, 53, 980-1023.
- Nastran, M. 2012. Dynamic Analysis User's Guide. 2012.
- Newton, I. 2005. Newton's laws of motion.
- Niw, C. C., Bakar, A. & Rahim, A. 2007. Finite element modeling of arc welded joints. Jurnal Mekanikal, 15-30.
- Nutakor, C. 2014. Modal testing and numerical modeling of the dynamic properties of layered sheet-steel structure.
- Palm, W. J. 2006. Mechanical vibration, Wiley Online Library.
- Palmonella, M., Friswell, M. I., Motterhead, J. E. & Lees, A. W. 2005. Finite element models of spot welds in structural dynamics: review and updating. Computers & structures, 83, 648-661.
- Qian, F. & Zheng, W. 2017. An evolutionary nested sampling algorithm for Bayesian model updating and model selection using modal measurement. Engineering Structures, 140, 298-307.
- Raghu, S. 2010. Finite Element Modelling Techniques in MSC. Nastran and LS/DYNA, CreateSpace.
- Rao, S. S. & Yap, F. F. 2011. Mechanical Vibrations, Prentice Hall.
- Remennikov, A. & Kaewunruen, S. 2005. Investigation of vibration characteristics of prestressed concrete sleepers in free-free and in-situ conditions. Faculty of Engineering-Papers, 284.
- Ren, W.-X. & De Roeck, G. 2002. Structural damage identification using modal data. II: Test verification. Journal of Structural Engineering, 128, 96-104.

- Rutman, A., Boshers, C., Pearce, L. & Parady, J. Fastener modeling for joining composite parts. Americas Virtual Product Development Conference, 2009. 1-28.
- Sadeesh, P., Kannan, M. V., Rajkumar, V., Avinash, P., Arivazhagan, N., Ramkumar, K. D. & Narayanan, S. 2014. Studies on friction stir welding of AA 2024 and AA 6061 dissimilar metals. Procedia Engineering, 75, 145-149.
- Salvini, P., Vivio, F. & Vullo, V. 2000. A spot weld finite element for structural modelling. International Journal of Fatigue, 22, 645-656.
- Sani, M., Abdullah, N., Zahari, S., Siregar, J. & Rahman, M. Finite element model updating of natural fibre reinforced composite structure in structural dynamics. MATEC Web of Conferences, 2016. EDP Sciences, 03007.
- Sani, M. S. M., Rahman, M. M., Noor, M. M., Kadirkama, K. & Izham, M. H. N. 2011. Identification of Dynamics Modal Parameter for Car Chassis. IOP Conference Series: Materials Science and Engineering, 17, 012038.
- Singh, B. R. 2012. A Handbook on Friction Stir Welding, Lap Lambert Academic Publishing GmbH KG.
- Siringoringo, D. & Fujino, Y. Response Analysis of Yokohama Bay Bridge under the 2011 Great East-Japan Earthquake. Proceedings of the 15th World Conference Earthquake Engineering, 2012.
- Sitton, G. 1997. MSC/NASTRAN basic dynamic analysis user's guide. Macneal-Schwendler Co.
- Thomas, W., Kallee, S., Staines, D. & Oakley, P. 2006. Friction stir welding—process variants and developments in the automotive industry. SAE Technical Paper.
- Thorby, D. 2008. Structural dynamics and vibration in practice: an engineering handbook, Butterworth-Heinemann.
- Ugander, S., Kumar, A. & Reddy, A. S. 2014. Microstructure and Mechanical Properties of AZ31B Magnesium Alloy by Friction Stir Welding. Procedia Materials Science, 6, 1600-1609.
- Wang, P., He, R., Chen, H., Zhu, X., Zhao, Q. & Fang, D. 2015. A novel predictive model for mechanical behavior of single-lap GFRP composite bolted joint under static and dynamic loading. Composites Part B: Engineering, 79, 322-330.
- Yoo, J., Hong, S., Choi, J. & Kang, Y. 2009. Design guide of bolt locations for bolted-joint plates considering dynamic characteristics. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 223, 363-375.
- Yunus, M. A. 2011. Finite element modelling and updating of structure of sheet metal with bolted and welded joints. University of Liverpool.
- Zahari, S. N., Sani, M. S. M., Husain, N. A., Ishak, M. & Zaman, I. 2016a. Dynamic analysis of friction stir welding joints in dissimilar material plate structure. Jurnal Teknologi (Sciences & Engineering), 78, 57-65.

- Zahari, S. N., Zakaria, A. A. R., Sani, M. S. M. & Zaman, I. 2016b. A review on model updating of joint structure for dynamic analysis purpose. MATEC Web Conf., 74, 00023.
- Zhao, Y., Lu, Z., Yan, K. & Huang, L. 2015. Microstructural characterizations and mechanical properties in underwater friction stir welding of aluminum and magnesium dissimilar alloys. Materials & Design, 65, 675-681.
- Zienkiewicz, O. C. & Taylor, R. L. 1989. The finite element method, Vol. 1. McGraw-Hill, London.