TEMPERATURE EFFECT ON DYNAMIC CHARACTERISTICS AND POWER FLOW OF THIN STRUCTURES

OO KYAW NYEIN

UNIVERSITI TEKNOLOGI MALAYSIA

TEMPERATURE EFFECT ON DYNAMIC CHARACTERISTIC AND POWER FLOW OF THIN STRUCTURES

OO KYAW NYEIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

JANUARY 2022

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

With the deep emotions of benevolence and gratitude, I would like to thank my supervisor Prof. Ir. Ts. Dr. Aminudin Bin Haji Abu for giving me the wonderful opportunity to carry out my research work in vibration field under his supervision. Without his continued support and interest, this thesis would not have been successful.

I am also grateful to Japan-ASEAN Integration Fund (JIAF) for funding my Ph.D study. This financial support is highly acknowledged. The research would be difficult to be completed successfully without the assistance from my individuals, who have lent me their helpful hands directly or indirectly.

Unfortunately, it is not possible to list all of them in this limited space. Special thanks go to my parents, teachers, friends, and laboratory mates for their understandings, encouragement, and support.

ABSTRACT

Thin plates are being used in many engineering applications. However, thin plate-like structures face vibration problems and are exposed to high temperature in the different operational conditions. These conditions can cause degradation, and seriously affect the structural integrity, safety, and stability of the structure. Hence, it is extremely important to identify the dynamic characteristics and vibration power flow of the thin structure at different temperatures that indicates the transmission path, position of vibration sources, and sinks. This study examined the potential changes in the dynamic characteristics and vibration power flow of the thin structure at different temperatures. In the first step, experimental and numerical studies of dynamic characteristics and vibration power flow for thin plate were conducted. The thin plate was modelled in Patran software, and modal analysis was performed using MSC Nastran software. Then the experimental modal analysis was conducted to validate the results of the numerical analysis. In the second step, the effects of temperature changes on the dynamic characteristics and vibrational power flow were investigated. A climate chamber room was used to investigate the temperature effect on the dynamic characteristics and power flow. Finally, vehicle exhaust system, actual complex structure, was used for actual life application of vibration power flow at different temperatures. Based on the results, the visualization of vibration power flow and transmission paths were generated at its first four natural frequencies. The changes of vibration power flow of the plate and the exhaust system at different temperatures were generated. The data from both experiment and simulation show a good agreement. The high temperature shifts the natural frequencies to lower frequencies. At 90°C, the first and second modes shifted about 3 Hz, and the third and fourth modes shifted about 5 Hz, lower than those at the normal temperature. The finding indicates the higher the temperature, the lower the frequency shifted. At higher mode, the power flow pattern changed at a certain temperature. In addition, the temperature effect on the dynamic characteristics of the exhaust system is not significant at the lower modes. At the higher mode, the natural frequency is shifted to about 2 Hz when the temperature reaches 270°C. Due to the hanger isolators, the vibration power of the exhaust system reduced overall 19%. The maximum total powers were at 180°C of the exhaust system (without hanger) and 150°C of the exhaust system (with hanger). The results showed that the boundary conditions of the exhaust system could lower the temperature at which the maximum power flow occurs. In sum, the findings on the effect of temperature on dynamic characteristics and vibration power flow are useful to those concerned with minimizing vibration level in engineering components to consider for their design criteria or maintenance process.

ABSTRAK

Plat nipis digunakan dalam pelbagai aplikasi kejuruteraan. Walau bagaimanapun, struktur seperti plat nipis berhadapan dengan masalah getaran dan terdedah kepada suhu tinggi dalam pelbagai keadaan operasi. Keadaan ini boleh menyebabkan degradasi dan mendatangkan keparahan kepada keutuhan struktur, keselamatan dan kestabilan struktur. Oleh itu, sangat penting untuk mengenal pasti ciri dinamik dan alir kuasa getaran plat nipis pada suhu berbeza yang menunjukkan laluan penghantaran, kedudukan sumber getaran, dan sinki. Kajian ini mengkaji potensi perubahan ciri dinamik dan alir kuasa getaran plat nipis pada suhu berbeza. Kajian eksperimen dan kaedah berangka ciri dinamik dan alir kuasa getaran plat nipis dijalankan sebagai langkah pertama. Plat nipis dimodelkan menggunakan perisian Patran dan analisis mod dijalankan menggunakan perisian MSC Nastran. Kemudian analisis mod eksperimen dijalankan untuk mengesahkan keputusan analisis berangka. Dalam langkah kedua, kesan perubahan suhu terhadap ciri dinamik dan alir kuasa getaran telah dikaji. Bilik kebuk iklim digunakan untuk mengkaji kesan suhu terhadap ciri dinamik dan alir kuasa getaran. Akhirnya, sistem ekzos kenderaan, struktur kompleks sebenar, digunakan sebagai aplikasi dunia nyata alir kuasa getaran dengan variasi suhu. Berdasarkan dapatan, pembayangan alir kuasa getaran dan laluan penghantaran dijana pada nilai empat pertama frekuensi tabii. Perubahan alir kuasa getaran plat dan sistem ekzos pada perubahan suhu telah dihasilkan. Data dari kedua-dua eksperimen dan simulasi menunjukkan keserasian. Suhu tinggi menganjak frekuensi asli kepada frekuensi lebih rendah. Pada suhu 90°C, mod pertama dan kedua dianjak sebanyak 3 Hz, mod ketiga dan keempat dianjak sebanyak 5 Hz, lebih rendah dari nilai yang didapati pada suhu purata. Penemuan dari kajian ini menunjukkan semakin tinggi suhu, semakin rendah frekuensi teranjak. Pada mod tinggi, corak alir kuasa getaran berubah pada suhu tertentu. Di samping itu, pengaruh suhu pada ciri dinamik sistem ekzos tidak begitu ketara pada mod yang lebih rendah. Pada mod tinggi, frekuensi asli beranjak sebanyak 2 Hz apabila suhu mencapai 270°C. Disebabkan oleh penggantung pemencil, kuasa getaran sistem ekzos berkurangan sebanyak 19%. Jumlah maksimum kuasa adalah pada suhu 180°C di sistem ekzos (tanpa penggantung) dan suhu 150°C di sistem ekzos (dengan penggantung). Keputusan kajian menunjukkan bahawa keadaan sempadan sistem ekzos boleh menurunkan suhu ketika alir kuasa maksimum terhasil. Kesimpulannya, penemuan berkenaan kesan suhu pada ciri dinamik dan alir kuasa getaran sangat berguna kepada mereka yang berkenaan dengan mengurangkan aras getaran dalam komponen kejuruteraan untuk dipertimbangkan bagi kriteria reka bentuk atau proses penyelenggaraan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

bdf	-	Bulk data file
FRF	-	Frequency Response Function
ICP	-	Integrated Circuit Pezoelectric
IEPE	-	Integrated Electronics Pizo-Electric
MSC	-	MacNeal-Schwendler Corporation
NVH	-	Noise, Vibration, and Harshness
SCADAS	-	Signal Conditioning and Data Acquisition System
SDOF	-	Single Degree of Freedom

LIST OF SYMBOLS

E	-	Modulus of elasticity
ρ	-	Material density
ν	-	Poisson's ratio
F_x	-	Axial force
V_1	-	Shear force in y direction
V_2	-	Shear force in z direction
T	-	Torsion about x
V_i	-	Translational velocities in direction i
V_x,V_y	-	Transverse shear forces
M_x, M_y	-	Bending moments
M_{xy}	-	Twisting moment
F_x, F_y	-	Membrane forces
F_{xy},F_{yx}	-	Membrane shear
ω_i	-	Rotational velocities about axis i
T^*	-	Increased temperature

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, a developed and modern city is usually associated with various mechanical systems, transportation systems and engineering structures, such as manufacturing plants, long-span bridges, rotating machinery, railway systems, automobiles, aircraft, and power generation systems. These structural systems are designed and built according to the industries' requirements and society for national interests such as the infrastructure projects, including production industries that utilize different kinds of machinery, other materials in various forms, and several buildings for production and assembly processes.

In the designing process, the structural systems must be satisfied specific criteria to provide a safe application and management. Generally, making a new structure or product is very time-consuming and cannot be replaced economically. The critical factor is that the designed structure can be utilized within their intended environment and design basis service life. Besides that, the existing structures or machines usually need to be examined for noise, vibration, and harshness (NVH) performance or maintenance or other preventive actions to avoid failure and its aftereffects.

With the advancement of technology, plates with various thickness used in civil work, mechanical, aerospace, naval architecture, and marine engineering applications. However, structures exposed to vibration in several frequencies ranges due to external dynamic loadings such as road surface condition and engine operation for automobiles, railway track conditions for trains, waves for ships, aerodynamic loading, and engine loading for aircraft spacecraft. Thus, it is essential to study the plate's vibration behavior or structure to avoid resonance excited by external forces.

If the structure vibrates at a frequency which is closed to its natural frequency, the vibration amplitude grows significantly. This condition could lead the undesirable consequences such as fatigue, NVH performance deficiency, system malfunctioning, wear, and destruction of mechanical equipment. Therefore, it becomes necessary to understand the dynamic characteristics of the structure such as natural frequency, frequency response function, and mode shape.

Structure-borne sound is the vibrational energy that passes through the dynamically loaded mechanical systems. This energy spread as noise into an acoustic medium. In the study presented by Wohlever and Bernhard [1], vibrational energy travelled along the aeroplane's wing to the main body and radiated into the cabin as sound. Thus, vibrational energy flow becomes an important issue of great interest to engineers concerned with minimizing vibration or noise levels [2].

For structural integrity, minimizing vibration level, dynamic characteristics, and vibrational power flow which indicates power transmission path, positions of sources, and sinks in the structure play an essential role in design and manufacturing processes. Some researchers examined the dominant transfer path to reveal the failure of mechanism [3-6] and to reduce the vibration or noise level [7, 8] based on power flow. Moreover, the vibrational power flow can be used for structural diagnostics such as crack or damage detection and mounted stiffness identification.

The power flow refers to the prediction and measurement of the propagating vibration power within a structure which is defined as the product of the generalized force with the in-phase part of the velocity in the same direction [9]. The power flow can be depicted as a vector which represents magnitude and direction. By utilizing that vector, the power flow map can be plotted. It shows power flow patterns which indicates the location of the power source and sink together with the transmission path. After the power flow has been investigated, the structure can be designed or optimized or controlled the dissipated power as required. Therefore, the vibration power flow becomes the advantageous technique to solve the NVH problems.

In real situations, some structures such as aircraft, space vehicles and automobiles etc., are bearing dynamic loading or external forces and exposed thermal environments across their service life. For instance, high-speed aircraft structures such as wing and rudder bear prolonged severe vibration and harsh aerodynamic heating during long and high-speed flights [10]. Another example is vehicle exhaust systems which are vibrating due to engine operation and road surface condition. After the engine operates a few hours or travels some distance, the vehicle exhaust system becomes hot due to the hot exhaust emission. For most engineering material, increased temperature decreases the structural ability to carry the load by reducing elastic and failure strength properties. The high temperature changes the structure materials' properties, including the modulus of elasticity, Poisson's ratio, and stiffness. These material properties variations may change the structure's dynamic characteristics, such as natural frequency, vibration mode, and vibration power flow. Sattar Mohammadi Esfarjani et al. [11] conducted the first concurrently study of evaluating the effect of temperature changes and considerable damages on the natural frequency. Modal changes produced by environmental temperature can be equivalent or greater than those produced by damage [12]. Therefore, the temperature effect on the dynamic characteristic and power flow of the structure should be investigated numerically and also experimentally.

Since the dynamic characteristics and power flow of the structure is important, obtaining experimental data at high temperature and intense vibration environments becomes necessary for the structure's dynamic characteristic analysis and safety design. However, measuring the structure's vibration parameters in a high-temperature environment or at various temperature conditions is difficult.

1.2 Problem Statement

Nowadays, the various thickness plates are being used in many engineering applications. However, thin plate-like structures face vibration problems and are exposed to high temperature in the different operational conditions such as an engine exhaust-washed structure of the aircraft which are exposed the hot exhaust gas and dynamic loading. These conditions can seriously affect the structural integrity, the safety, and the stability of the structure. Therefore, the accurate determination of the structure's dynamic characteristics at a different temperature or elevated temperature is essential.

To solve the vibration problem of the structure, modal analysis has been usually conducted in the field of vibration research to investigate dynamic characteristics of the structure. Besides, the vibration power flow becomes the recent interest of the most researchers because it can evaluate the location of vibration sources and sinks. It can confirm the vibration transmission paths. Therefore, dynamic characteristics and vibration power flow become important to engineers concerned with structural integrity. Since the power flow can be visualized as the vector plot, clear power flow visualization is required to understand the changes in the power transmission path and identify the location of sources and sinks.

A few researchers have performed the experimental measurement of temperature effect on the dynamic characteristic of the structure using the conventional heating method. The quartz lamp and aluminium box were used in their studies as a heater and an oven [10, 13]. The measuring sensors were hanging from the specimen by the poles. This kind of the experimental setup lessens the accuracy of the frequency response measurement. In addition, it also remains to evaluate the effect of temperature changes on the structure's vibration power flow. Therefore, it becomes current research interest to investigate the temperature effect on the dynamic characteristic and power flow of the plate structure. Moreover, this research is extended to the complex structure (vehicle exhaust system) as a case study to examine the temperature influences on the vibration power of the exhaust system which travels to the vehicle body.

1.3 Aim and Objectives

This research aims to investigate the effect of temperature on the dynamic characteristics and the vibration power flow of a thin structure due to the temperature changes. The following objectives can accomplish the desired goals:

(1) To identify the thin plate's dynamic characteristics and power flow through numerical and experimental modal analysis.

(2) To characterize the vibration power flow path of the thin plate with vector visualization.

(3) To examine the thin plate's vibration power flow changes due to temperature changes numerically and experimentally.

(4) To investigate the changes in vibration power flow of complex structure (exhaust system) at the high-temperature condition.

1.4 Significance of Study

In many practical circumstances, every structure's dynamic characteristics play an essential role in the structure's stability, integrity, durability, and system design. Since plates of various thickness with the advancement of technology are used in civil work, mechanical, aerospace, naval architecture and marine engineering applications, this study will help these industries. Then, vibration power flow indicates the vibrational transmission path, position of sources and sink of vibration in the structure. In this study, the power flow maps were plotted as a vector and streamline plot which can show not only the magnitude and direction of the power but also power transmission paths clearly. This can be used in many industries such as the car floor panel manufacturing to identify where the stiffer rail is required, etc. It can also be utilized for structural diagnostics such as crack or damage detection and mounted stiffness identification.

The temperature influences on dynamic characteristics and vibration power flow of structure are identified in this study. Some structures such as high-speed aircraft and automobile exhaust systems bear prolonged severe vibration and temperature variation during service life. This study evaluated the effectiveness of the hanger isolators of the exhaust system and the temperature effect on the power flow at the hanger locations. This method can also be used as a tool to determine hanger locations. The increased temperature decreases the structural ability of the structure by reducing both elastic property and failure strength. A design engineer or engineer who concerned with minimizing vibration or noise level can decide whether temperature effect is necessary to consider for their design criteria or maintenance process. It could benefit the manufacturing industries and the structure that is bearing dynamic loading and thermal loading simultaneously. Then, it would be the most significant contribution of this study.

1.5 Scope of Study

This study focusses on the temperature effect on the dynamic characteristic and power flow of the structure. The following are the scope of this study

(a) The heat transfer process such as conduction, convection and radiation through the specimen or specimen and its surrounding were not calculated because the interest of this study is only the different temperature of the plate.

(b) A thermal chamber was used to create the required temperature of the plate.

(c) All materials used in this study were assumed as isotropic material.

(d) The elevated temperature in the experiment was considered up to 90℃ to be safe of accelerometers and impendence sensor.

(e) For the exhaust system, the effect of the flexible bellow and internal construction of the muffler were ignored.

1.6 Outline of Thesis

This thesis consists of five chapters. In the first chapter, the background of the study is briefly discussed. Then, problem statement and objectives of the research are identified. After that scope and significances of the study are discussed. Chapter two mainly describes the literature review which consists of a review of earlier works of vibration power flow, temperature effect on dynamic characteristics, and automobile exhaust system. Besides, fundamental theory of vibration and power flow are discussed. In Chapter three, the research methodology of the present study is introduced. The experimental works which consist of the experimental apparatus, setup, and procedures are explained. Then, the numerical analysis which was performed in MSC Patran/Nastran is discussed. The results are discussed in Chapter four. In this chapter, the model validation of the plate and the exhaust system is described first. Then, the dynamic characteristics and power flow of the plate are discussed and follows the investigation of the temperature effect. In addition, the temperature effect on the dynamic characteristics and power flow of the exhaust system are examined. This evaluates how much power variation due to the increased temperature which travel to the vehicle body. Chapter five describe the conclusion which are drawn for the results of the present study. Then the significance contribution and the recommendations for future research presented.

REFERESNCES

1. Wohlever, J. C. and Bernhard, R. J. Vibrational Power Flow Analysis of Rods and Beams. Structural Mechanics 1988(19880020767):1-179.
2. Wohlever, J. C. and Bernhard, R. J. Mechanical Energy Flow Models of Rods and Beams. Journal of Sound and Vibration. 1992;153(1):1-19.
3. Lee, S. K. Identification of a Vibration Transmission Path in a Vehicle by Measuring Vibrational Power Flow. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2004;218(2):167-75.
4. Baoping, Z. and Zhenyue, M. Path Transmissibility Analysis Considering Two Types of Correlation in Hydropower Stations. Journal of Applied Mathematics. 2013:9.
5. Huang, W., Sun, H., Hongyin, D. and Wang, W. Study of Transfer Path of Wind Turbine Gearbox Fault Vibration Signal Based on Power Flow Finite Element Method. Advances in Mechanical Engineering. 2017;9(5):1687814017703899.
6. Liu, Z., Yuan, S., Xiao, S., Du, S., Zhang, Y. and Lu C. Full Vechicle Vibration and Noise Analysis Based on Substructure Power Flow. Shock and Vibration. 2017.(2017):1-17.
7. Noori, B., Arnau Clot, R. A. and Romeu, J. Study the Efficiency of Dynamic Vibration Absorbers in Minimizing Vibration Power Flow Radiated from a Double-Deck Tunnel. the 45th International Congress and Exposition on Noise Control Engineering, INTER-NOISE 2016; Hamburg, Germany2016.
8. Rejab, M. N. A., Abdul Shukor, S. A., Mohd Sofian, M. R., Inayat-Hussain, J. I., Nazirah, A. and Asyraf, I. Evaluation of The Effectiveness of Elastomeric Mount Using Vibration Power Flow and Transmissibility Methods. IOP Conference Series: Journal of Physics. 2017.
9. Vuye, C., Guillaume, P., Vanlanduit, S., Presezniak, F. and Steenackers, G. Determining the Power Flow in a Rectangular Plate Using a Generalized Two-Step Regressive Discrete Fourier Series. Journal of Vibration and Acoustics. 2012;134(6):061007-9.

10. Zhao, S. G., Wang, Y. W., Wu, D. F., Pu, Y. and Shang L. Experimental Research on Thermal-Vibration for Composite Trilaminated Wing Structure. Advanced Materials Research. 2014;1061-1062:799-805.
11. Esfarjani, S. M., Salehi, M. and Ghassemi A. Effect of the Multiple Damages and Temperature Chnages on the Natural Frequency. Journal of Theoretical and Applied Mechanics. 2017;55(3):11.
12. Meruane, V. and Heylen, W. Structural Damage Assessment under Varying Temperature Conditons. Structural Health Monitoring. 2011;11(3).
13. Snyder, H. T. and Kehoe, M. W. Determination of the effects of heating on modal characteristics of an aluminum plate with application to hypersonic vehicles. NASA Technical Memorandum 4274. 1991.
14. Pinnington, R. J. and White, R. G. Power Flow Through Machine Isolators to Resonant and Non-Resonant Beams. Journal of Sound and Vibration. 1981;75(2):179-97.
15. Cuschieri, J. M. Structural Power-Flow Analysis Using a Mobility Approach of an L-Shaped Plate. Journal of The Acoustical Society of America - J ACOUST SOC AMER. 1990;87:1159-65.
16. Cuschieri, J. M. and McCollum, M. D. In-Plane and Out-of-Plane Waves' Power Transmission Through an L-Plate Junction Using the Mobility Power Flow Approach. The Journal of the Acoustical Society of America. 1996;100(2):857-70.
17. Wang, Z. H., Xing, J. T. and Price, W. G. An Investigation of Power Flow Characteristics of L-Shaped Plates Adopting a Substructure Approach. Journal of Sound and Vibration. 2002;250(4):627-48.
18. Hambric, S. A. Power Flow and Mechanical Intensity Calculations in Structural Finite Element Analysis. Journal of Vibration and Acoustics. 1990;112(4):542-9.
19. Ahmida, K. M. and Arruda, J. R. F. Spectral Element-Based Prediction of Active Power Flow in Timoshenko Beams. International Journal of Solids and Structures. 2001;38(10):1669-79.
20. Chen, X. L. and Sheng, M. P. Research on Vibration Characteristicsof L-Shaped Plate Using a Mobility Power Flow Approach. Journal of Marine Science and Application. 2007;6(3):12-6.

21. Song, J. H., Hong, S. Y., Kang, Y. and Kil, H. G. Vibrational Energy Flow Analysis of Penetration Beam-Plate Coupled Structures. Journal of Mechanical Science and Technology. 2011;25(3):567-76.
22. Zhu, C., Yang, J. and Rudd, C. Vibration transmission and power flow of laminated composite plates with inerter-based suppression configurations. International Journal of Mechanical Sciences. 2021;190:106012.
23. Dai, W. and Yang, J. Vibration transmission and energy flow of impact oscillators with nonlinear motion constraints created by diamond-shaped linkage mechanism. International Journal of Mechanical Sciences. 2021;194:106212.
24. Xu, D., Du, J. and Zhao, Y. Flexural vibration and power flow analyses of axially loaded beams with general boundary and non-uniform elastic foundations. Advances in Mechanical Engineering. 2020;12(5):1687814020921719.
25. Xu, D., Du, J. and Tian, C. Vibration Characteristics and Power Flow Analyses of a Ship Propulsion Shafting System with General Support and Thrust Loading. Shock and Vibration. 2020;2020:3761590.
26. Shi, B. and Yang, J. Quantification of vibration force and power flow transmission between coupled nonlinear oscillators. International Journal of Dynamics and Control. 2020;8(2):418-35.
27. Dai, W., Yang, J. and Shi, B. Vibration transmission and power flow in impact oscillators with linear and nonlinear constraints. International Journal of Mechanical Sciences. 2020;168:105234.
28. Li, T. Y., Liu, J. X. and Zhang, T. Vibrational Power Flow Characteristics of Circular Plate Structures with Peripheral Surface Crack. Journal of Sound and Vibration. 2004;276(3):1081-91.
29. Zhu, X., Li, T. Y., Zhao, Y. and Liu JX. Structural Power Flow Analysis of Timoshenko Beam with an Open Crack. Journal of Sound and Vibration. 2006;297(1):215-26.
30. Tufoi, M., Gillich, G. R., Praisach, Z. I., Ntakpe, J. L. and Hatiegan, C. An Analysis of the Dynamic Behavior of Circular Plates from a Damage Detection Perspective. Romanian Journal of Acoustics & Vibration. 2014;11(1):6.
31. Praisach, Z. I., Micliuc, D. M., Gillich, G. R. and Korka Z. I. Natural Frequency Shift of Damaged Circular Plate Clamped All Around. Annals of the Faculty

of Engineering Hunedoara - International Journal of Engineering. 2016;14(4):57-62.

32. Zhu, X., Li, T. Y., Zhao, Y. and Yan, J. Vibrational Power Flow Analysis of Thin Cylindrical Shell with a Circumferential Surface Crack. Journal of Sound and Vibration. 2007;302(1):332-49.

33. Wang, X. Q., Wong, W. O. and Cheng, L. Modal Power Flow with Application to Damage Detection. International Journal of Engineering Science. 2009;47(4):512-23.

34. Li, T. Y., Zhu, X., Zhao, Y. and Hu, X. The Wave Propagation and Vibrational Energy Flow Characteristics of a Plate with a Part-Through Surface Crack. International Journal of Engineering Science. 2009;47.

35. Zhao, Y., Wang, Y. Y. and Ma W. L. Active Control of Power Flow Transmission in Complex Space Truss Structures Based on the Advanced Timoshenko Theory. Journal of Vibration and Control. 2015;21(8):1594-607.

36. Wu W, Yin X, Li, Hui, Zhong K. Power Flow Analysis of Built-Up Plate Structures Using the Dynamic Stiffness Method. Journal of Vibration and Control. 2018;24(13):2815-31.

37. Zhang, X., Wu, J. W. and Lin, Z. M. Characteristics Analysis of the Vibration Power Flow in a Simply Supported Laminate Composite Plates. Applied Mechanics and Materials. 2014;633-634:1174-8.

38. Ullmann, R., Sicklinger, S., Buchschmid, M. and Müller G. Power-Based Approach for Assessment of Structure-Borne Sound in Mechanical Networks of Vehicle Structures. Procedia Engineering. 2017;199:1386-91.

39. Silva, O. M., Neves, M. M., Jordan, R. and Lenzi, A. An FEM-based method to evaluate and optimize vibration power flow through a beam-to-plate connection. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2017;39(2):413-26.

40. Liu, C. C., Li, F. M., Liang T. W. and Huang, W. H. The Wave and Vibratory Power Transmission in a Finite L-Shaped Mindlin Plate with Two Simply Supported Opposite Edges. Acta Mechanica Sinica. 2011;27(5):785.

41. Qiao, B., Zhao, T., Chen, X. and Liu, J. The Assessment of Active Vibration Isolation Performance of Rotating Machinery Using Power Flow and Vibrational Energy: Experimental Investigation. Proceedings of the Institution

of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2016;230(2):159-73.

42. Eck, T. and Walsh, S. J. Measurement of Vibrational Energy Flow in a Plate with High Energy Flow Boundary Crossing Using Electronic Speckle Pattern Interferometry. Applied Acoustics. 2012;73(9):936-51.

43. Navazi, H. M., Nokhbatolfoghahaei, A., Ghobad, Y. and Haddadpour, H. Experimental measurement of energy density in a vibrating plate and comparison with energy finite element analysis. Journal of Sound and Vibration. 2016;375:289-307.

44. Mandal, N. K., Rahman, R. A. and Leong, M. S. Experimental Investigation of Vibration Power Flow in Thin Technical Orthotropic Plates by the Method of Vibration Intensity. Journal of Sound and Vibration. 2005;285(3):669-95.

45. Khun, M. S., Lee, H. P. and Lim, S. P. Structural Intensity in Plates with Multiple Discrete and Distributed Spring–Dashpot Systems. Journal of Sound and Vibration. 2004;276(3):627-48.

46. Li, Y. J. and Lai, J. C. S. Prediction of Surface Mobility of a Finite Plate with Uniform Force Excitation by Structural Intensity. Applied Acoustics. 2000;60(3):371-83.

47. Cieślik, J. and Bochniak, W. Vibration Energy Flow in Welded Connection of Plates. Archives of Acoustics. 2006;31(4(S)): 53-8.

48. Bochniak, W. and Cieślik, J. Uncertainty in Vibration Energy Flow Analysis. Archives of Acoustics. 2005;30(4):451-63.

49. Sparavigna, A. and Montrucchio, B. Vector Field Visualization With Streamlines. In: Physics Department, Control and Computer Engineering Departmetn PdT, editors. Italy2006.

50. Xu, X. D., Lee, H. P., Lu, C. and Guo J. Streamline Representation for Structural Intensity Fields. Journal of Sound and Vibration. 2005;280:449-54.

51. Fawazi, N., Jeong, U. C. and Oh, J. E. Improved Transmission Path Visualization of Vibration Power Flow for Stiffened Plate Using Streamlines Representation. Transactions of the Korean Society for Noise and Vibration Engineering. 2012;22(7).

52. Wang, B., Li, D. X., Jiang, J. P. and Liao, Y. H. A Judging Principle of Crucial Vibrational Transmission Paths in Plates. Journal of Sound and Vibration. 2016;380:146-64.

53. Pires, F., Muyshondt, P. G. G., Keustermans, W., Vanlanduit, S., Roozen, N. B. and Dirckx J. J. J. Structural Intensity Analysis of Flat Plates Based on Digital Stroboscopic Holography Measurements. Journal of Sound and Vibration. 2018;428:168-78.

54. Li, K., Li, S. and Zhao, D. Y. Investigation on Vibration Energy Flow Characteristics in Coupled Plates by Visualization Techniques. Journal of Marine Science and Technology. 2010;18(6):8.

55. Park, Y. H. Energy Flow Analysis of Out-of-Plane Vibration in Coplanar Coupled Finite Mindlin Plates. International Journal of Naval Architecture and Ocean Engineering. 2015;7(1):174-94.

56. Chen, Y., Jin, G. and Liu, Z. Vibrational Energy Flow Analysis of Coupled Cylindrical Shell-Plate Structure with General Boundary and Coupling Conditions. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2015;229(10):1727-44.

57. Chen, Y. H., Jin, G. Y., Du, J. T. and Liu, Z. G. Power Transmission of Two Coupled Rectangular Plates with Elastically Restrained Coupling Edge. Key Engineering Materials. 2011;450:71-4.

58. Chen, Y. H., Jin, G. Y., Du, J. T. and Liu, Z. G. Power Transmission Analysis of Coupled Rectangular Plates with Elastically Restrained Coupling Edge Including In-Plane Vibration. 29th International Congress on acoustic, ICA Sudney, Australia2010.

59. Xu, H. A. and Li, W. L. Vibration and Power Flow Analysis of Periodically Reinforced Plates. Science China Technological Sciences. 2011;54(5):1141-53.

60. Petrone, G., De Vendittis, M. and De Rosa, S. Franco F. Numerical and Experimental Investigations on Structural Intensity in Plates. Composite Structures. 2016;140:94-105.

61. Akbulut, Y. E., Altunişik, A.C., Başağa, H. B., Mostofi, S., Mosallam, A. and Wafa, L. F. Elevated Temperature Effect on the Dynamic Characteristics of Steel Columns and Frames. International Journal of Steel Structures. 2021;21(3):861-82.

62. Akbulut, Y. E., Altunisik, A. C., Başağa, H. B., Mostofi, S., Mosallam, A. and Wafa, L. F.. Numerical investigation on dynamic characteristics changes of RC

columns and frames under elevated temperature. Computers and Concrete. 2021;28(2):149-87.

63. Zu, X., Wu, H., Lv, H., Zheng, Y. and Li, H. An Amplitude- and Temperature-Dependent Vibration Model of Fiber-Reinforced Composite Thin Plates in a Thermal Environment. Materials (Basel). 2020;13(7):1590.

64. Haţiegan, C., Gillich, G. R., Popovici, G. and Haţiegan L. The Influence of Temperature Changes on the Eigen - Frequencies and Mode Shapes for Rectangular Plates Clamped on the Contour. International conference Knowledge-Based Organization2017. p. 168.

65. Alshorbagy, A. E. Temperature Effects on The Vibration Characteristics of a Functionally Graded Thick Beam. Ain Shams Engineering Journal. 2013;4(3):455-64.

66. Gupta, A. K. and Mamta, J. Effect of Exponentail Temperature Variation on Frequencies of a Rectangular Plate of Non-Linear Varying Thickness. Asian Journal of Applied Sciences. 2013;01(01):8-15.

67. Gupta, A. K. and Mamta, J. Exponential Temperature Effect on Frequencies of a Rectangular Plate of Non-Linear Varying Thickness: A Quintic Spline Technique . Theoretical And Applied Mechanics. 2014;52(1):15-24.

68. Janghorban, M. and Zare, A. Thermal Effect on Free Vibration Analysis of Functionally Graded Arbitrary Sraight-Sided Plates with Different Cutourts. Latin American Journal of Solids and Structures. 2011;8:245-57.

69. Han, J., Yu, K., Li, X. and Zhao, R. Modal Density and Mode Counts of Sandwich Panels in Thermal Environments. Composite Structures. 2016;153:69-80.

70. Li, X., Yu, K., Han, J., Song, H. and Zhao, R. Buckling and Vibro-Acoustic Response of the Clamped Composite Laminated Plate in Thermal Environment. International Journal of Mechanical Sciences. 2016;119:370-82.

71. Vangipuram, P. and Ganesan, N. Buckling and Vibration of Rectangular Composite Viscoelastic Sandwich Plates under Thermal Loads. Composite Structures. 2007;77(4):419-29.

72. Kong, X. H. and Wang, Z. J. Thermally Induced Vibration Analysis of Composite Laminate Based on Equivalent Displacement Method. Applied Mechanics and Materials. 2014;576:87-93.

73. Prakash, T. and Ganapathi, M. Asymmetric Flexural Vibration and Thermoelastic Stability of FGM Circular Plates Using Finite Element Method. Composites Part B: Engineering. 2006;37(7):642-9.

74. Wu, Y., Yu, K., Yang, L., Zhao, R., Shi, X. and Tian K. Effect of Thermal Stresses on Frequency Band Structures of Elastic Metamaterial Plates. Journal of Sound and Vibration. 2018;413:101-19.

75. Pourasghar, A. and Chen, Z. Thermoelastic Response of CNT Reinforced Cylindrical Panel Resting on Elastic Foundation Using Theory of Elasticity. Composites Part B: Engineering. 2016;99:436-44.

76. Malik, P. and Kadoli, R. Thermo-Elastic Response of SUS316-AL2O3 Functionally Graded Beams Under Various Heat Loads. International Journal of Mechanical Sciences. 2017;128-129:206-23.

77. Wang, D., Xie, M. and Li, Y. High-Frequency Dynamic Analysis of Plates in Thermal Environments Based on Energy Finite Element Method. Shock and Vibration. 2015;2015:14.

78. Tran, T. Q. N., Lee, H. P. and Lim, S. P. Structural Intensity Analysis of Thin Laminated Composite Plates Subjected to Thermally Induced Vibration. Composite Structures. 2007;78(1):70-83.

79. Mahi, A., Adda Bedia, E. A., Tounsi, A. and Mechab, I. An Analytical Method for Temperature-Dependent Free Vibration Analysis of Functionally Graded Beams with General Boundary Conditions. Composite Structures. 2010;92(8):1877-87.

80. Kazanci, Z. and Mecitoglui, Z. Flutter Analysis of A Laminated Composite Plate with Temperature Dependent Material Properties. International Journal of Aeronautical Science & Aerospace Research (IJASAR) 2016;3(3):106-14

81. Zhang, W., Chen, H., Zhu, D. and Kong, X. The Thermal Effects on High-Frequency Vibration of Beams Using Energy Flow Analysis. Journal of Sound and Vibration. 2014;333(9):2588-600.

82. Baptista, F. G., Budoya, D. E., De Almeida, V. A. and Ulson, J. A. An Experimental Study on the Effect of Temperature on Piezoelectric Sensors for Impedance-Based Structural Health Monitoring. Sensors (Basel, Switzerland). 2014;14(1):1208-27.

83. Zhang, X., Yu, K., Bai, Y. and Zhao, R. Thermal Vibration Characteristics of Fiber-Reinforced Mullite Sandwich Structure with Ceramic Foams Core. Composite Structures. 2015;131:99-106.
84. Wu, D., Wang, Y., Shang, L., Wang, H. and Pu, Y. Experimental and computational investigations of thermal modal parameters for a plate-structure under 1200°C high temperature environment. Measurement. 2016;94:80-91.
85. Bajza SndSB. Auto Repair: The Exhaust System. [Available from: http://www.military.com/off-duty/autos/auto-repair-the-exhaust-system.html (Accessed 20 December 2018).
86. Your Car Exhaust System Explained 2011 [Available from: http://www.autorepairkey.com/2011/06/your-car-exhaust-system-explained/ ((Accessed 20 December 2018).
87. Oktav, A., Hashemi Gavgani, V., Anlas, G. and Yilmaz, C. Reducing Force Transmission Through Exhaust Mounts of a Vehicle. Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering. 2018;1(11): 2809-2819.
88. He, H., Zhou, H. and Wang, S. L. Modal Testing Analysis and Dynamic Properties Estimate on the Exhaust System of a Medium-Sized Bus. Applied Mechanics and Materials. 2012;224:146-50.
89. Liu, H. J. and Zhi, S. Y. Exhaust System Finite Element Analysis and Optimizing Design. Advanced Materials Research. 2012;538-541:590-4.
90. Storck, H., Sumali, H. and Pu, Y. Experimental Modal Analysis of Automotive Exhaust Structures. SAE International; 2001.
91. Li, S. B., Guan, X. Q., Lu, T. L. and Zhang, J. W. Vehicle Modeling with the Exhaust System and Experimental Validation to Investigate the Exhaust Vertical Vibration Characteristics Excited by Road Surface Inputs. International Journal of Automotive Technology. 2008;9(4):483-91.
92. Soundararajan, S. A Finite Element Methodology to Design and Validate the Performance of an Automotive Exhaust System. SAE Technical Paper. 2012: 9
93. George, J., Chen, Y. and Shih, H. R. A Doe Based Study to Evaluate the Dynamic Performance of an Automotive Exhaust System. SAE International 2013.

94. Jianwang, S., Aimin, D. and Xiaoxiong, J. Research of Automotive Exhaust System Hanger Location. 2008 IEEE Vehicle Power and Propulsion Conference; 2008 3-5 Sept. 2008.
95. Yansong, W., Weiwei, W. and Jianghua, L. A New Technique for Hanger Position Optimization of Vehicle Exhaust System. 2010 International Conference on Intelligent Computation Technology and Automation; 2010 11-12 May 2010.
96. Noorazizi, M. S., Aminudin, B. A. and Zetty, M. I. Systematic Fea Study of Vehicle Exhaust System Hanger Location Using Addofd Method. Applied Mechanics and Materials. 2013;392:161-4.
97. Noorazizi, M. S, Aminudin, B. A. and Faraziah, H. Technique for Hanger Location of Vehicle Exhaust System Using Finite Element Method. Applied Mechanics and Materials. 2014;663:485-9.
98. Maruthi, B. H., Chanakeshavalu, K., Mallika, K. and Shwethasree, B. Design and Analysis of Hangers for Exhaust System. International Journal of Engineering Research and Technology. 2015;4(06).
99. Zhang, P. and Song, X. L. Simulation Research of Vehicle Exhaust System Hanger Location. Advanced Materials Research. 2012;482-484:347-53.
100. Yuan, S. L., Zhang, W. C., Liu, Z. E., Wang, C. and Fu, D. Y. Research on Influence of Flexible Parts' Rigidity to Passenger Car Exhaust System's Modal. Applied Mechanics and Materials. 2012;117-119:141-5.
101. Xu, J. M., Zhou, S. and Chen, S. X. An Analysis of the Vibration Characteristics of Automotive Exhaust Systems and Optimization of Suspension Points. The Open Mechanical Engineering Journal. 2014;8:574-80.
102. Gaonkar, C. D. Modal Analysis of Exhaust System to Optimize Mounting Hanger Location. International Journal of Engineering Research and Technology. 2015;4(03):24-9.
103. Dwivedi, A. and Soundararajan, S. Optimization of Exhaust Hanger Location for NVH Performance. Hyperworks Technology Conference; 2010; Americas.
104. Shojaeifard, M. and Kamarkhani, S. Optimization of Exhaust System Hangers for Reduction of Vehicle Cabin Vibrations. International journal of automotive engineering. 2017;7:2314-24.
105. Wenzhu, W., Gang, L., Mianhong, C. and Jun, W. Hanger Location Layout of Automotive Exhaust System. SAE International; 2015.

106. Chen, X., Zhang, Y., Zhang, Y. and Jiang, M. Hanger Location Design and Vibration Isolation of an Exhaust System. SAE International; 2014.

107. Liu, Z., Zhang, Y., Du, S. and Xiao, S. Analysis on Hanger Location and Hanger Isolator of an Exhaust System with Powertrain. International Conference on Mechatronics, Electronic, Industrial and Control Engineering (MEIC-14); 2014 2014/11/15: Atlantis Press.

108. Iyer, G., Mohan, S. and Rao, N., Unnithan S. Evaluation of Dynamic Characteristics of an Automotive Exhaust System Using Operational Modal Analysis (OMA) and Experimental Modal Analysis (EMA). SAE International; 2013.

109. Schwarz, B. J. and Richardson, M. H. Experimental Modal Analysis. CSI Reliability Week. 1999.

110. Verheij, J. W. Cross spectral density methods for measuring structure borne power flow on beams and pipes. Journal of Sound and Vibration. 1980;70(1):133-8.

111. Mandal, N. K. and Biswas, S. Vibration power flow: A critical review. The Shock and Vibration Digest. 2005;37:3-11.

112. Avitabile, P. SEM Experimental Techniques Modal Space - In Our Own Little World. 2008.

113. Maia, N. M. M. and Silva, J. M. M. Theoretical and experimental modal analysis. Taunton: Research Studies Press. 1997.

114. Gokhale, N. S., Deshpande, S. S., Thite, A. N and Bedekar, S. V. Practical Finite Element Analysis International Edition ed: Finite To Infinite; 2008.

115. Weck, O., Wallace, D., Young, P. and Kim, I. Y. Engineering Design and Rapid Prototyping In: Engineering Systems Division MIoT. 2004.

116. Knight, C. E. A Finite Element Mothod Primer For Mechanical Design. Pap/Dis ed: PWS Publishing Company. 1993.

117. Rajadurai, S., Afnas, M., Ananth, S. and Surendhar, S. Materials for Automotive Exhaust System. International Journal of Recent Development in Engineering and Technology. 2014;2(3).

118. Seif, M., Main, J., Sadek, F., Choe, L., Zhang, C., Gross, J., Luecke, W. and McColskey, D. Temperature-Dependent Material Modeling for Structural Steels: Formulation and Application. In: National Institute of Standards and Technology G, MD, editor. Technical Note (NIST TN)2016.

119. Monteagudo Galindo, M. Mobility at the Development of Exhaust System. SAE International Journal of Passenger Cars - Mechanical Systems. 2011;4(2):983-8.

120. Rao, M. D., Gruengerg, S. and Griffiths, D. Measurement of Dynamic Parameters of Automotive Exhaust Hangers. SAE Technical Paper 2001;01:1446.

LIST OF PUBLICATIONS

1. Oo Kyaw Nyein, Aminudin Bin Haji Abu, and Asnizah Sahekhani, "Experimental and Numerical Investigation of Vibration Power Flow of Thin Plate Using Cross Power Spectral Density Based Technique", Materials Sciences and Engineering, 1051(2021) 012043, doi:10.1088/1757-899X/1051/1/012043.

2. Oo Kyaw Nyein, Aminudin Bin Haji Abu, Asnizah Sahekhani, and Muhammad Nubhan B Mohd Takiyuddin, "Measurement of Vibration Power Flow in Thin Plate Structure with Cross Power Spectral Density Based Technique", International Journal of Psychosocial Rehabilitation, 24(04), 2020, pp1873-1881.

3. Sanda Pyae Sone, Aminudin Abu, and Oo Kyaw Nyein, "Parametric Study on Vibration Response for Automobile Crankshaft", Asia Proceeding of Social Sciences, 1(4), 2019, doi:10.31580/apss.v1i4.460

4. Sanda Pyae Sone, Aminudin Abu, Asnizah Binti Sahekhaini, Oo Kyaw Nyein, Nor Azizi Bin Othman, and Aung Lwin Moe, "Design of experiment Approach on Vibration Characteristics in Automobile Crankshaft", The European Proceeding of Social & Behavioural Sciences, 2019, doi:10.15405/epsbs.2019.05.02.8