International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-12 Issue-6, May 2023

Car Door Assembly FE Analysis - A Review for NVH Performance Research

Pandurang Maruti Jadhav, Kishor B. Waghulde, Rupesh V. Bhortake

Abstract*: When talking about the car door and its importance, all aspects should be considered. Main applications of the door is the protection of passengers from outside weather variations such as air flow, temperatures, dust, side impact, etc. As a part of the car, it is connected to the car body by means of hinges, latch, and weather seals. It is excited by all excitation sources which excite to the vehicle plus vehicle accessories. Car door design evaluation is nothing but simulation of real application of door with different loading and boundary connections. An extensive literature survey and study of technical papers have been done to understand the amount of work done on Car door design evaluation during 2002 - 2022. A mainly top-level study was done to find the number of analysis papers published, the number of papers published per year, and the number of papers published of each type of analysis, and a detailed study was carried out of the papers published on NVH analysis. NVH analysis of a Car door itself is a broad area for study and research. To make it simple and streamline NVH analysis papers are sub-divided into further classes that are modal analysis, vibration and noise analysis, correlation of modal, vibration, noise, and other NVH analysis results. A thorough review of published papers provided an inside picture of the subject, the current status of Car door NVH, and the scope of future research on Car door.

Keywords: NVH, Car Door, Modal Test, Modal Analysis, FEA, Car Door NVH

I. INTRODUCTION

This paper is dedicated to find and study the literature on Car door design evaluation and application evaluation. A detailed study and analysis of relevant research work from past two decades (2002-2022) have been done. The applicability and importance of Car door and their top-level descriptions have depicted down under the introduction. Car door is key accessary, when we think about the car aesthetics design, car handling performance, passenger safety, car body reliability, car body vibrations, car overall noise and first interaction point of all human beings who want to use or access the car. For better alignment of door to the above important performance attributes, it is need cum requirement to study the car door. Car door means, car door assembly which includes door main frame structure, hinges, latch, window glass, window glass regulator mechanism, window glass seals, door primary and secondary seals, door handle and door mounted side mirror.

Going ahead to rank all these important performance attributes of a car door in accordance of the customer focus and intent of evaluating the car before purchasing. Approximately these will come as aesthetics, mileage, NVH (noise, vibration and harshness), safety, life (durability & reliability), interior comfort, cost, and after-sales services. Out of these attributes most irritating and impactful is the NVH, which will instantly force anybody to make decision about the car or brand of the cars.

II. OBJECTIVE OF THIS RESEARCH WORK AND ITS NOVELTY

Many research papers are available on Car door. Each paper focused on particular performance attribute and evaluated that attribute by CAE method or analysis type. All these performance attributes and their analysis methods have summarised together. Which will helps to find the Car door performance evaluation gap and will helps to set-up the new methodology to evaluate most concern performance attributes such as noise and vibration.

To work on any attribute or to set-up new methodology or to work on specific technological gap, it is required to understand and should be aver of past and current ongoing technological developments in same field. To work on the car door NVH, first find the current status of technological developments. Literature survey is the right way to understand the historical and current technological developments related to the car door NVH.

Fig. 1. Door Assembly on Car / vehicle.

Manuscript received on 02 February 2023 | Revised Manuscript received on 15 April 2023 | Manuscript Accepted on 15 May 2023 | Manuscript published on 30 May 2023.
*Correspondence Author(s)
Mr. Pandurang Maruti Jadhav*, Department of Mechanical Engineering, Dr. D Y Patil Institute of Technology, Pune (Maharashtra), India. Email: pmjadhav@rediffmail.com, ORCID ID: https://orcid.org/0000-0002-6811-1909
Dr. Kishor B. Waghulde, Professor, Department of Mechanical Engineering, Dr. D Y Patil Institute of Technology, Pune (Maharashtra), India. Email: kishor.waghulde@dypvp.edu.in
Dr. Rupesh V. Bhortake, Principal, Marathwada Mitramandal's Institute of Technology, SPPU Pune, (Maharashtra), India. Email: 3ruprani_2000@yahoo.com

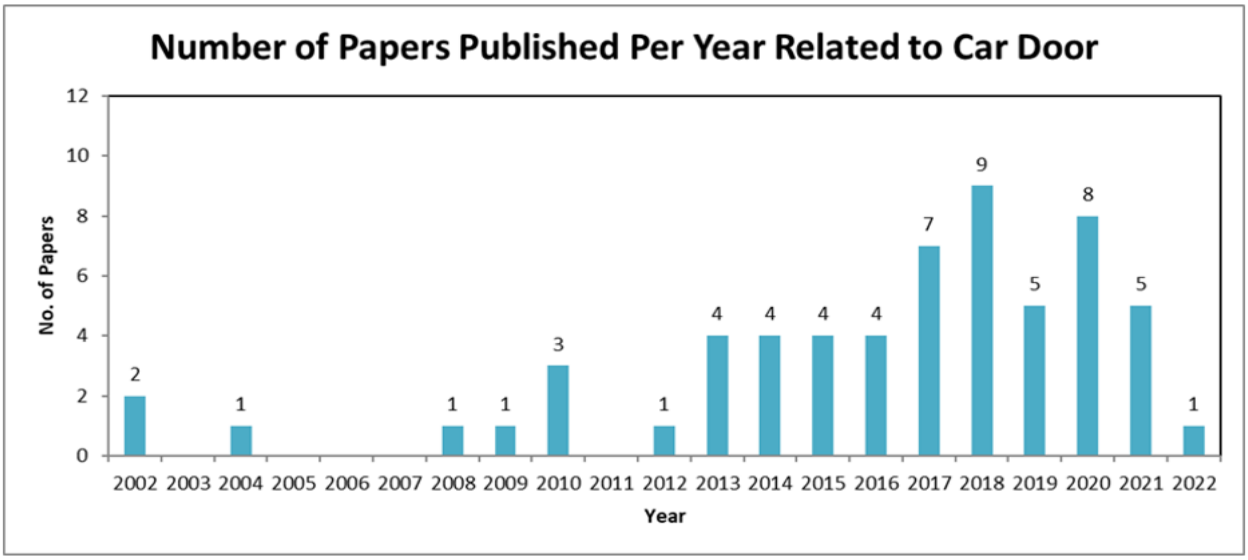

Fig. 2. Research on Car Door using CAE in last 20 Year

Literature survey has been done related to the car door CAE, which covers the study of last 20 years published paper on the car door Finite Element Analysis. Between 2002 and 2022, approximately 81 technical papers were published on car door using the finite element analysis method. Out of 81 papers relevant 60 papers has been reviewed. Statistical analysis of these 60 papers is that around 87% papers are published in last decade i.e., "2012 – 2022" which indicates that currently more focus has given on CAE analysis (Fig.2).

When we see the distribution of 60 papers based on types of finite element analysis then 44 papers are on NVH [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], eight papers are on durability or Static [45], [46], [47], [48], [49], [50],[51], [52], three papers are on Crash [53], [54], [55], two papers are on CFD [56], [57], and rest of the three papers are about the other types of analysis [58], [59], [60]. It indicates that more focus is on NVH and Durability (Fig. 3).

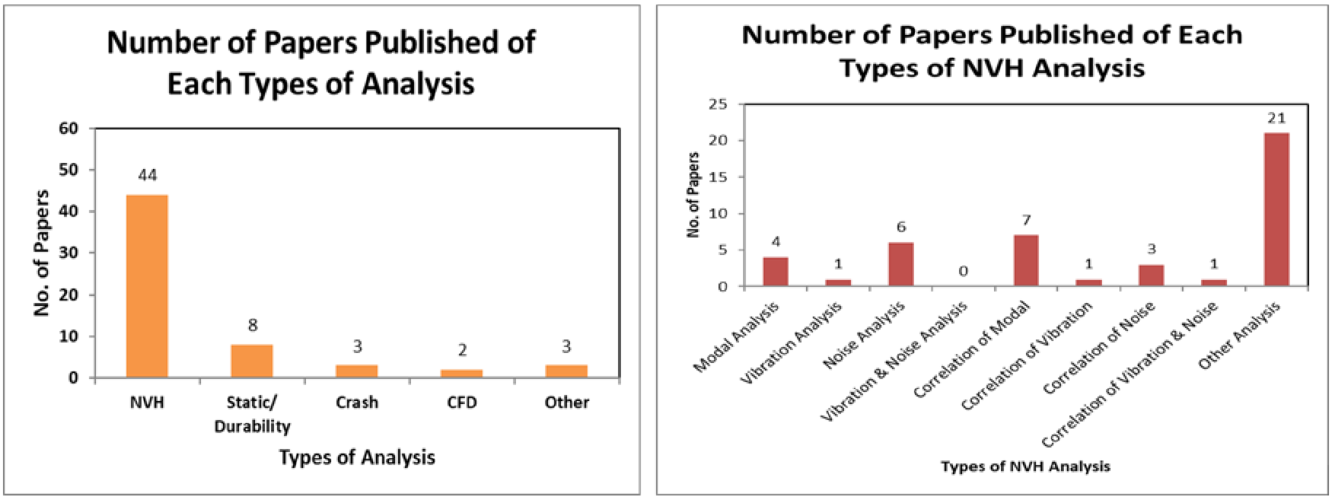

Fig. 3. Types of Analysis & Types of NVH Analysis in last 20 Years

NVH is not a single attribute, at top level it covers (1) modal analysis, (2) vibration analysis, (3) noise analysis, (4) vibration and noise analysis, (5) correlation of first three basic analyses with test / field data and (6) other analysis types used for simulation of specific attribute or application. Based on the NVH literature survey of last two decades maximum work has been done related to the modal analysis, either basic modal analysis or correlational modal analysis. Next to modal analysis is noise analysis, either basic noise analysis or correlational noise analysis. Comparatively less consideration has given to vibration analysis (Fig. 3).

Above statistical analysis of NVH attributes based on "Types of NVH Analysis" helps to draw rough conclusion that very less efforts have gone to address basic attributes of NVH and their correlation for same application or simulation project. The basic attributes of NVH are nothing but modal analysis, vibration analysis, and noise analysis. The output of these three analyses is nothing but the dynamic behaviour of any system, and all are interlinked. Modal analysis is the primary requirement or basic of vibration and noise analysis and to understand its dynamic behaviours. It is mandatory to understand / interpret the modal behaviours. Based on the above conclusion about basic attributes, there is scope / gap to work on all three basic attributes of NVH of a system and laydown the process to simulate,

Retrieval Number: 100.1/ijitee.D94550312423
DOI: 10.35940/ijitee.D9455.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

correlate and address the NVH issues or suggest the design improvement idles to make that system better in terms of NVH attributes or performance.

III. DIFFERENT NVH ANALYSIS METHODS USED

A. Modal Analysis and its Correlation

Hao Chen et al [1] carried out a surface response method to find highly sensitive panels of the SUV door. Door modal simulation results were verified with modal test data as a finite element model correlation. Thickness sensitivity study of door structural panels was done to find out highly sensitive panels to natural modes. Surface response point data was collected on highly sensitive panels and using thickness as design variable the modal frequencies were optimised. Modal frequencies of optimized model were matching after 5.74% mass reduction.

Wentao Yu [2] worked on interior noise issue at 40 km/h constant speed on the rough asphalt road. Detail problem investigation concluded that there was resonance because of frequency coupling between rear back door and car cavity. Author selected the easy way of de-coupling the modes by optimizing rear back door means of simulation, experimentation and by adding more dynamic absorbers. After optimization model frequency of door was reduced to 37.2 Hz from 43.1 Hz and interior noise at 42 Hz was reduced by 8 dB at 40 km/h constant speed on rough road (Fig. 4).

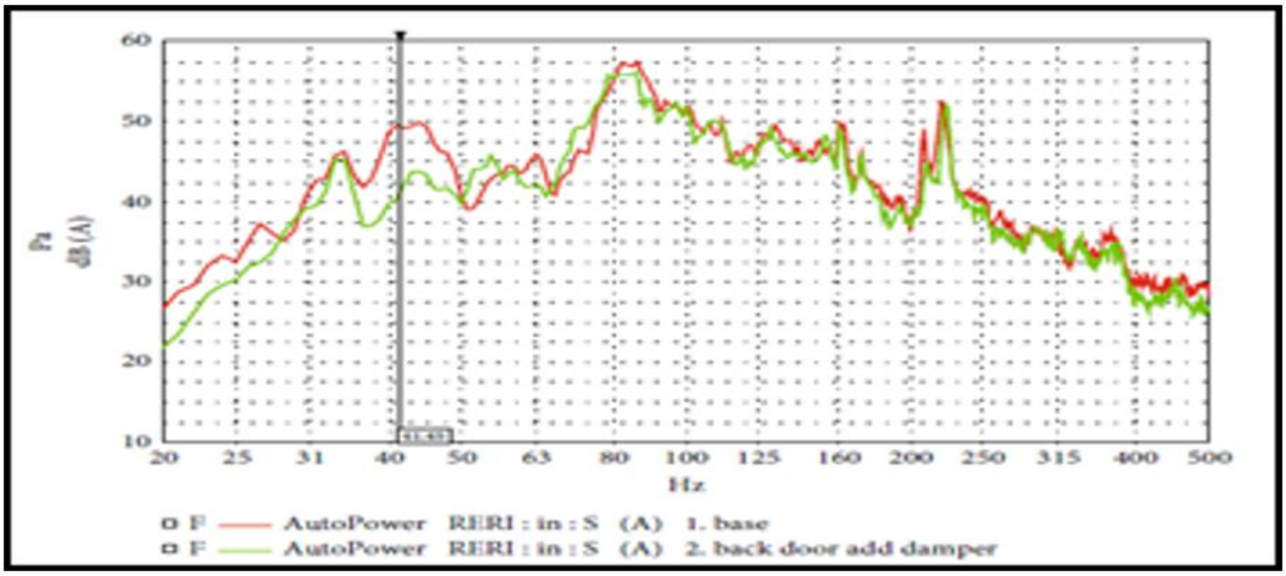

Fig. 4. Comparison of back row seat noise before and after optimization of absorber [2]

XIQUAN QI et al [3] carried out the door modal analysis and finite element model accuracy has been verified by physical vibration test of door in semi anechoic chamber. Here author has done correlation of first two global modes and output of response point for same modes (Fig. 5). After model verification based on the transfer function is concluded that a pole of transfer function of door has respective modal frequency which points a pole of transfer and modal frequency of door will be same.

Table- I: Modal Frequencies of The First Six Orders or Modes [3]

Number of Order	1	2	3	4	5	6
Simulation	45.13	50.58	56.15	57.86	61.91	75.41
Test	45.06	50.12	55.79	57.48	61.72	74.96

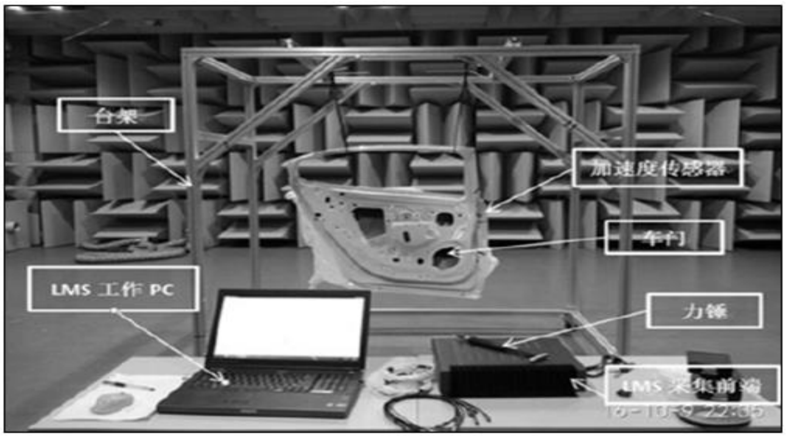

Fig. 5. Semi Anechoic Chamber for Validation Test [3]

WII Wan Iskandar Mirza et al [4] did the research to optimize the FRF points of the car door. General it is time consuming activity to find appropriate location to take response for mode shape correlation. Mostly FRF locations are selected based on experience or trial and error method. Author applied the effective impedance method (EIM) to find 30 FRF points on car door structure. Study reveals that effective impedance method is more useful and it is highly relies on accuracy of finite element model. In simple way on complex structure maximum number of FRF locations will be selected and if FRF peaks are not there within frequency range (0 – 100 Hz) of interest then that location will discard for further analysis (Fig. 6).

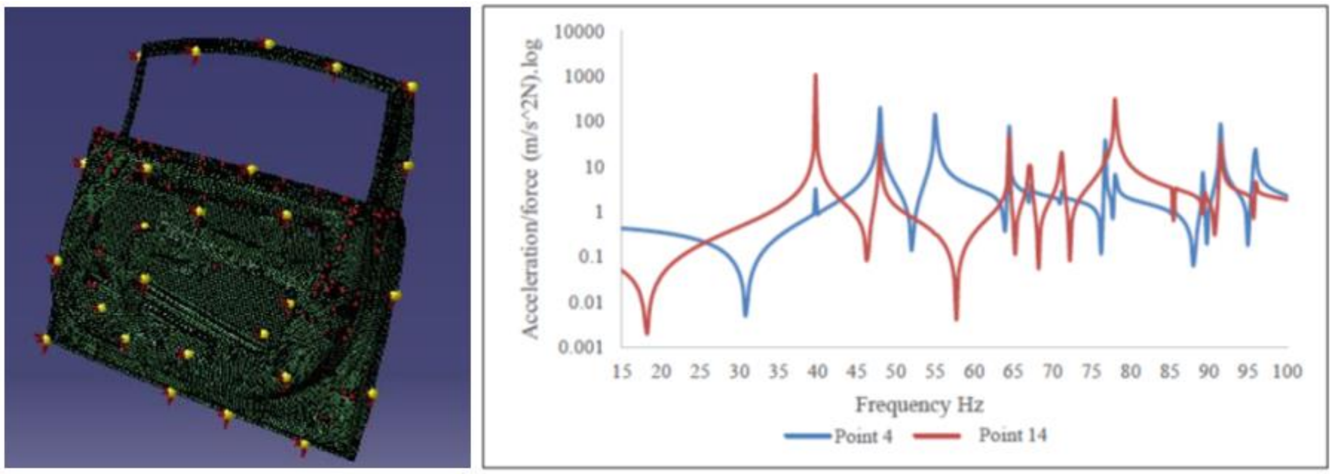

Fig. 6. Suggested Points for FRF & FRF of P 4 & P 14 [4]

Chandru B.T. et al [5] had carried the experimental modal testing and free-free finite element modal analysis. They found good matching of frequencies, which indicated that the finite element model is validated and close to reality. Using validated model author has done design modifications and achieved significant vibration reduction on finite element only.

Neelappagowda Jagali et al [6] tried to work on the damping effect on the experimental modal test and finite element modal. Did the door free-free modal analysis without damper and with damper same way did experimental modal analysis. Frequencies of finite element analysis and experimental modal testing were compared but there was high difference. Without damper FEA 7th mode was at 43.51 Hz and EMT 7th mode was at 53.7 Hz. But damper effect on FEA and EMT is approximately same.

Mohan Kumar G R [7] carried out the finite element modal analysis and experimental modal testing and correlated the frequency results, which was closely matching. On same FE model author added stiffener to improve the modal frequencies, which was working well.

B. Vibration Analysis and its Correlation

Sunil S. Patil et al [8] worked on the car door slam analysis. Transient analysis of on validated finite element model of car door was done. While testing of door slam, Car door was closed from 20-degree open position with 1 m/sec closing velocity and results are taken out for 0.35 second duration with time step of 0.01 second. Acceleration, stress, strain and buckling energy was compared from finite element transient analysis and door slam test. An acceleration and stress result was correlated well and others were having minor deviations (Fig. 7).

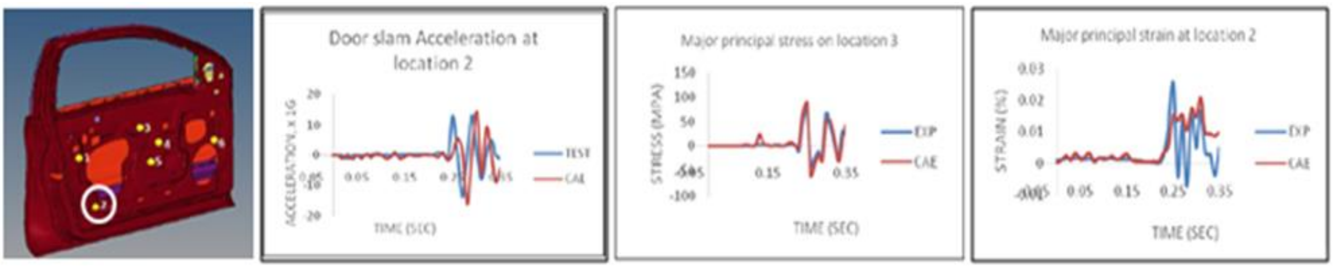

Fig. 7.Door Slam Results : Acceleration, Stress, and Strain [8]

C. Noise Analysis and its Correlation

Gao Yunkai et al [9] worked on the door collision test and Boundary Element Model (BEM) simulation of it. Main focus was on the sound quality checking by experimental method and the way BEM results would be correlated with it, so that other vehicle door also can be simulated with same BEM methodology without physical test. Sound pressure results of test and BEM are having good agreement between 20 – 200 Hz (Fig. 8).

Retrieval Number: 100.1/ijitee.D94550312423
DOI: 10.35940/ijitee.D9455.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

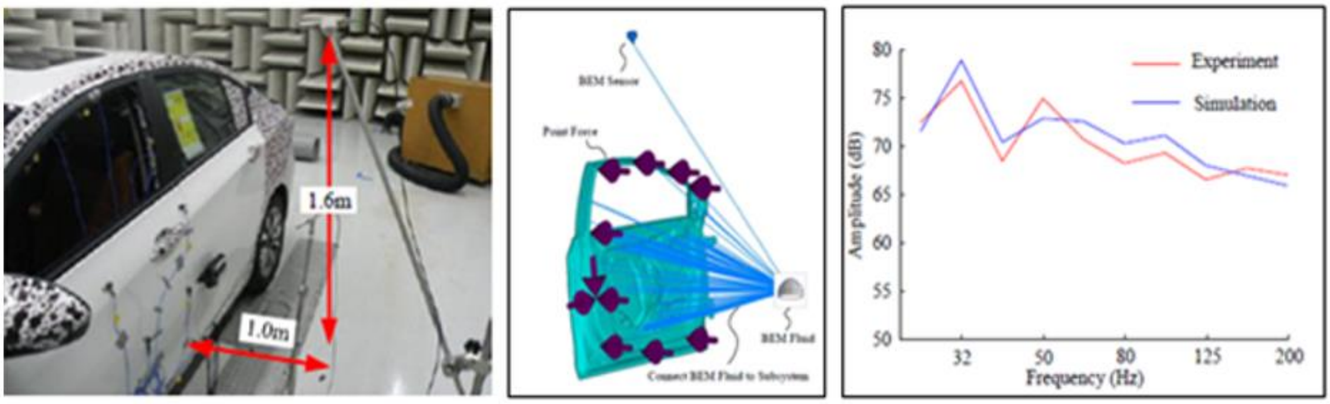

Fig. 8.Door Closing Collision Impact Results : Sound Pressure Level Outside Car [9]

Erkut Yalcm et al [10] assessed the car door model similar to the other researcher but one difference was there that was the transient analysis for noise calculation using vibro-acoustic finite element model. Experimental test was carried out for door slam loading and exterior sound was recorded in time domain. Results from vibro-acoustic model were taken out in time domain after simulating door slam loading condition. Exterior sound pressure of test and vibro-acoustic FEM were well correlated (Fig. 9). Using same vibro-acoustic model author studied the sensitivity different panels of door structure.

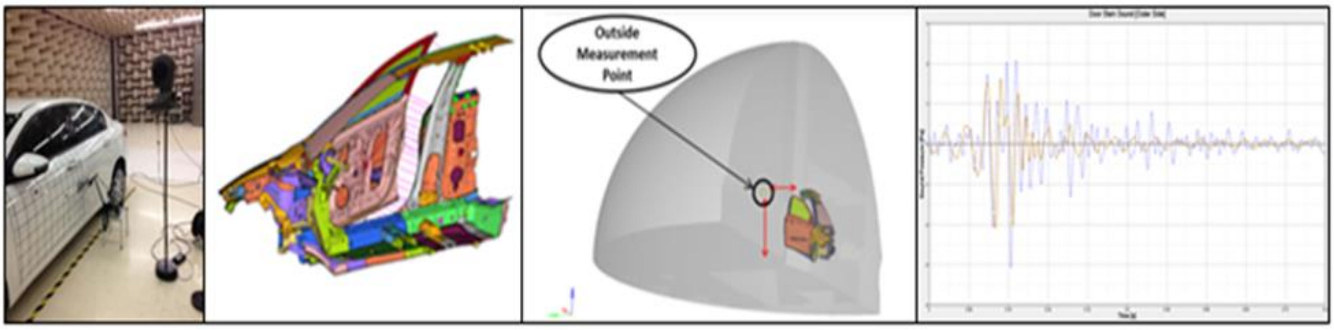

Fig. 9.Door Slam Test and Vibro-acoustic Results [10]

A. Lucifredi et al [11] worked on car door slam pressure calculation correlation. Here they have done triple validation – instruments used for experimental test, trimmed door FE model (Fig. 10), acoustic FRF results on door panels (Fig. 11). These were positive steps for final result validation. All these validation results were well correlated and final results of vibro-acoustic FEM and test results of exterior sound pressure was satisfactory (Fig. 12).

Fig. 10. Trimmed Door Modal Testing Set-up [11]

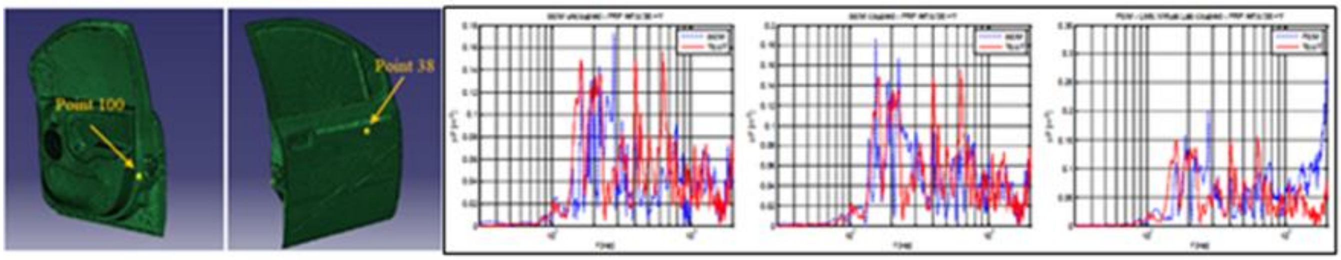

Fig. 11. FEM-BEM acoustic FRF location and Results Comparison [11]

Retrieval Number: 100.1/ijitee.D94550312423
DOI: 10.35940/ijitee.D9455.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

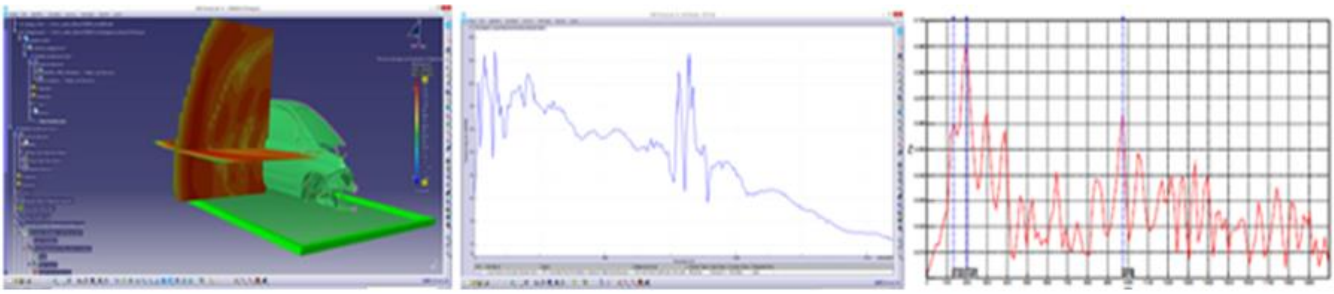

Fig. 12. FEM-BEM Model & Exteriror location Results Comparison [11]

D. Vibration and Noise Analysis and its Correlation

D. A. Desai [12] worked on the objective of interior noise a car and studies the effect of car door on it. Experimental test of interior noise was carried on simplified model in anechoic chamber. Same simplified model was simulated in ABAQUS. Car body and car cavity vibro-acoustic FEM was used for transient analysis for door impact load of 1000 N for 1 milli-second. Effect of door impact was studied on door in term of vibration and inside cabin at driver ear location in term of noise. Both results were showing good agreements (Fig. 13).

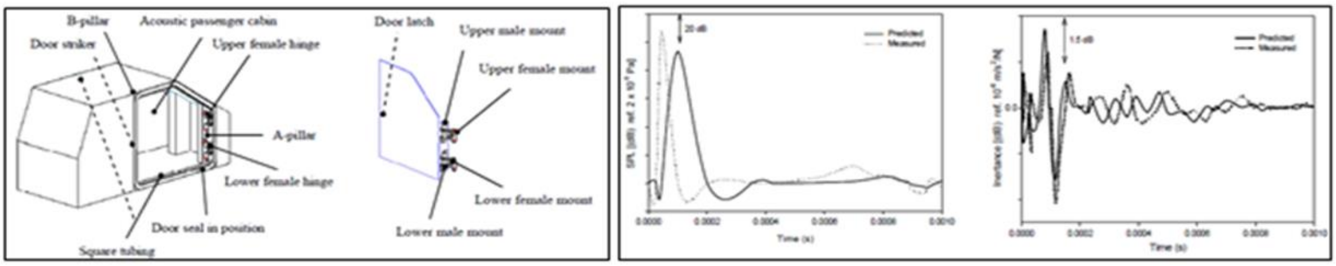

Fig. 13. Simplified Car model and results at driver ear noise (middle) and on door vibration (left) [12]

E. Other NVH load Cases Analysis

Chunlong Ma et al [13] worked on the car door wind glass squeaks and rattle noise during sliding operations. Sensitivity of main parameter related to the glass assembly, like frame side, gap between glass and door inner panel, friction, etc. were studied and suggested optimal range to reduce noise.

Hyeonho JO et al [14] put efforts to study the latch noise because of various operations. Based on juries' observations researcher prepared quality index for assessment of loudness, sharpness, impact sounds, etc. which will be used for other product evaluation.

Yoshiaki ITOH et al [15] developed digital filter method cum algorithm to analyse time based as well as steady state vibrations. Vibration outputs of standard excitation inputs such impulse, sine swept and sinusoidal were analysed compared with Fast Fourier Transformer (FFT) and are equivalent.

Sajjad Beigmoradi et al [16] tried to use hybrid statistical energy – finite element analysis method to address the car door trims squeak and rattle (S&R) noise. Based on this they worked to control gap between trim and door panels to control S&R.

Maressa et al [17] worked on noise optimization using topography method. Beading patterns were added based on Wave-Based Sub-structuring (WBS) on plane area components and finally achieved vehicle level noise improvement.

J Niermann et al [18] outlined the procedure of Short-Time Fourier Transformation (STFT) and Wavelet Transformation (WT) to analyse transient behavioural noises generated in vehicle. Mihir H. Patel et al [19] worked on acoustic complex signals by real time transient data recording with different sampling rates which will be analysed in Fast Fourier Transform (FFT) to find fundamental frequencies of systems.

IV. CAR DOOR NVH RESULTS DISCUSSION

Most of the work related to the car door has been done in the beats and pieces like only FE based modal analysis, FE and test based modal analysis, FE and test-based vibration analysis, FE and test-based noise analysis. Few papers are there which talks about modal, vibration and noise analysis at a time which is the basic requirement of NVH investigation.

Entire literature survey related car door NVH tells that maximum work has been done related to modal analysis then comes noise analysis and very few (~3 no.) efforts gone for vibration analysis. Door effect on car NVH performance has been tried to address by modal analysis and door exterior noise analysis, only one paper talked about door effect on interior noise.

Other research work is related to door hinges stress analysis, door internal stiffener analysis for side impact, wind effect on cabin noise and door operations, some researcher worked on effect of door and glass seals.

V. CONCLUSION

As the door is one of the important parts of car and its dynamic behaviours affect the overall performance of vehicle. More attention has been given to assess the door performance attributes in term of NVH and durability attributes. Door NVH main attributes such as modal, Vibration and noise are assessed as individual contributor or its effect on vehicle performance.

Retrieval Number: 100.1/ijitee.D94550312423
DOI: 10.35940/ijitee.D9455.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Table- II: Summary of The Findings Related to The Car Door Assembly [1] TO [10]

S. N.	Authors > Types of NVH Analysis	Used > Softwares / Instruments	Methods Used > Analytical / FEA	Major Findings >
1	Hao Chen, Chihua Lu, Zhien Liu, Cunrui Shen, Yi Sun, and Menglei Sun, 2020 > Correlation of modal > Optimization	> Hyperworks > Nastran	> Constrained Modal analysis > The response surface method (RSM) > Constrained modale and test results	> A sensitivity analysis for the thickness of door panels was proposed based on the fifth-order modal frequency of the door. > An optimization model was established according to the response surface method
2	Wentao Yu, 2021 > Correlation of modal > Optimization	> Hypermesh, Opti-struct > LMS Test.Lab/ Impact testing module	> Modal Analysis	> By increasing the dynamic vibration absorber, makes its modal frequency avoid the acoustic cavity modal frequency, > After optimization, the vehicle noise is reduced by 8 dBA at 42 Hz under 40 km/h working condition of rough road surface
3	XIQUAN QI, YANSONG WANG, HUI GUO and LIHUI ZHAO, 2017 > Correlation of modal	> Hypermesh > Nastran > LMS data acquisition system	> Modal Analysis > Frequency Response Function	> The research shows that the natural frequency of a passenger car door is not necessarily a pole of the passenger car door transfer function > A pole of transfer function is bound to be a natural frequency of the passenger car door
4	WII Wan Iskandar Mirza, M N Abdul Rani, M F Musa, M A Yunus, C Peter and M A S Aziz Shah, 2019 > Correlation of Modal	> HyperWorks > LMS - SCADAS System	> Free-Free modal analysis > Effective impedance method (EIM) > Experimental modal analysis	> The appropriate FRF driving points of the car door have been successfully identified using the effective impendence method, which is highly dependent on the accuracy and reliability of the FE model.
5	Chandru B. T, Suresh P. M, 2016 > Correlation of modal	> HyperMesh > Opti-Struct	> Modal and Harmonic Analysis > Experimental modal analysis	> It is observed that there will be significant vibration reduction seen with stiffener from the 7th mode to 10th mode and 11th mode.
6	Neelappagowda Jagali, Chandru B. T, Dr. Maruthi B. H, Dr. Suresh P. M, 2016 > Correlation of modal	> CATIA > HyperMesh > ABAQUS	> Free-Free modal analysis > Modal Test > Frequency response function (FRF)	> From the two conditions with damper and without damper the frequency values obtained from the FE method and experimental method are comparable
7	Mohan Kumar G R, 2017 > Correlation of modal	> CATIA V5 > HyperMesh 12.0 > Opti-struct solver	> Free-free modal analysis > Experimental modal analysis	> Accomplished both Experimentally and Finite Element analysis using with and without stiffener under the Free- Free conditions, there were significant vibration decrease was seen
8	Sunil S. Patil, Gautami U. Dhuri, 2020 > Correlation of vibration and strain	CATIA V5, Hypermesh v12, LS-DynaExplicit Dynamic Solver	> Free-Free modal analysis > Frequency response function > Modal & FRF Test	> The detailed comparison of experimental acceleration and strain results. While these results shows excellent agreement in CAE and test for accelerations on the outer panel.
9	Gao Yunkai and Liu Zhe, 2020 > Correlation of noise	> Hypermesh > Nastran > LMS Virtual.Lab > LMS SCADAS	> Modal Analysis > Frequency response function > Experimental FRF data	> The results show that the sound pressure values obtained by experiment and simulation are highly consistent. > It shows that this method is feasible in predicting the sound quality.
10	Erkut Yalcın, Halil Bilal, Ayhan Yagcı, Haluk Erol, 2020 > Correlation of noise	> HyperMesh > Abaqus > Artemis software	> FEA & BEM : Transient Analysis > Design sensitivity analysis > Testing of noise outside Car	> For predicting the transient door slam noise using a twostep FEM + Boundary Element Method analysis in sequence have got good noise pattern agreement within 25 - 100 Hz.

Retrieval Number: 100.1/ijitee.D94550312423
DOI: 10.35940/ijitee.D9455.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Table- II: Summary of The Findings Related to The Car Door Assembly (CON.) [11] to [20]

S. N.	Authors > Types of NVH Analysis	Used > Softwares / Instruments	Methods Used > Analytical / FEA	Major Findings >
11	A. Lucifredi, P. Silvestri, P. Cavasotto, F. Denevi, A. Camia, 2014 > Correlation of modal and noise	> Patran/Nastran, > LMS Virtual.Lab, > LMS Test.Lab and > Matlab > LMS SCADAS	> Modal analysis (SOL 103) > Transient nonlinear analysis (SOL 400) > Test of modal and FRF data	> The MAC & FRAC indicates the degree of correlation > A good agreement between the FEM and the experimental data was found for all the vibration modes > A strong correlation of the frequency peaks may be seen
12	D. A. Desai, 2013 > Correlation of vibration and noise	>ABAQUS > DSP SigLab spectrum analyser > MODENT modal-analysis software	> FEM with full coupling between the passenger cabin and vehicle body. > A transient vibro-acoustic dynamic analysis was carried > Testing of vibration & noise	> The measured and the predicted results exhibited good correlation
13	Chunlong Ma, Dongyan Shi, Mengnan Wang, Dongze He, Chao Li & Xingsheng Yu, 2021 > Improvement of S & R noise	> ABAQUS,	> FE Analysis > 6 Sigma Method > Deflection measurement	> The key dimensions of automobile windows were improved using the 6 sigma analysis method > The S&R problem of window lifting and lowering was completely solved with glass seal parameter fine tuning.
14	Hyeonho JO; Weonchan SEONG; Hyeongrae Lee; Seonghyeon Kim; Dongchul Park; Yeon June Kang, 2014 > Sound quality improvement	> Spiral array caemra	> Sound field visualization using acoustic camera > Method of Jury evaluation of Latch 'locking' & 'unlocking' sounds > Risa of Ricardo, which was used in jury evaluation	> To reduce the impact sound of door latch, high viscosity grease was working
15	Yoshiaki ITOH, Naoto YAMAGUCHI and Toru YAMAZAKI, 2013 > Vibration analysis	> Time frequency algorithm > Analogue and digital filter	> The time frequency analysis & algorithm > Fast Fourier Transform > Short Time Fourier Transform (STFT)	> The proposed analysis has the advantage over FFT analysis
16	Sajjad Beigmoradi, Kambiz Jahani, Hassan Hajabdollahi, 2013 > S&R Noise analysis		> Modal analysis > Hybrid statistical energy > Finite element method analysis	> Probable locations for generating rattle noise are investigated using hybrid SEA-FEM method
17	A. Maressa, B. Pluymers, S. Donders, W. Desmet, 2010 > Noise analysis	> Controller-based algorithm > Nastran > Virtual.Lab	> ATV (Acoustical Transfer Vector) approach > The WBS (Wave-Based-Substructuring) technique	> The interior acoustics comfort has been improved by means of structural bead modifications applied on a critical component
18	J. Niermann, Stephen J. Walsh K. Becker, 2010 > Noise Analysis		> The Short-Time Fourier Transformation (STFT) > The Wavelet Transformation (WT)	> Fourier Transformation (FT) is not suitable for the investigation of non-stationary signals > The STFT is able to furnish a frequency spectrum
19	Mihir H. Patel, Ankit J. Desai, 2020 > Vibration analysis	> MEMS, > Arduino Megha2560 > FFT algorithm > MatLab	> The varification of this FFT analyzer with analytical answer and Matlab software	> Test and analytical results having minor difference
20	Yashas S, > Modal Analysis	> Hypermesh > Nastran	> Finite Element Analysis (FEA)	> Increasing the mass of the door trim and by increasing the density and also provide the extra stiffness, thereby attain the desired natural frequency (25Hz).

ACKNOWLEDGMENT

I would like to thanks my research mentor cum guide Dr. Kishor B. Waghulde for timely guidance, inputs and in detailed explanation about the research topic. I sincerely thanks to my research centre Dr. D. Y. Patil Institute of Technology, Pimpri, India for providing opportunity and facilitate to work on this highly sensitive and current topic "Car Door NVH Performance Improvement."

DECLARATION

Funding/ Grants/ Financial Support	No, I did not receive.
Conflicts of Interest/ Competing Interests	No conflicts of interest to the best of our knowledge.
Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
Availability of Data and Material/ Data Access Statement	Not relevant.
Authors Contributions	All authors have equal participation in this article.

REFERENCES

1. Hao Chen, Chihua Lu, Zhien Liu , Cunrui Shen, Yi Sun, and Menglei Sun, "Structural Modal Analysis and Optimization of SUV Door Based on Response Surface Method", Hindawi, Shock and Vibration, Volume 2020, Article ID 9362434, 11 pages, https://doi.org/10.1155/2020/9362434. [CrossRef]
2. Wentao Yu, "Analysis and Optimization of Low-Speed Road Noise in Electric Vehicles", Hindawi, Wireless Communications and Mobile Computing Volume 2021, Article ID 5537704, 15 pages, https://doi.org/10.1155/2021/5537704 [CrossRef]
3. XIQUAN QI, YANSONG WANG, HUI GUO and LIHUI ZHAO, "Characteristic Analysis of Passenger Car Door Vibration Transfer Function", 2017 2nd International Conference on Artificial Intelligence and Engineering Applications (AIEA 2017) ISBN: 978-1-60595-485-1.
4. WII Wan Iskandar Mirza, M N Abdul Rani, M F Musa, M A Yunus, C Peter and M A S Aziz Shah., "Identifying the Appropriate Frequency Response Function Driving Point of a Car Door Using Finite Element Analysis and Modal Testing.", IOP Conf. Series: Journal of Physics: Conf. Series 1262 (2019) 012007, doi:10.1088/1742-6596/1262/1/012007 [CrossRef]
5. Chandru B.T, Suresh P.M., "Finite Element and Experimental Modal Analysis of Car Door", Journal of Chemical and Pharmaceutical Sciences ISSN: 0974-2115, JCHPS Special Issue 2: August 2016, Pages 85 – 88.
6. Neelappagowda Jagali, Chandru B. T, Dr. Maruthi B. H, Dr. Suresh P. M, "Evaluation of Natural Frequency of Car Door with and without Damper using Experimental Method and Validate using Numerical Method.", International Journal of Advanced and Innovative Research (2278-7844) / # 36 / Volume 5 Issue 6,.
7. Mohan Kumar G R, "Vibration Analysis of Car Door Using FE and Experimental Technique", International Research Journal of Engineering and Technology (IRJET), Volume: 04 Issue: 06, June -2017, e-ISSN: 2395 -0056, p-ISSN: 2395-0072.
8. Sunil S. Patil, Gautami U. Dhuri, "Assessment of Automobile Door Slam using Finite Element Method", International Journal of Innovative Technology and Exploring Engineering (IJITEE), ISSN: 2278-3075 (Online), Volume-9 Issue-4, February 2020. [CrossRef]
9. Gao Yunkai and Liu Zhe, "Sound Quality Prediction of Vehicle Door Closing Based on Experiment and Boundary Element Method", IOP Conf. Series: Materials Science and Engineering 825 (2020) 012046, doi:10.1088/1757-899X/825/1/012046. [CrossRef]
10. Erkut Yalcın, Halil Bilal, Ayhan Yagcı, and Hakan Erol, "A Numerical Approach for Sound Quality of Vehicle Doors", International Journal of Acoustics and Vibration, Vol. 25, No. 1, 2020 (pp. 9 -16), https://doi.org/10.20855/ijav.2020.25.11475 [CrossRef]
11. A. Lucifredi, P. Silvestri, P. Cavasotto, F. Denevi, A. Camia, "Analytical investigation, development and experimental validation of vibroacoustic models with BEM and FEM approaches and applications for the simulation of car door slamming phenomenon", https://www.researchgate.net/publication/288118784
12. D. A. Desai, "Simulation and experimental validation of vibro-acoustic transmission through a passive automotive door mount system", WIT Transactions on The Built Environment, Vol 129, 2013 WIT Press, www.witpress.com, ISSN 1743-3509 (on-line), doi:10.2495/FSI130211. [CrossRef]
13. Chunlong Ma, Dongyan Shi, Mengnan Wang, Dongze He, Chao Li and Xingsheng Yu, "Research on Improving NVH Performance of Automobile Side Door Glass in Use Based on 6 Sigma Method", Materials 2021, 14, 3748. https://doi.org/10.3390/ma14133748. [CrossRef]
14. Hyeonho JO, Weonchan SEONG, Hyeongrae Lee, Seonghyeon Kim, Dongchul Park, Yeon June Kang, "A Study on sound quality evaluation index of car door latch and improving sound quality by modifying door latch assembly design", Inter-noise 2014, Page 1 to 8.
15. Yoshiaki ITOH, Naoto YAMAGUCHI, and Toru YAMAZAKI, "Vibration Analysis Based on Time-Frequency Analysis with Digital Filter", Journal of System Design and Dynamics, Vol. 7, No. 4, 2013, Page 441 to 455. [CrossRef]
16. Sajjad Beigmoradi, Kambiz Jahani and Hassan Hajabdollahi, "Squeak and rattle noise prediction for trimmed door of a car using hybrid statistical energy - Finite element method analysis", Proceedings of Meetings on Acoustics, Vol. 19, 065052 (2013), DOI: 10.1121/1.4801014, Page 1 – 7. [CrossRef]
17. A. Maressa, B. Pluymers, S. Donders, W. Desmet, "NVH optimization methodologies based on bead modification analysis in vehicle body design", PROCEEDINGS OF ISMA2010 INCLUDING USD2010, Page 4319 – 4336.
18. Niermann J, Stephen J Walsh, and K. Becker, "Wavelet Analysis of Vehicle Door Closure Sounds", 2010, https://hdl.handle.net/2134/6582.
19. Mihir H. Patel, Ankit J. Desai, "Development of FFT Analyzer for measuring Vibration", The International Journal of Analytical and Experimental modal analysis, Volume XII, Issue IV, April/2020, ISSN NO:0886-9367, Page 1717 – 1721.
20. Yashas S, "Development and Analysis of Automotive Car Door Crop by using FEA Method", International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 9 Issue 10, October-2020. [CrossRef]
21. Chandru B. T, Maruthi B. H, Dileep Kumar, Vinay. V. Nesaragi, "NVH Characteristics Study of Automotive Car Door by Numerical Method", International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 3 Issue 6, June – 2014.
22. Said Darwish, H. M. A. Hussein and Ahmad Gemeal, "Numerical Study of Automotive Doors", International Journal of Engineering & Technology IJET-IJENS Vol:12 No:04, Page 82 – 92.
23. M. Grujicic, G. Arakere, V. Sellappan, J. C. Ziegert, F. Y. Koçer, D. Schmueser, "MULTI-DISCIPLINARY DESIGN OPTIMIZATION OF A COMPOSITE CAR DOOR FOR STRUCTURAL PERFORMANCE, NVH, CRASHWORTHINESS, DURABILITY AND MANUFACTURABILITY", www.brill.nl/mmms.
24. Rui Feng, Yuchen Jin, Xiaochen Yang, Guikai Guo, "First Order Sensitivity Calculation of Car Door Based on Combined Approximate Reanalysis Method", MEMA 2020, Journal of Physics: Conference Series, doi:10.1088/1742-6596/1750/1/012080. [CrossRef]
25. LIU Xing, "Research on Improvement Methods of Automotive NVH Performance", International Conference on Energy, Power and Mechanical Engineering (EPME2019), doi:10.1088/1757-899X/793/1/012011. [CrossRef]
26. Liu Ying-jie, Lu Wen-bo, Peng Cheng-jian, "Numerical Investigation on the Interior Wind Noise of a Passenger Car", International Scholarly and Scientific Research & Innovation 13(12) 2019, ISNI:0000000091950263
27. Sidramappagoud Patil, G. U. Raju, Chetanakumar Chavan, "NVH Analysis of Car Cabin Compartment", International Journal of Scientific Development and Research (IJSDR), ISSN: 2455-2631, July 2018 IJSDR | Volume 3, Issue 7, Page 317 – 324.

28. Xiaoping Xie, Fandong Zeng, and Guangjian Shen, "Investigation of Objective Parameters of Vehicle Door Closing Transient Sound Quality Based on Complex Analytic Wavelet Method", Hindawi, Shock and Vibration, Volume 2018, https://doi.org/10.1155/2018/9478672. [CrossRef]
29. M. French and M. Jay, "AN INTRODUCTION TO AUTOMOTIVE NVHTESTING", ttps://www.researchgate.net/publication/264454929
30. Mohan Kumar G R, "NVH Analysis of a Car Roof Using Numerical and Experimental Method", International Research Journal of Engineering and Technology (IRJET), Volume: 04 Issue: 06 | June -2017, e-ISSN: 2395 -0056, p-ISSN: 2395-0072.
31. Zhien Liu, Shuai Yuan, Shenghao Xiao, Songze Du, Yan Zhang, and Chihua Lu, "Full Vehicle Vibration and Noise Analysis Based on Substructure Power Flow", Hindawi, Shock and Vibration, Volume 2017, https://doi.org/10.1155/2017/8725346. [CrossRef]
32. Rong Guo, Xiao-kang Wei, Jun Gao, "Experimental NVH evaluation of a pure electric vehicle in transient operation modes", JVE INTERNATIONAL LTD. VIBROENGINEERING PROCEDIA. DEC 2016, VOL. 10. ISSN 2345-0533.
33. Miss A. Dowsett, Dr D. J. O'Boy, Dr S. J. Walsh and Dr A. Abolfathi, Mr S. Fisher, "Experimental Testing of Door Panel Boundary Conditions to Determine NVH Variability", The 23rd International Congress on Sound and Vibration, ICSV23, Athens (Greece), 10-14 July 2016.
34. Maria Antonietta Panza, "A review of experimental techniques for NVH analysis on a commercial vehicle", ScienceDirect, Energy Procedia 82 (2015) 1017 – 1023, doi: 10.1016/j.egypro.2015.11.861. [CrossRef]
35. MAHADEV N. HARKUDEa1 AND RAVINDRA R. MALAGI, "AUTOMOBILE NOISE AND VIBRATION-SOURCES, PREDICTION, AND CONTROL", NCRIET-2015 & Indian J.Sci.Res. 12(1):001-006, 2015, ISSN: 0976-2876 (Print), ISSN: 2250-0138 (Online).
36. Mr. Navalkumar Kavthekar and Dr. Prof. Avinash Badadhe, "NUMERICAL ANALYSIS OF DOOR CLOSING VELOCITY FOR A PASSENGER CAR", International Journal on Cybernetics & Informatics (IJCI) Vol. 4, No. 2, April 2015, DOI: 10.5121/ijci.2015.4201. [CrossRef]
37. Guohua Qiu, Aiquan Yu, Shanshan Wang, Gang Long, "The Algorithm Improvement of Sealing System Energy Consumption in Side Door Closing Process", 3rd International Conference on Mechatronics and Industrial Informatics (ICMII 2015).
38. Marie-Celine Bezat, Richard Kronland-Martinet, Vincent Roussarie, Sølvi Ystad, "From acoustic descriptors to evoked quality of car door sounds", J. Acoust. Soc. Am., Vol. 136, No. 1, July 2014, Pages: 226–241. [CrossRef]
39. Etienne Parizet, Erald Guyader, Valery Nosulenko, "Analysis of car door closing sound quality" https://hal.archives-ouvertes.fr/hal-00849046. Jul 2013
40. Marie-Céline Bezat, Vincent Roussarie, Thierry Voinier, Richard Kronland-Martinet, Solvi Ystad, "Car door closure sounds: characterization of perceptual properties through analysis-synthesis approach", https://hal.archives-ouvertes.fr/hal-00463358, Mar 2010.
41. Shahram Azadi, Mohammad Azadi, and Farshad Zahedi, "NVH analysis and improvement of a vehicle body structure using DOE method", Journal of Mechanical Science and Technology 23 (2009) 2980~2989. [CrossRef]
42. Philipp Sellerbeck, Christian Nettelbeck, "Door Operating Sound Imrpvement based on Jury Testing and System Analysis", CFA/DAGA-04, Strasbourg, 22-25/03/2004.
43. Sonoko Kuwano, Hugo Fastl, Seiichiro Namba, Seishi Nakamura, Hiroshi Uchida, "SUBJECTIVE EVALUATION OF CAR DOOR SOUND", DEARBORN, MICHIGAN SOUND QUALITY SYMPOSIUM, SQS 2002 August 22.
44. Victor V. Krylov, "Simplified analytical models for prediction of vehicle interior noise", PROCEEDINGS OF ISMA2002 - VOLUME V, http://www.isma-isaac.be/past/conf/isma2002.
45. Brahmanand Singh, Prof. Pawankumar R. Sonawane, Dr. Kiran C. More, "Optimization and Experimental Testing of Car Door Handle Using 3 Point Bending Test and 3D Printing Technology", International Journal of Advanced Research in Science, Communication and Technology (IJARSCT), Volume 7, Issue 2, July 2021, ISSN (Online) 2581-9429, DOI: 10.48175/IJARSCT-1776. [CrossRef]
46. Onur Erol, and Hande Güler Özgü, "Determining Simulation Parameters of Prototype Door Hinge for Correlation between Simulation and Experimental Results in United Nations Economic Commission for Europe Regulation No: 11 Tests", Designs 2019, doi:10.3390/designs3010017 [CrossRef]
47. V.N. Fazil, Dr. A. Dhanapal, M. Raja Mohan, E. Manopriya, "DESIGN OPTIMIZATION AND RAPID PROTOTYPE OF CAR FRONT DOOR STRUCTURAL COMPONENTS", International Research Journal of Engineering and Technology (IRJET), Volume: 06 Issue: 05 | May 2019, e-ISSN: 2395-0056, p-ISSN: 2395-0072.
48. Dr. M. SHAMEER BASHA, "DESIGN AND FINITE ELEMENT ANALYSIS OF A CAR DOOR ON DIFFERENT SPEEDS & DIFFERENT MATERIALS", International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), ISSN(P): 2249–6890; ISSN(E): 2249–8001, Vol. 9, Issue 6, Dec 2019, 63-72. [CrossRef]
49. T A Abdul Razak, M N Abdul Hamid, A Mohd Ghazali, S N Mohamed Soid and K S Shafee, "A Stress Analysis and Design Improvement of a Car Door Hinge for Compact Cars", Advanced Structured Materials 85, https://doi.org/10.1007/978-3-319-72697-7_11 [CrossRef]
50. M Kena and D Newton, J P Hakenberg, A Ali and A Aljabr, "Calculate the Cabin Air Bind Effort on Door Closing Efforts for Passenger Vehicle", Proceedings of the International Conference on Industrial Engineering and Operations Management Washington DC, USA, September 27-29, 2018, Page 156 – 168.
51. Eskezia E, Abera A and Daniel Tilahun, "Finite Element Analysis of Internal Door Panel of a Car by Cons idering Bamboo Fiber Reinforced Epoxy Composite", J Appl Mech Eng 2017, 6:1, DOI: 10.4172/2168-9873.1000247. [CrossRef]
52. Yogesh K. Nichit, Prof. Arun. K. Battu, "Development of Side Door Intrusion Beam of Passenger Car For Maximum Bending Load", IJSART - Volume 3 Issue 8 –AUGUST 2017 ISSN [ONLINE]: 2395-1052.
53. Cheng-Yong Huang, "Vehicle Door Opening Control Model Based on a Fuzzy Inference System to Prevent Motorcycle–Vehicle Door Crashes", Sustainability 2021, 13, 12558, https://doi.org/10.3390/su132212558. [CrossRef]
54. Suraj Shinde, Himadri Majumder, "Opportunities in Optimizing Car Door Weight", Engineering Science & Technology, DOI: https://doi.org/10.37256/est.222021699. [CrossRef]
55. Prem Kumar.D, Dr. V. Balaji, Mohamed Muzammil Sherief, Chinnarasu.M, Hariharan.S.B., "Design and impact analysis of car door", 2018 IJCRT Volume 6, Issue 1 February 2018, ISSN: 2320-2882.
56. M Kena and D Newton, A Ali and A Aljabr, "Study the effect of the weather strip on side door closing effort for passenger vehicle", Proceedings of the International Conference on Industrial Engineering and Operations Management Washington DC, USA, September 27-29, 2018, Page 142 – 155.
57. Nicholas Oettle, David Sims-Williams, "Automotive Aeroacoustics: An Overview", Prepared using sagej.cls, Version: 2015/06/09 v1.01.
58. Jiaxing Hu, Zhengnong Li and Zhefei Zhao, "Estimation Formula of Modal Frequency of High-Rise Buildings under DifferentWind Speeds during Typhoons", Appl. Sci. 2022, 12, 47, https://doi.org/10.3390/app12010047. [CrossRef]
59. Mekonnen Asmare Fentahun, Prof. Dr. Mahmut Ahsen Savaş, "Materials Used in Automotive Manufacture and Material Selection Using Ashby Charts", International Journal of Materials Engineering 2018, 8(3): 40-54, DOI: 10.5923/j.ijme.20180803.02.
60. D. I. G. Chomo D. S. Yawas Z. S. Johnson, "Development of an Automatic Door System", American Journal of Engineering Research (AJER) e-ISSN: 2320-0847, p-ISSN: 2320-0936, Volume-7, Issue-5, pp-168-173.

AUTHORS PROFILE

Mr. Pandurang Maruti Jadhav is a research scholar, the Mechanical Engineering Department, Dr D Y Patil Institute of Technology, Pune, India. His main area of research includes Car Door NVH, Vehicle NVH. He is having industrial experience of 30+ years in Design, Development, Powertrain and Vehicle CAE. He published 5+ nos. research papers in international journals.

Dr. Kishor B. Waghulde is a professor and research guide, Mechanical Engineering Department, Dr. D Y Patil Institute of Technology, Pune, India. . His main area of research includes Vibration. He is having 25+ years' experience in teaching and research. He published 30+ nos. research papers in national and international journals and conferences. He published 30+ nos. patents.

Dr. Rupesh V. Bhortake, Principal at Marathwada Mitra Mandal's Institute of Technology, Lohgaon, Tal Haveli, Pune 32. His main area of research includes Noise and Vibration. He is having 25+ years' experience in teaching and research. He published 15+ nos. research papers in national and international journals and conferences.