

Experimentally-Based Analytical Prediction of Structural Vibration

by

Chetan J. Dhruva

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Mechanical Engineering

Approved:

Mehdi Ahmadian, Chairman

Larry D. Mitchell

Robert L. West

December 1, 1997

Blacksburg, Virginia

Keywords: Structure, Testing, Modeling, Vibration, Prediction, Locomotive,
Cab

Experimentally-Based Analytical Prediction of Structural Vibration

by

Chetan J. Dhruva

Mehdi Ahmadian, Chairman

Mechanical Engineering

This study evaluates the vibration isolation effect of various mounting systems in a heavy freight locomotive cab, and provides an analytical method for the prediction of structural vibration. The cab is set up in a controlled laboratory environment in a manner similar to the installation on a locomotive. Field measurements are used to emulate actual vibration input to the cab structure. A 16-channel data acquisition system is used to collect vibration data at various points on and inside the cab structure.

The cab was isolated from the sill structure through six elastomeric mounts fixed at the base of the cab and at the crash posts. The mounts at the base were selected such that they support the static weight of the cab and offer good lateral and longitudinal stability. Two cylindrical elastomeric mounts were placed between the cab structure and the crash posts which attach to the front of the sill structure.

Upon establishing the baseline for laboratory vibration measurements and correlating them with field data, acceleration data was collected at discrete locations, both inside and outside of the cab. The data was used in conjunction with an analytical formulation to generate vibration approximations of the discrete locations. To validate the analytical approximations, experimental results were compared with the analytical predictions using simulated field input to the cab

The test results from the analytical model approximations proved to have a strong correlation with experimental results. Vibration approximations of locations outside the cab had a higher correlation to the experimental data than the points on the inside. Although the model did not yield exact results for several positions inside the cab, it resulted in several recommendations for future work.

Acknowledgments

I would like to say thank you to my advisor, Dr. Mehdi Ahmadian, for his help and encouragement throughout my time working with him in the Mechanical Engineering Department. I would also like to thank Drs. Larry Mitchell and Robert West for serving on my graduate committee.

Special thanks are due to General Electric Transportation Systems, Lord Corporation, and PCB Piezotronics for their generous support throughout this study. General Electric Transportation Systems provided the locomotive cab that was used for our study. Lord Corporation donated the elastomeric mounts that were used for soft-mounting the locomotive cab. PCB Piezotronics donated the acceleration measurement system that was used in collecting the data.

I thank the Mechanical Engineering Department at Virginia Tech for providing funding towards my graduate studies.

I would also like to thank Brian Reichert for providing help with developing the MATLAB programs that were used in this research as well as helping with setting up the experimentation of the cab.

Finally, I would like to say thank you to Vinod Raju, Jaime Venezia, and Mom/Dad Raja. I would not have been able to complete my studies without your love and support over the past two years.

Contents

1	Background	1
1.1	Introduction.....	1
1.2	Literature Review.....	2
1.2.1	Structural Vibration Prediction.....	3
1.2.2	Vehicle Vibration Prediction.....	5
1.2.3	Locomotive Vibration.....	5
1.3	Research Objective.....	6
1.4	Outline.....	7
2	Analytical Structural Vibration Prediction	8
2.1	Vibration Prediction.....	8
2.2	Previous Simulation Approach.....	9
2.3	New Simulation Approach.....	13
2.3.1	Analytical Model.....	16
2.3.1.1	Experiment.....	17
2.3.1.2	Model.....	18
2.3.1.3	Prediction.....	18
3	Vibration Test Setup	19
3.1	Cab Configuration.....	19
3.2	Actuation System.....	23
3.3	Data Acquisition System.....	27
3.4	Accelerometer Locations.....	31
3.5	Data Analysis.....	34
3.5.1	Hanning Window.....	36
3.6	Data Analysis Theory.....	38
4	Baseline Testing and Validation	42
4.1	Baseline Cab Configuration.....	42
4.2	Baseline Test Input.....	46

4.3	Baseline Test Results.....	51
4.4	Baseline Output Validation.....	53
4.5	Repeatability.....	56
5	Vibration Prediction for Outside the Cab	58
5.1	Hard-Mounted Cab Results.....	58
5.2	Soft-Mounted Cab Results.....	64
5.2.1	Configuration A - Soft-Mounted Cab.....	65
5.2.2	Configuration B - Soft-Mounted Cab.....	70
5.2.3	Configuration C - Soft-Mounted Cab.....	75
5.3	Concluding Remarks.....	76
6	Vibration Prediction for Inside the Cab	81
6.1	Hard-Mounted Cab Results.....	81
6.2	Soft-Mounted Cab Results.....	84
6.2.1	Configuration A - Soft-Mounted Cab.....	84
6.2.2	Configuration B - Soft-Mounted Cab.....	87
6.2.3	Configuration C - Soft-Mounted Cab.....	90
6.3	Concluding Remarks.....	93
7	Conclusions	94
7.1	Summary.....	94
7.2	Recommendations for Future Research.....	95
	References	96
	Appendices	99
A	Matlab Programs for Simulation	99
A.1	Matlab Code for Power Spectral Density Functions.....	99
A.2	Matlab Function for Taking an FFT.....	101
A.3	Matlab Code for Integrating Acceleration Data.....	102
A.4	Matlab Code for Analytical Prediction Model.....	104
	Vita	109

List of Figures

1.1	Literature Search Flow Chart	3
2.1	Single-Degree-of-Freedom Representation of a Mounted Structure.....	10
2.2	Comparison Between Test and Simulation Results for $\zeta = 0.05$	11
2.3	Comparison Between Test and Simulation Results for $\zeta = 0.90$	11
2.4	Measured Mount Transmissibility.....	12
2.5	Mount Transmissibility Included in Simulation.....	13
2.6	Mechanical Impedance of a Base-Excited System.....	14
2.7	Simulation Process Overview.....	16
2.8	Force Plot from the Actuator.....	17
3.1	Side View of Locomotive Cab.....	19
3.2	Plan View of Locomotive Cab.....	20
3.3	Goodyear Airbag Installation.....	22
3.4	Typical Elastomeric Mounts after Lord Corp.....	23
3.5	MTS 506 Series Hydraulic Power Supply after MTS.....	24
3.6	MTS 263 Hydraulic Service Manifold after MTS.....	25
3.7	MTS 249 Actuator with Swivel Ends after MTS.....	25
3.8	MTS Model 407 Servo Hydraulic Controller after MTS.....	26
3.9	Actuator Installation on the Locomotive Cab.....	27
3.10	Data Acquisition Flow Chart.....	28
3.11	PCB Accelerometers Used for Vibration Measurements.....	29
3.12	PCB Signal Conditioner Used for Vibration Measurements.....	30
3.13	HP 35665A Spectrum Analyzer.....	30
3.14	Sony DAT Recorder.....	31
3.15	Accelerometer Locations for External Cab Testing.....	32
3.16	Global Coordinate System.....	33
3.17	Accelerometer Locations for Interior Cab Testing.....	33

3.18	Data Analysis Flow Chart.....	35
3.19	(a) Periodic Sinusoid (b) Non-Periodic Sinusoid.....	37
3.20	Digital Filter Characteristics for Hanning Window after McConnell.....	38
4.1	The Locomotive (a) Cab (b) Sill Structure.....	43
4.2	B-Side Front Soft Mounting.....	44
4.3	Crash Post Mount.....	45
4.4	B-Side Front Hard Mounting.....	45
4.5	Modifications for Stiffening the Cab Floor	46
4.6	Hard-Mounted Cab/Sill Interface.....	47
4.7	Accelerometer B-Side Aft.....	48
4.8	Field Acceleration at B-Side Aft Location.....	49
4.9	Excitation Input to Actuator.....	50
4.10	(a) LabVIEW Input File and (b) LabVIEW Diagram.....	51
4.11	Sony Data Accelerometer at B-Side Aft Location.....	52
4.12	HP Analyzer Data Acquisition.....	53
4.13	HP Analyzer Setup.....	54
4.14	HP and Sony Data Accelerometer at B-Side Aft Location.....	55
4.15	Error Criteria for Sony and HP data.....	56
4.16	Minimum and Maximum Spectrum Values.....	57
5.1	Analytical and Experimental Results Comparison Process.....	59
5.2	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at B-side Aft Location; (a) Sill (b) Cab Structure.....	60
5.3	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at B-side Front Location; (a) Sill (b) Cab Structure.....	61
5.4	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at A-side Aft Location; (a) Sill (b) Cab Structure.....	62
5.5	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at A-side Front Location; (a) Sill (b) Cab Structure.....	63

5.6	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at B-side Aft Location; (a) Sill (b) Cab Structure.....	66
5.7	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at B-side Front Location; (a) Sill (b) Cab Structure.....	67
5.8	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at A-side Aft Location; (a) Sill (b) Cab Structure.....	68
5.9	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at A-side Front Location; (a) Sill (b) Cab Structure.....	69
5.10	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at B-side Aft Location; (a) Sill (b) Cab Structure.....	71
5.11	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at B-side Front Location; (a) Sill (b) Cab Structure.....	72
5.12	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at A-side Aft Location; (a) Sill (b) Cab Structure.....	73
5.13	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at A-side Front Location; (a) Sill (b) Cab Structure.....	74
5.14	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at B-side Aft Location; (a) Sill (b) Cab Structure.....	77
5.15	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at B-side Front Location; (a) Sill (b) Cab Structure.....	78
5.16	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at A-side Aft Location; (a) Sill (b) Cab Structure.....	79
5.17	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at A-side Front Location; (a) Sill (b) Cab Structure.....	80
6.1	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at Conductor Table.....	82
6.2	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at Cab Floor.....	82

6.3	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at CA1 Cabinet Door.....	83
6.4	Comparison Between Actual and Predicted Results for the Hard-Mounted Case ($K=1,000,000$ lb/in) at Floor Opposite Lavatory Door.....	83
6.5	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at Conductor Table.....	85
6.6	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at Cab Floor.....	86
6.7	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at CA1 Cabinet Door.....	86
6.8	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=10,000$ lb/in) at Floor Opposite Lavatory Door.....	87
6.9	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at Conductor Table.....	88
6.10	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at Cab Floor.....	89
6.11	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at CA1 Cabinet Door.....	89
6.12	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=16,700$ lb/in) at Floor Opposite Lavatory Door.....	90
6.13	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at Conductor Table.....	91
6.14	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at Cab Floor.....	91
6.15	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at CA1 Cabinet Door.....	92
6.16	Comparison Between Actual and Predicted Results for the Soft-Mounted Case ($K=23,300$ lb/in) at Floor Opposite Lavatory Door.....	92

List of Tables

3.1	Coordinates of Accelerometers for External Testing.....	32
3.2	Coordinates of Accelerometers for Internal Testing.....	34
5.1	Error Criteria for Experimental and Analytical Predictions.....	75
6.1	Error Criteria for Experimental and Analytical Predictions.....	93