

Master's Thesis

Development of a Methodology for Accelerating Vibration Endurance Tests on Complex Assemblies

Presented to the Institute for Sustainable and Autonomous Maritime Systems (INAM)
in the University of Duisburg Essen &
Performed at Vorwerk Elektrowerke GmbH & Co. KG Wuppertal

by

Rohan Maniwade
Matriculation No.: 3157316

Examiner	Prof. Dr.-Ing. Bettar Ould el Moctar
Supervisors:	Clément Gorges Corselli Dr.-Ing. Philipp Ingenlath
Degree Program:	M.Sc. Mechanical Engineering (Mechatronics)
Academic Semester:	Summer Semester 2025
Date:	31.10.2025



GHV in Bezug auf die **Masterarbeit von Herrn** Rohan Dhananjay Maniwade

Hiermit verpflichte ich mich, die Informationen und Ergebnisse während und im Zusammenhang der Betreuung und Prüfung der **Masterarbeit** mit dem Thema: „**Accelerated Product Testing with Optimised Vibration Profiles (Working Title)**“, die von **Herrn** Rohan Dhananjay Maniwade als externe **Masterarbeit** bei der Vorwerk Elektrowerke GmbH & Co. KG in Wuppertal bearbeitet wird, nicht an Dritte weiterzugeben oder zu veröffentlichen. Die **Masterarbeit** ist nur den Mitarbeitenden des betreuenden Lehrstuhls sowie den Mitgliedern des Prüfungsausschusses zugänglich zu machen.

Ould el
Moctar

Prof. Dr. Bettar el Moctar

Vorwerk Elektrowerke GmbH & Co. KG • Blombacher Bach 3 • 42270 Wuppertal • www.vorwerk.com
Amtsgericht Wuppertal, HR A 14 580 • Steuer-Nr. (5) 131/5852/0027
persönlich haftende Gesellschafterin: Vorwerk Elektrowerke Verwaltungsgesellschaft mbH, Wuppertal • Amtsgericht Wuppertal HR B 7852
Geschäftsführung: Dr.-Ing. Hendrik Wehr (Vorsitz), Dr.-Ing. Michael Homuth, Frank Meyer, Christian Spormann, Carsten Vollmar
Deutsche Bank AG • BLZ 330 700 90 • Konto 2 912 228 • BIC DEUTDE33XXX • IBAN DE56 3307 0090 0291 2228 00
Commerzbank AG • BLZ 330 400 01 • Konto 4 211 009 • BIC COBADE33XXX • IBAN DE62 3304 0001 0421 1009 00

CONFIDENTIAL



Non-Disclosure Notice

The present **bachelor thesis / master thesis / internship report / report / proof of etc.** with the title "Sample Title" contains internal and confidential information of the company Vorwerk Elektrowerke GmbH & Co.KG and the Vorwerk Group.

An insight into this bachelor thesis / master thesis / internship report / report / proof of etc. is not permitted to third parties. Exceptions are the supervising lecturers as well as the authorized members of the examination board. A publication and duplication of the bachelor thesis / master thesis / internship report / report / proof of etc. - also in excerpts - is not permitted within the restricted period of 10 years.

Exceptions to this rule require the approval of Vorwerk Elektrowerke GmbH & Co. KG.

A handwritten signature in blue ink, appearing to read "F. Han".

Employee Signature

The non-disclosure notice is to be documented directly behind the title page, is not listed in the table of contents and does not contain a page number.

Vorlage Sperrvermerk

Der/Die vorliegende **Bachelorarbeit/ Masterarbeit/ Praktikumsbericht/ Bericht /Nachweis etc.** mit dem Titel „**Mustertitel**“ beinhaltet interne und vertrauliche Informationen des Unternehmens Vorwerk Elektrowerke GmbH & Co.KG sowie der Vorwerk Gruppe.

Eine Einsicht in diese/n Bachelorarbeit/Masterarbeit/Praktikumsbericht/ Bericht/ Nachweis etc. ist Dritten nicht gestattet. Ausgenommen davon sind die betreuenden Dozierenden sowie die befugten Mitglieder des Prüfungsausschusses. Eine Veröffentlichung und Vervielfältigung der/des Bachelorarbeit/ Masterarbeit/Praktikumsbericht/ Bericht/ Nachweis etc. – auch in Auszügen – ist innerhalb der Sperrfrist von 10 Jahren nicht gestattet.

Ausnahmen von dieser Regelung bedürfen einer Genehmigung der Vorwerk Elektrowerke GmbH & Co. KG.

A handwritten signature in blue ink, appearing to read "Max Mustermann".

Max Mustermann

Der Sperrvermerk kommt direkt hinter das Titelblatt, wird nicht im Inhaltsverzeichnis mit aufgeführt und enthält keine Seitenzahl.

Acronyms

N - Number of cycles to failure

ζ - Damping factor

σ - Stress

b - Parameter b of basquin relationship $N \sigma^b = C$

Abstract

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aequale doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguere possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius. Ego autem mirari satis non queo unde hoc sit tam insolens domesticarum rerum fastidium. Non est omnino hic docendi locus; sed ita prorsus existimo, neque eum Torquatum, qui hoc primus cognomen invenerit, aut torquem illum hosti detraxisse, ut aliquam ex eo est consecutus? – Laudem et caritatem, quae sunt vitae.

Table of Content

Acronyms	IV
Abstract	V
List of Figures	VIII
List of Tables	IX
1 Introduction	1
1.1 Problem Statement	1
1.2 Thermomix® TM7	2
1.3 Endurance profile for Thermomix® TM7	3
1.4 Objective	3
2 Literature Review	4
3 Theoretical Background	4
3.1 Mission Synthesis	4
3.2 Fatigue Damage Spectrum (FDS)	4
3.3 Extreme Response Spectrum (ERS)	5
3.4 Shock Response Spectrum (SRS)	5
4 Endurance profile	5
5 Methodology	5
5.1 Research Design	5
5.2 Data Acquisition	6
5.2.1 Vibration Data Acquisition	6
5.2.2 Accelerometer Placement	6
5.2.3 Squadriga - Frontend	7
5.3 Signal Processing Pipeline	7
5.4 Accelerated PSD Generation	7

5.5	Time History Synthesis from PSD	7
5.6	Validation Procedure	7
6	Experimental Setup	7
6.1	Design and Modal Analysis of test fixture for the backend	7
7	Results and Discussion	7
7.1	Finding 1	7
7.2	Finding 2	8
7.3	Analysis	9
7.4	Implications	10
8	Conclusion and Outlook	11
8.1	Summary	11
8.2	Future Work	11
	Bibliography	12

List of Figures

Figure 1 Thermomix® TM7 [1]	2
-----------------------------------	---

List of Tables

1 Introduction

1.1 Problem Statement

Many engineered products operate in complex vibration environments over their service life. This can gradually lead to mechanical fatigue that threatens reliability and safety. To manage that risk, manufacturers run endurance tests to show that a product meets a specified lifetime in the field. The challenge is that traditional endurance testing is lengthy and resource intensive, which makes it hard to iterate and slows down development.

The Thermomix® TM7, a product of the Vorwerk Group, is affected by vibrational and thermal loads that originate within the device itself. Inside the company, a combined vibration and thermal endurance profile is used to assure 4,000 field hours of service. Running this complete profile on a complex assembly takes considerable time and effort, which motivates a more efficient approach.

This thesis formulates a methodology to derive an accelerated test profile that reproduces, in a laboratory setting, the fatigue damage and relevant operational loads observed in the field, while reducing test duration. The TM7 serves as the case study; the methodology is intended to generalise to other complex assemblies.

1.2 Thermomix® TM7



Figure 1: Thermomix® TM7 [1]

Thermomix® TM7 is the latest generation multifunctional cooking appliance by Vorwerk, designed to integrate numerous cooking, mixing, heating, and food-preparation capabilities into a single device.

Key features and specifications,

- Dimensions: 33.6cm × 25.3cm × 40.5cm
- Speed range: 40-10700rpm
- Weight: 8.6kg
- Mixing bowl capacity: 2.2L
- Heating power: 1000W
- Motor power: 500W [2]

1.3 Endurance profile for Thermomix® TM7

Vorwerk has developed an endurance testing profile for the Thermomix® TM7 based on usage patterns observed in earlier product generations. If the appliance experiences a characteristic distribution of knife speeds and heating temperatures over 4,000 hours in the field, the qualification test should reproduce that distribution. Accordingly, field data captures how frequently each speed mode is engaged, its average dwell time, and associated temperature ranges. Each mode is therefore assigned a percentage share of the cumulative operating interval.

To shorten development cycles, the same workload is transformed into an accelerated profile. Time and cycle allocations across modes are rebalanced so that essential exposure to critical combinations of speed and temperature is retained while the total laboratory duration is reduced to roughly 800 hours. The resulting schedule still exercises representative operating segments but in a more concentrated form that preserves relevance to real field use.

Even in this accelerated form, the campaign remains lengthy and resource demanding once pauses, handling, and supervision are included. This residual duration highlights a clear need for methods that can achieve additional reduction without sacrificing representativeness.

1.4 Objective

The main objective of this thesis is to establish a reliable and efficient methodology for accelerating vibration endurance testing of complex assemblies. In our case, The endurance profile for the

By leveraging the Fatigue Damage Spectrum (FDS) as the link between measured time histories of different modes of the test subject and laboratory test specifications, the study aims to generate equivalent and accelerated Power Spectral Densities (PSDs) that reproduce real operational fatigue damage within a reduced test duration. The methodology will be applied to Thermomix® TM7 backend as a representative case study validated through experimental vibration testing and response spectrum criteria following the MIL-STD-810G for test tailoring specification and the works of Christian Lalanne on Specification Development.

2 Literature Review

3 Theoretical Background

3.1 Mission Synthesis

3.2 Fatigue Damage Spectrum (FDS)

Fatigue Damage Spectrum (FDS) describes how a single-degree-of-freedom system accumulates fatigue damage when subjected to a specific vibration input, as a function of its natural frequency f_0 and a chosen damping ratio ζ .

The calculation of the FDS is based on several assumptions:

- The system is modeled as a single-degree-of-freedom linear oscillator.
- The S-N curve follows Basquin's relation ($N\sigma_p^b = C$).
- The peak stress is assumed proportional to the maximum relative displacement ($\sigma_p = Kz_p$).

- the rainflow counting method is used to count the response peaks.
- Miner's Damage accumulation rule is assumed.

[3]

3.3 Extreme Response Spectrum (ERS)

3.4 Shock Response Spectrum (SRS)

4 Endurance profile

5 Methodology

5.1 Research Design

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata

desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius.

5.2 Data Acquisition

5.2.1 Vibration Data Acquisition

For the synthesis of an accelerated PSD that provides equivalent damage as all the rotational speeds of the Thermomix according to the endurance profile, we need to first measure the vibration signals acting on the Thermomix, more precisely, the backend.

5.2.2 Accelerometer Placement

Since in our case we are focusing only on the backend circuit board of the TM7, we need to figure out which places are the most important for the placement of accelerometers. For that purpose, a modal analysis of the backend is conducted to find out the various mode shapes. This was conducted both in ANSYS and experimentally using impulse hammer test. From the mode shapes, the points of maximum deformation are noted and accelerometer placement is determined likewise.

[Insert images of Modal Analysis to make justifications]

Through a compromise, the sensors were placed as shown in the figure taking into account the restrictions but still making sure the critical areas are covered. 2 minitriaxial accelerometers and 1 triaxial accelerometer was used for the data acquisition.

5.2.3 Squadriga - Frontend

5.3 Signal Processing Pipeline

5.4 Accelerated PSD Generation

5.5 Time History Synthesis from PSD

5.6 Validation Procedure

6 Experimental Setup

6.1 Design and Modal Analysis of test fixture for the backend

7 Results and Discussion

7.1 Finding 1

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aequale doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguere possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus,

omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius. Ego autem mirari satis non queo unde hoc sit tam insolens domesticarum rerum fastidium. Non est omnino hic docendi locus; sed ita prorsus existimo, neque eum Torquatum, qui hoc primus cognomen invenerit, aut torquem illum hosti detraxisse, ut aliquam ex eo est consecutus? – Laudem et caritatem, quae sunt vitae.

7.2 Finding 2

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aequale doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguere possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius. Ego autem mirari satis non queo unde hoc sit tam insolens domesticarum rerum fastidium. Non est omnino hic docendi locus; sed ita prorsus existimo, neque eum Torquatum, qui

hoc primus cognomen invenerit, aut torquem illum hosti detraxisse, ut aliquam ex eo est consecutus? – Laudem et caritatem, quae sunt vitae.

7.3 Analysis

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aequale doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguere possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius. Ego autem mirari satis non queo unde hoc sit tam insolens domesticarum rerum fastidium. Non est omnino hic docendi locus; sed ita prorsus existimo, neque eum Torquatum, qui hoc primus cognomen invenerit, aut torquem illum hosti detraxisse, ut aliquam ex eo est consecutus? – Laudem et caritatem, quae sunt vitae sine metu degendae praesidia firmissima. – Filium morte multavit. – Si sine causa, nollem me ab eo delectari, quod ista Platonis, Aristoteli, Theophrasti orationis ornamenta neglexerit. Nam illud quidem physici, credere aliquid esse minimum, quod profecto numquam putavisset, si a Polyaeo, familiari suo, geometrica discere maluisset quam illum etiam ipsum.

7.4 Implications

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aequale doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguere possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in qua a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius. Ego autem mirari satis non queo unde hoc sit tam insolens domesticarum rerum fastidium. Non est omnino hic docendi locus; sed ita prorsus existimo, neque eum Torquatum, qui hoc primus cognomen invenerit, aut torquem illum hosti detraxisse, ut aliquam ex eo est consecutus? – Laudem et caritatem, quae sunt vitae sine metu degendae praesidia firmissima. – Filium morte multavit. – Si sine causa, nollem me ab eo delectari, quod ista Platonis, Aristoteli, Theophrasti orationis ornamenta neglexerit. Nam illud quidem physici, credere aliquid esse minimum, quod profecto numquam putavisset, si a Polyaeo, familiari suo, geometrica discere maluisset quam illum etiam ipsum.

8 Conclusion and Outlook

8.1 Summary

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aequale doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguere possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius.

8.2 Future Work

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aequale doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguere possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo a nobis philosophia defensa et collaudata est, cum id, quod maxime placeat, facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et

aut officiis debitis aut rerum necessitatibus saepe eveniet, ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum defuturum, quas natura non depravata desiderat. Et quem ad me accedis, saluto: 'chaere,' inquam, 'Tite!' lictores, turma omnis chorusque: 'chaere, Tite!' hinc hostis mi Albucius, hinc inimicus. Sed iure Mucius.

Bibliography

- [1] Vorwerk, “Thermomix TM7 Product Photo.” [Online]. Available: https://static.android.com.pl/uploads/2025/02/Thermomix_TM7_Product_Photo_MainDeviceSide-scaled.jpeg
- [2] Vorwerk, “Thermomix TM7.” [Online]. Available: <https://support-gb.vorwerk.com/hc/en-gb/sections/18497372886940-Technical-specifications>
- [3] C. Lalanne, *Mechanical vibration and shock analysis, specification development*. John Wiley & Sons, 2010.