



TECHNISCHE
UNIVERSITÄT
DARMSTADT

Mihir Joshi

**Development of semi-actively damped
milling chuck for chatter reduction in
high dynamic milling**

**Schriftenreihe des PTW
„Innovation Fertigungstechnik“**

Herausgeber
Prof. Dr.-Ing. Eberhard Abele
Prof. Dr.-Ing. Joachim Metternich
Prof. Dr.-Ing. Matthias Weigold



Institut für
Produktionsmanagement,
Technologie und
Werkzeugmaschinen

Development of semi-actively damped milling chuck for chatter reduction in high dynamic milling

Dem Fachbereich Maschinenbau
an der Technischen Universität Darmstadt
zur
Erlangung des Grades eines Doktor-Ingenieurs (Dr.-Ing.)
eingereichte

D i s s e r t a t i o n

vorgelegt von

Mihir Joshi. M. Sc.
aus Mumbai, Indien

Berichterstatter:	Prof. Dr.-Ing. E. Abele
Mitberichterstatter:	Prof. Dr.-Ing. R. Anderl
Tag der Einreichung:	24.01.2022
Tag der mündlichen Prüfung:	31.05.2022

Schriftenreihe des PTW: "Innovation Fertigungstechnik"

Mihir Joshi

**Development of semi-actively damped milling chuck
for chatter reduction in high dynamic milling**

D 17 (Diss. TU Darmstadt)

Shaker Verlag
Düren 2023

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Darmstadt, Techn. Univ., Diss., 2022

Copyright Shaker Verlag 2023

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-8878-6

ISSN 1864-2179

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: www.shaker.de • e-mail: info@shaker.de

Contents

- 1 Motivation 1**
- 2 State of the art 5**
 - 2.1 Fundamentals of vibration theory 5
 - 2.1.1 Single degree of freedom system with a dynamic vibration absorber 8
 - 2.1.2 Multiple degree of freedom system with a dynamic vibration absorber 10
 - 2.1.3 Non-linear harmonic absorber 10
 - 2.2 Fundamentals of milling process and machine tool vibrations 11
 - 2.2.1 Kinematics and dynamics of milling 11
 - 2.2.2 Design of cutting tool systems 11
 - 2.2.3 Dynamic compliance of cutting tool systems 13
 - 2.2.4 Vibrations in machine tools 15
 - 2.2.5 Vibration reduction in machine tools 18
 - 2.3 Fundamentals of electro- and magneto-rheological fluids . . . 25
 - 2.3.1 Dynamic characterisation of ER Fluids 28
 - 2.3.2 Industrial applications of smart fluids for vibration reduction 31
 - 2.4 Intermediate conclusion 34
- 3 Definition of scope and research approach 35**
- 4 Experimental investigations with reference milling chuck 37**
 - 4.1 Description of used equipment and experimental boundary conditions 37
 - 4.1.1 Machine tool 37
 - 4.1.2 Milling chuck and tool clamping 39
 - 4.1.3 Cutting tool 39
 - 4.1.4 Workpiece - chemical composition and geometry . . . 41
 - 4.1.5 Measurement equipment 43
 - 4.2 Reference experiments - FRF of standard milling chuck . . . 47

4.3	Reference experiments - Milling experiments with standard chuck	48
4.3.1	Effect of the cutting tool engagement on the dynamic component of the active force	50
4.3.2	Analysis of measured active force	56
4.4	Reference experiments - Static deflection under lateral force .	62
4.5	Intermediate conclusion	63
5	Development and design of the ERF chuck	65
5.1	Definition of system requirements	65
5.2	Morphological analysis for design of milling chuck with a variable impedance	66
5.3	Concept phase	69
5.3.1	Ordering of function structures	69
5.3.2	Discussion of design possibilities	69
5.3.3	Morphological box	76
5.4	Detailed design of milling chuck with ERF	80
5.4.1	Added Mass	80
5.4.2	Electrode	88
5.4.3	Voltage transmission	90
5.4.4	Filling and operational voltage of electro rheological fluid in the new milling chuck system	93
5.5	Qualitative evaluation of behaviour of the electro-rheological fluid	94
5.6	Final Design and intermediate conclusion	98
6	Experimental trials on milling chuck with electro-rheological fluid	101
6.1	Modal Analysis	101
6.1.1	Free vibration with impact hammer	101
6.1.2	Harmonic vibration with shaker	102
6.2	Milling experiments	104
7	Conclusion and outlook	111
8	Appendix	115
	Bibliography	117

List of Figures

Figure 1.1	Process chain in the machining of moulds and low immersion milling	1
Figure 2.1	Mechanical model of vibration absorber	6
Figure 2.2	Possible methods of damping of mechanical systems	7
Figure 2.3	Assembly schematic of a standard collet chuck	12
Figure 2.4	Detailed drawing of collet and collet taper	14
Figure 2.5	Externally excited and self-excited vibrations (Weck and Brecher 2006 pp. 250)	16
Figure 2.6	Regenerative chatter in milling process (Schmitz and Smith 2009 P. 114)	18
Figure 2.7	Passively damped milling chuck (MAPAL 2016)	22
Figure 2.8	Integration of passively damped vibration absorbers (Nakano, Takahara and Kondo 2013)	23
Figure 2.9	Flow behaviour of non-newtonian fluids compared to newtonian fluids	26
Figure 2.10	Flow modes of an ERF	27
Figure 2.11	Basic electrical circuit for mechanical system consisting of (a) ERF and (b) MRF (Weiss et al. 1993)	30
Figure 2.12	Integration of smart fluids in boring bars	33
Figure 4.1	Characteristics of the machine tool DMG DMC 75V Linear	38
Figure 4.2	Cutting tool micro-geometry	41
Figure 4.3	Mechanical properties and chemical composition of mild steel alloy 1.2738 (Source:ASTM Steel)	42
Figure 4.4	Geometry and fixation of workpiece used for milling experiments	42
Figure 4.5	Positioning of sensors and measurement chain to determine cutting tool behaviour under free vibration	44
Figure 4.6	Measurement chain with force dynamometer for milling experiments	46

Figure 4.7	FRF Reference Comparison ER16 ER32	47
Figure 4.8	Progression of force signal in time domain	49
Figure 4.9	Progression of cutting edges through the engagement zone during tool rotation	51
Figure 4.10	Progression of cutting edges through the engagement zone during tool rotation	53
Figure 4.11	Progression of cutting edges through the engagement zone during tool rotation	54
Figure 4.12	Effect of variation of cutting velocity and radial depth of cut on active force in milling	57
Figure 4.13	Effect of variation of cutting velocity and radial depth of cut on active force amplitude $F_{a,amp}$ in milling	57
Figure 4.14	Cutting force signal analysis in frequency domain using FFT	59
Figure 4.15	Cutting force signal analysis in time domain using Poincare sectioning analysis	60
Figure 4.16	Magnitude of poincare section under the influence of variation of technology parameters	61
Figure 4.17	Static deflection of milling chuck under laterally acting force	62
Figure 5.1	Hierarchical order of system function structure	70
Figure 5.2	Abstract design of milling chuck system with positioning of the electrodes	73
Figure 5.3	Abstract design of voltage application with	74
Figure 5.4	Conceptual view of position of added mass to the milling chuck	81
Figure 5.5	Effect of increase in outer diameter of milling chuck on calculated frequency response function	83
Figure 5.6	Effect of increase in outer diameter of milling chuck on the experimentally determined frequency response function	84
Figure 5.7	Effect of the change in the length of the vibration absorber ring on the frequency response of the milling chuck system	86
Figure 5.8	Effect of the change in viscosity of analogy fluid on the frequency response of the milling chuck system	87
Figure 5.9	Conceptual diagram of position of voltage transmission cable and electrode in milling chuck with ERF	88
Figure 5.10	CAD model of the final design of the milling chuck with electro-rheological fluid	92

Figure 5.11 CAD Model of ERF Test bench to understand fluid behaviour under force and electric voltage	95
Figure 5.12 Behaviour of ERF under the variation of electrical voltage and harmonic excitation in squeeze mode	98
Figure 5.13 Behaviour of ERF under the variation of electrical voltage and harmonic excitation in shear mode	99
Figure 6.1 FRF of milling chuck integrated with ERF under free vibration	102
Figure 6.2 FRF of milling chuck integrated with ERF under harmonic excitation	103
Figure 6.3 Effect of variation of process technology parameters and electrical voltage on active force with ERF-milling chuck . . .	105
Figure 6.4 Effect of variation of process technology parameters and electrical voltage on amplitude of active force with ERF-milling chuck	106
Figure 6.5 Effect of electrical field magnitude on process stability in frequency domain with ERF-milling chuck	107
Figure 6.6 Effect of electrical field magnitude on process stability in time domain with ERF-milling chuck	108
Figure 8.1 Engagement conditions on a discretized tool disc during cutting tool rotation	115
Figure 8.2 Effect of lateral static loading on deflection along axis of milling chuck	116

List of Tables

2.1 Summary of literature of ER fluid characterisation 29

4.1 List of technology and process parameters for milling experiments 48

5.1 Requirement list for milling chuck with electro rheological fluid 67

5.2 Morphological box for semi-actively damped milling chuck system 76

5.3 Comparison of evaluation criteria for weighting 78

5.4 Points based evaluation of the possible solution concepts . . . 79

Greek letters and other symbols

Variable	Unit	Description
A_{sp}	mm^2	uncut chip cross-section
\mathbf{C}	-	damping matrix
D	-	damping co-efficient according to LEHR
D_{opt}	-	optimal damping ratio
E	-	modulus of elasticity
F	N	force
$F(\omega)$	-	force matrix in frequency domain
F_a	N	active cutting force
F_x	N	measured force in x-direction
F_y	N	measured force in y-direction
$G(\omega)$	-	compliance matrix in frequency domain
I	mm^4	Area moment of inertia
I_A	mm^4	Area moment of inertia about a particular axis

List of Tables

Variable	Unit	Description
I_c	A	electric current
K	-	stiffness matrix
M	-	mass matrix
Q	cm^3	material removal rate
R_m	N/m^2	ultimate tensile strength
U	-	uniformity ratio
X	m	displacement matrix
$X(\omega)$	-	displacement matrix in frequency domain
X_0	-	maximum amplitude
\dot{X}	m/s	velocity matrix
\ddot{X}	m/s^2	acceleration
a_{cr}	mm	critical axial depth of cut
a_e	mm	radial depth of cut
a_p	mm	axial depth of cut
b	-	damping constant
b_{lim}	mm	maximum depth of cut
c		damping co-efficient
d_i	mm	diameter
f_0	Hz	eigen-frequency
f_z	mm	feed per cutting edge
h_c	mm	uncut chip thickness
i	-	imaginary number
l_c	mm	cutting edge contact length
l_i	mm	length
k	N/m	stiffness
m	kg	mass
m_{va}	kg	mass of vibration absorber
n_i	1/s	natural frequencies
r_T	mm	cutting tool radius
t	s	time
v_c	m/min	cutting speed
v_f	m/min	feed speed

Variable	Unit	Description
\dot{x}	m/s	velocity
\ddot{x}	m/s^2	acceleration
x	m	displacement
α_i	°	relief angle
β_i	°	wedge angle
γ_i	°	rake angle
λ	°	helix angle
μ_A	-	mass ratio
μ_T	-	mass ratio
τ_0	N/m^2	shear stress
τ_i	°	pitch angle
ω_0	rad/s	first eigen(circular) frequency

Symbols and Abbreviations

Abbreviations

HSC	High-Speed-Cutting, Hochgeschwindigkeitsbearbeitung
ISO	International Standards Organisation
DIN	Deutsches Institut für Normung / German institute for standardisation
EN	English
SK	Steilkegel / for taper shank
HSK	Hohlschaftkegel / for hollow taper shank
HPC	High-Performance-Cutting, Hochleistungsbearbeitung
ERF	Electro-rheological fluid
MRF	Magneto-rheological fluid
DVA	Dynamic vibration absorber
SLD	Stability lobe diagram
HB	Brinell Hardness
HRC	Rockwell hardness constant
CNC	Computerised numerical control

List of Tables

NC	Numerical control
FFT	Fourier frequency transformation
BNC	Bayonet Neill–Concelman
PCB	printed circuit board

Preface by the editor

Der Einsatz von Zerspanungswerkzeugen zur Bearbeitung von Formen und Gesenken mit einem größtmöglichen Produktivitätsgewinn steht seit Jahrzehnten im Mittelpunkt der Forschung. Dieses Thema ist für Hochlohnländer von strategischer Bedeutung, um wettbewerbsfähig zu bleiben. Die Werkzeugsysteme, bestehend aus Werkzeugen und Spannfuttern insbesondere bei einem großen Aspektverhältnis, stellen das schwächste Glied in der Konstruktion der Werkzeugmaschine dar. Wodurch die einsetzbare Schnittgeschwindigkeit aufgrund Rattern signifikant eingeschränkt wird.

Ziel dieser Arbeit ist daher die Entwicklung eines semi-aktiv gedämpften Spannfutters zur Reduzierung von Rattern. Zunächst wurden die Randbedingungen des bestehenden Spannfutters mittels Modalanalyse ermittelt. Anschließend wurden die Grenzen des Prozesses für das bestehende Fräsfutter experimentell untersucht. Bei der Konstruktion des Prototyps wird die Produktentwicklungsmethodik nach der VDI-Richtlinie 2221 angewendet. Elektrorheologische Flüssigkeiten ändern ihre Viskosität, wenn sie durch ein elektrisches Feld aktiviert werden. Die Anpassung des bestehenden Werkzeugsystems für die Integration von elektrorheologischen Flüssigkeiten wird in zwei Hauptaspekten gegliedert. Erstens die Konstruktion eines Massenrings, der mit Hilfe der elektrorheologischen Flüssigkeit an das Fräsfutter zur Schwingungsdämpfung gekoppelt wurde. Die Konstruktion des Massenrings wurde iterativ durch Experimente bestimmt. Zweitens die Integration der Möglichkeit zur Übertragung der elektrischen Spannung beim Fräsen. Die größte Herausforderung besteht hier darin, eine stabile Spannungsübertragung in das rotierende System zu ermöglichen. Die Validierung des Prototyps wurde durch Schwingungsanalyse durchgeführt. Durch Fräsexperimente wurde die Anwendung des entwickelten Prototyps für einen Anwendungsfall demonstriert.

Darmstadt, im Januar 2022

Prof.Dr.-Ing. Eberhard Abele

Acknowledgement

This thesis was written as a part of my work at Institute for Production Management, Technology and Machine Tools, PTW at the Technical University of Darmstadt.

I express my gratitude to the chair professor Prof. Dr.-Ing. Eberhard Abele for his supervision of this thesis and his constructive feedback. I would also like to thank him for giving me the chance to pursue my higher education at his chair and gain invaluable experience during my time there.

To my colleagues at the the institute, I would like to thank you all especially for the highly co-operative work environment. A special thanks here goes to all the members of the cutting tools department during my tenure at the institute. I will always remember the after-work team building events. In the same vein, I would thank all the students, who assisted me in the execution of the experiments. Without your excellent work ethic and support, this work would have taken a lot longer.

The biggest thanks, without doubt, goes to my mother Mrs. Mrudula Joshi and my father Mr. Dhananjay Joshi. Without your never ending support for my decisions and belief in me all through out these years, none of this would have been possible. A very special thanks goes to my loving aunt Mrs. Manjusha Gawde, for your help and support. Last but not least, thank you to Julia Kolb and Lukas Freudl for being not just the best flatmates, but also for being my substitute family during all the many years in Darmstadt.

Gießen im Januar. 2022

Mihir Joshi