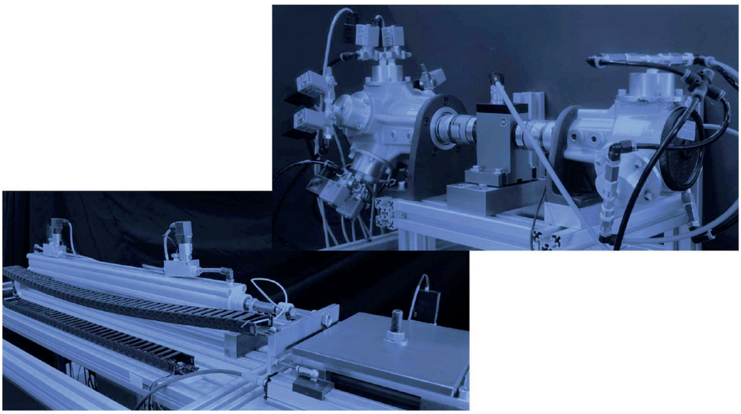
Reihe
Fluidtechnik

Stephan Merkelbach

Analysis of the Economic and Ecological Properties of Pneumatic Actuator Systems with Pneumatic Transformers



“Analysis of the Economic and Ecological Properties of Pneumatic Actuator Systems with Pneumatic Transformers”

„Analyse der wirtschaftlichen und ökologischen Eigenschaften pneumatischer Antriebssysteme mit pneumatischen Druckwandlern“

Von der Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

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Tag der mündlichen Prüfung: 31.10.2019

Reihe Fluidtechnik

D / Band 96

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Shaker Verlag
Düren 2020

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.: D 82 (Diss. RWTH Aachen University, 2019)

Printed in Germany.

ISBN 978-3-8440-7161-0
ISSN 1437-8434

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

"Large increases in cost with questionable increases in performance can be tolerated only in race horses and fancy women."

William Thomson, 1st Baron Kelvin (1824 – 1907)

I Preface

Long before even thinking about writing anything like this thesis, I first came to ifas when I wrote my Bachelor Thesis in Augsburg. At that time, Heino worked as scientific director of the institute and supervised my work. Thank you very much for that and for offering me the possibility of working as a student assistant in the famous “Baggerbüro” with Sgro. Thanks to Sgro and Milos, I learned seeing the beauty and fun in the simulation of hydraulic systems.

When I first thought of staying at ifas, I talked to Olivier who was Chief Engineer at that time. When he got to know that I know at least some thermodynamics, my fate was sealed, and I became part of the pneumatics group at ifas. For this and for your support throughout my research, I have to thank you very much, Olivier!

At the beginning of my pneumatic research, Christian, also known as “Grubi” or “Dr. von Gräbe” was my group leader. With his help and support I got a good start and got to know many tricks and facts around pneumatics. After Grubi left ifas, Mäxchen took over as group leader. Many discussions about the future of pneumatics and maybe even more off-work activities later, our group changed its name to “Digitalization and Automation” but kept its unique spirit. Thanks a lot to both of you.

In the last one and a half years of my time at the institute, the “ifas-Kochgruppe” always kept me well fed and supplied good talks during lunchtime. Thanks a lot, guys!

During my years at ifas, I shared my office with Jan, Stefan, Christoph, Marcel, Ximena and Andris as well as our guest researchers Chaoqin, Chuan and especially Chong. It was a real pleasure working, discussing and celebrating with all of you.

Many thanks go to Prof. Hubertus Murrenhoff for taking me as part of the scientific staff at ifas and for his support and supervision during my time at the institute. Also, I want to thank Prof. Katharina Schmitz for acting as second examiner, Prof. Christian Schindler for chairing my examination and Prof. Volker Stich for acting as co-chair.

Special thanks go out to the ifas-staff, especially to Jutta, Susanne, Morena and Klaus who have always been good support in organisational and technical matters.

I need to thank my student assistants Piyusha, Gero, Yannick, Fabian and Kaspar. Without you, this thesis could not have been finished. Also, I want to thank all the students whose theses I supervised during my time here at ifas. These are Armin, Borja, Bünyamin, Elisa, Joan, Jonas, Matevz, Micha and Mirko. Thanks a lot!

Many of the results presented in this thesis were obtained during the different research projects I worked on with different partner institutes. Therefore, I want to thank Bastian from the WZL at RWTH Aachen, Elvira and Fedor from IFD at TU Dresden and Dominik and Andreas from FIR at RWTH for the collaboration in the projects.

During my time in Aachen (and Augsburg in between), my parents and sisters always supported me. Thanks a lot for this!

Finally, I want to thank Vera for always supporting me during my time at ifas and for keeping me working on the thesis. Without you, none of this would have been possible.

II Kurzfassung

Pneumatische Antriebe werden in vielen indrustriellen Anwendungen eingesetzt. In jüngerer Vergangenheit treten neben den Anschaffungskosten immer öfter auch die gesamten Lebenszykluskosten bei der Investitionsentscheidung in den Vordergrund.
Die Arbeit beschreibt eine ökonomische und ökologische Lebenszyklusanalyse pneumatischer Antriebe. Die Lebenszykluskosten pneumatischer Antriebe werden für typische Lastzyklen ermittelt und mit denen elektromechanischer Antriebe verglichen. Auf Basis des Exergiekonzepts wird die Effizienz der beiden Antriebsarten ermittelt. Aus den Energiekosten wird mit der notwendigen Investition sowie weiteren anfallenden Kosten der gesamte Lebenszyklus bilanziert. Weiterhin erfolgt eine Untersuchung des Effizienzpotentials pneumatischer Antriebe mit verschiedenen, einfach umzusetzenden Energiesparschaltungen, die die Betriebskosten mit verhältnismäßig geringem Implementierungsaufwand erheblich senken können.
Um thermodynamisch bedingte Verluste zu reduzieren, kommt einer Reduktion des Betriebsdrucks steigende Aufmerksamtkeit zu. Um die gleiche Antriebskraft und Laststeifigkeit zu erreichen, macht dies jedoch den Einsatz größerer Antriebe notwendig. Manche Anwendungen erfordern jedoch weiterhin kompakte Antriebe bei gleichzeitig hoher Kraft. Um die Installation eines zusätzlichen Hochdruckluftnetzes zu vermeiden, besteht die Möglichkeit des Einsatzes druckluftgetriebener Doppelkolbendruckübersetzer, die prinzipbedingt hohe Verluste und ein sehr lautes Betriebsgeräusch aufweisen. Die Arbeit stellt die Entwicklung und Funktionsprüfung eines neuartigen, auf Radialkolbeneinheiten basierenden Druckübersetzerkonzepts vor. Nach einer Simulationsstudie wird ein Funktionsmuster entwickelt und untersucht. Zur Steigerung der Effizienz werden verschiedene Optimierungen durchgeführt und validiert. Weiterhin erfolgt eine Abschätzung des Einflusses eines Niederdrucksystems mit Einsatz pneumatischer Druckverstärker auf die Effizienz sowie die Lebenszykluskosten der am Niederdrucknetz bzw. mit Luft auf verstärktem Hochdruck betriebenen Antriebe.
Vor dem Hintergrund des Klimawandels wird der durch die Antriebe verursachte Ausstoß an Klimagasen zu einer wichtigeren Größe bei der Entscheidung zwischen unterschiedlichen Antriebssystemen. Zum Abschluss der Arbeit erfolgt daher eine Betrachtung der ökologischen Auswirkungen pneumatischer Linearantriebe mit Fokus auf den CO_2-Ausstoß. Hierzu wird anhand eines beispielhaften pneumatischen Zylinders eine Analyse der Emissionen über den Lebenszyklus von der Rohstoffherstellung bis zum Recycling durchgeführt.

III Abstract

Pneumatic drives are used in a wide variety of industrial applications. Recently, the life cycle costs (LCC) of the actuators become more important in investment decisions as the acquisition costs do not necessarily reflect the drives' economic efficiency. This thesis describes an economic and ecological life cycle analysis of pneumatic actuators. First, the LCC of the drives are estimated based on typical load cycles and compared the LCC of comparable electromechanical actuators. Therefore, the efficiency of both drive types is compared based on the exergy concept. Together with the acquisition costs and further cost elements, the LCC are calculated depending on the load cycles.

Furthermore, an assessment of the reduction potential for the exergy demand of the pneumatic drives is executed by an experimental investigation of different exergy saving measures with low installation effort which can reduce the demand for compressed air and working costs immensely while affording relatively low installation effort.

In addition to these measures installed in direct vicinity to the drive, nowadays, the operation of the whole pneumatic system at lower pressure gathers growing attention. A lower system pressure leads to a reduction of losses in the compressor. On the downside, the implementation of larger drives to gain the same output force and load stiffness is necessary. Some applications still afford small drives with high force. To avoid the implementation costs of an additional high-pressure system, local pressure boosting by means of pneumatically driven boosters is feasible. For this, double piston boosters are state of the art. Their working principle implies high exergy losses and noise emissions. The thesis presents the development and functional testing of a novel pressure booster concept based on pneumatic radial piston units. The concept is evaluated in a simulation study and a functional model is designed and manufactured. It is examined experimentally and different optimisations to increase its exergy efficiency are implemented and validated. As a conclusion, the impact of low-pressure pneumatic systems including pneumatic boosters on the overall efficiency and the LCC of the drives is estimated. This includes drives working at a reduced driving pressure as well as at boosted high pressure.

Facing climate change, the emissions of greenhouse gases (GHG) become more important as an additional parameter for the decision between different drive technologies. Besides the economic analysis of the drives, the thesis shows the results of a life cycle analysis focusing on the GHG emissions for one exemplary actuator including its whole life cycle from production of the materials up to the recycling of the components after their end-of-life.

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IV Formula Symbols

Latin Symbols

Symbol	Description	Unit
a_i	Expenses in year i	€
c_p	Specific isobaric heat capacity	$\mathrm{J/(kg \cdot K)}$
D	Diameter	m
e_i	Earnings in year i	€
E	Exergy	J
F	Force	N
h	Specific enthalpy	$\mathrm{J/kg}$
J	Moment of inertia	$\mathrm{kg\,m^2}$
k	Heat transfer coefficient	$\mathrm{W/(m^2 \cdot K)}$
K_0	Present value	€
l	Length	m
L	Residual value	€
m	Mass	kg
M	Torque	Nm
MRR	Material removal rate	$\mathrm{kg/s}$
n	Polytropic coefficient	$-$
p	Pressure	Pa
P	Power	W
q	Discount factor	$-$
R	Specific gas constant	$\mathrm{J/(kg \cdot K)}$
s	Specific entropy	$\mathrm{J/(kg \cdot K)}$

SEC	Specific energy consumption	$\mathrm{J/kg}$
t	Time	s
T	Temperature	K
v	Specific volume	$\mathrm{m^3/kg}$
V	Volume	$\mathrm{m^3}$
w	Specific energy	$\mathrm{J/kg}$
W	Energy	J
x	Piston stroke	m

Greek Symbols

Symbol	**Description**	**Unit**
ζ	Exergy Efficiency	$-$
κ	Isentropic coefficent	$-$
λ_s	Push rod ratio	$-$
Λ	Mass flow ratio	$-$
Π	Pressure ratio	$-$
ρ	Density	$\mathrm{kg/m^3}$
φ	Angular position	$-$
$\dot{\varphi}, \omega$	Angular velocity	$\mathrm{s^{-1}}$

V Abbreviations

Abbreviation	Description
AC	Alternating current
CA	Compressed air
CAS	Compressed air system
CO_{2eq}	Equivalent of CO_2-emissions
DC	Direct current
EM	Electromechanical
FS	Full scale
GHG	Greenhouse gas
GWP	Global warming potential
HP	High pressure
IDC	Inner dead centre
LCA	Life cycle analysis
LCC	Life cycle costs
LCCBOU	Life cycle cost based on users
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
LP	Low pressure
NBR	Nitrile butadiene rubber
ODC	Outer dead centre
PCF	Product carbon footprint
PN	Pneumatic
Rd	Random error

rpm	Revolutions per minute
TCO	Total cost of ownership
tkm	Ton kilometer