OPTIMIZATION OF MAGNETO-RHEOLOGICAL FLUID IN SQUEEZE MODE USING COMBINED D-OPTIMAL MIXTURE DESIGN

SITI AISHAH BINTI WAHID

MASTER OF ENGINEERING
(MANUFACTURING)

UNIVERSITI MALAYSIA PAHANG

Universiti Malaysia PAHANG

Engineering • Technology • Creativity

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Engineering (Manufacturing).

____

(Supervisor's Signature)

Full Name : DR. IZWAN BIN ISMAIL

Position : SENIOR LECTURER

Date :

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : SITI AISHAH BINTI WAHID

ID Number : MMF14003

Date :

OPTIMIZATION OF MAGNETO-RHEOLOGICAL FLUID IN SQUEEZE MODE USING COMBINED D-OPTIMAL MIXTURE DESIGN

SITI AISHAH BINTI WAHID

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Engineering (Manufacturing)

Faculty of Mechanical & Manufacturing Engineering

UNIVERSITI MALAYSIA PAHANG

AUGUST 2019

ACKNOWLEDGEMENTS

I would first like to thank my supervisor Dr. Izwan bin Ismail of the Faculty of Mechanical & Manufacturing Engineering at Universiti Malaysia Pahang. The door to Dr. Izwan office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

I would also like to thank the teams and colleagues at Faculty of Mechanical & Manufacturing Engineering, University Malaysia Pahang who were involved in this research project. Without their passionate participation and input, the research and thesis could not have been successfully completed.

My sincere thanks to the Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia Kuala Lumpur, who provided me an opportunity to join their team and who gave access to the laboratory and research facilities. Without their precious support it would not be possible to conduct this research.

Finally, I must express my very profound gratitude to my husband, Mohd Fakhurozi bin Abdullah, for providing me with unfailing support throughout my years of study. Not forgotten to my parents and children for their continuous encouragement and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

ABSTRAK

Cecair magneto-rheologi (MR) dalam mod perahan boleh menghasilkan sehingga 80kPa rintangan tegasan yang mana melebihi kehendak biasa aplikasi mekanikal. Walaubagaimanapun, untuk mencapai prestasi rintangan tegasan dan kestabilan yang baik, kadar komposisi cecair MR hendaklah dioptimumkan. Tujuan kajian ini dijalankan adalah untuk mengoptimumkan kadar komposisi bahan campuran cecair MR dalam mod perahan. Ini dilakukan dengan mengkaji kesan parameter bahan terhadap kestabilan dan kadar rintangan tegasan. Kajian ini dijalankan melalui rekabentuk eksperimen (*DOE*) menggunakan model Rekabentuk Campuran D-Optimal (*CDMD*). *CDMD* membenarkan kadar komposisi bahan campuran cecair MR dan kelikatan cecair pembawa dioptimumkan untuk menghasilkan kesan parameter bahan terhadap kestabilan dan kadar rintangan tegasan. Kadar komposisi bahan ditentukan menggunakan DOE faktorial dan data dari kajian terdahulu. Kadar komposisi minyak mineral (MO), zarah besi karboksil (CIP) dan silika terwasap (FS) adalah 60-75vol%, 20-40vol% dan 5-10vol%. Sementara itu, kadar kelikatan cecair pembawa ialah di antara 18.5cP hingga 98.1cP. Kestabilan cecair MR diukur dengan menggunakan analisis pemantauan manakala kadar rintangan tegasan diukur dengan menggunakan analisis rheologi dan analisis ujian mampatan. Dapatan kajian menunjukkan bahawa peningkatan kelikatan cecair pembawa menurunkan kadar pemendapan dari 8.75% ke 2.5% dan menurunkan kadar rintangan tegasan mampatan dari 0.86MPa ke 0.72MPa. Komposisi CIP merupakan faktor yang paling penting untuk mempengaruhi kadar pemendapan dan kadar rintangan tegasan cecair MR. Peningkatan komposisi CIP menurunkan kadar pemendapan tetapi meningkatkan rintangan tegasan. Walaupun komposisi FS menunjukkan kurang penting dalam perubahan rintangan tegasan, namun ia penting untuk menstabilkan cecair MR. Selepas analisis *CDMD*, sebanyak lima model analisis yang dihasilkan mempunyai nilai keinginan 1. Komposisi terbaik dalam kajian ini menghasilkan pemendapan 0.09%, tegasan ricih 89kPa dan tegasan mampatan 18.9MPa. Kajian ini menunjukkan cecair MR yang stabil dapat dihasilkan untuk aplikasi mod perahan dengan memilih kelikatan cecair pembawa yang lebih tinggi dan meningkatkan komposisi CIP. Model optimum yang dihasilkan dalam kajian ini adalah penting untuk menghasilkan cecair MR untuk peranti MR dalam mod perahan.

ABSTRACT

Magneto-rheological (MR) fluids in squeeze mode able to produce stress resistance up to 80kPa which is exceeded most basic requirement of normal mechanical application. However, to attain the good performance of stress resistance at acceptable suspension stability, the composition of MR fluids has to be optimized. The aim of this study is to optimize the MR fluid materials' component mixture in squeeze mode application through investigation on the effect of materials parameter on suspension stability and stress resistance. This study has been conducted through design of experiment (DOE) methodology using combined D-Optimal Mixture Design (CDMD) model. The CDMD allowed optimization of combined MR fluid components mixture and carrier fluid viscosity to produce relationship between material parameters and both stability and stress resistance. Ranges of materials composition were determined using factorial DOE and data from previous work. The investigated range of mineral oil (MO), carbonyl iron particles (CIP) and fumed silica (FS) were between 60-75vol%, 20-40vol% and 5-10vol% respectively. Meanwhile the investigated range of carrier fluid viscosity was set between 18.5cP to 98.1cP. The stability was measured using sedimentation observation analysis while the stress resistances were measured using rheological analysis and compression test analysis. The finding of this study shows that increment of carrier fluid viscosity reduced sedimentation rate from 8.75% to 2.5% and reduced the compression stress resistance from 0.86MPa to 0.72MPa. Composition of CIP is the most significant factor to affect both sedimentation and stress resistance. Increment of CIP composition reduced the sedimentation rate but increased the stress resistance. Though FS composition shows least significant in the changes of stress resistance, it's important to stabilize the suspension. Optimization of materials parameter through CDMD model analysis resulting five resultant compositions at desirability value of 1. The best resultant composition produced 0.09% of sedimentation rate, 89kPa of shear stress and 18.9MPa compression stress. This study shows stabilized MR fluid can be produced for squeeze mode application by selecting higher viscosity of carrier fluid and increasing magnetic particles composition. Optimization model produced in this study is crucial for composing dedicated MR fluid for squeeze mode MR devices.

TABLE OF CONTENT

REFERENCES

Adjerid, K. (2011). *A Study on the Dynamic Characterization of a Tunable Magneto-Rheological Fluid-Elastic Mount in Squeeze Mode Vibration.* (Masters of Science in Mechanical Engineering), Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

An, H.-N., Sun, B., Picken, S. J., & Mendes, E. (2012). Long Time Response of Soft Magnetorheological Gels. *The Journal of Physical Chemistry B, 116*(15), 4702-4711.

Ashtiani, M., Hashemabadi, S., & Ghaffari, A. (2015). A Review on the Magnetorheological Fluid Preparation and Stabilization. *Journal of Magnetism and Magnetic Materials, 374*, 716-730.

Ashtiani, M., Hashemabadi, S., & Shirvani, M. (2014). Experimental Study of Stearic Acid Effect on Stabilization of Magnetorheological Fluids (MRFs). *Proceedings of the 8th International Chemical Engineering Congress & Exhibition, Kish, Iran*.

Avraam, M. (2009). MR-Fluid Brake Design and Its Application to a Portable Muscular Rehabilitation Device. *Doktora Tezi, Université Libre De Bruxelles, Faculté De Sciences Appliquées*.

Basson, D. K., Berres, S., & Bürger, R. (2009). On Models of Polydisperse Sedimentation With Particle-Size-Specific Hindered-Settling Factors. *Applied mathematical modelling, 33*(4), 1815-1835.

Brown, E., Forman, N. A., Orellana, C. S., Zhang, H., Maynor, B. W., Betts, D. E., . . . Jaeger, H. M. (2010). Generality of Shear Thickening in Dense Suspensions. *Nature materials, 9*(3), 220-224.

Chae, H. S., Piao, S. H., Maity, A., & Choi, H. J. (2015). Additive Role of Attapulgite Nanoclay on Carbonyl Iron-Based Magnetorheological Suspension. *Colloid and Polymer Science, 293*(1), 89-95.

Chen, S., Huang, J., Shu, H., Sun, T., & Jian, K. (2013). Analysis and Testing of Chain Characteristics and Rheological Properties for Magnetorheological Fluid. *Advances in Materials Science and Engineering, 2013*.

Chhabra, R. P. (2010). Non-Newtonian Fluids: An Introduction *Rheology of complex fluids* (pp. 3-34): Springer.

Chuah, W. H., Zhang, W. L., Choi, H. J., & Seo, Y. (2015). Magnetorheology of Core–Shell Structured Carbonyl Iron/Polystyrene Foam Microparticles Suspension with Enhanced Stability. *Macromolecules*.

Claracq, J., Sarrazin, J., & Montfort, J.-P. (2003). Viscoelastic Properties of Magnetorheological Fluids. *Rheologica Acta, 43*(1), 38-49.

Coetzer, R., & Haines, L. M. (2017). The Construction of D-and I-Optimal Designs for Mixture Experiments with Linear Constraints on the Components. *Chemometrics and Intelligent Laboratory Systems, 171*, 112-124.

De Vicente, J., Klingenberg, D. J., & Hidalgo-Alvarez, R. (2011). Magnetorheological Fluids: A Review. *Soft Matter, 7*(8), 3701-3710.

Desrosiers, J., Bigué, J. L., Denninger, M., Julió, G., Plante, J., & Charron, F. (2013). Preliminary Investigation of Magneto-rheological Fluid Durability in Continuous Slippage Clutch. *Journal of Physics: Conference Series*
412(1), 012022.

Du, C. B., Chen, W. Q., & Wan, F. X. (2010). Influence of HLB Parameters of Surfactants on Properties of Magneto-Rheological Fluid. *Advanced Materials Research*
97, 843-847.

Esmaeilnezhad, E., Choi, H. J., Schaffie, M., Gholizadeh, M., Ranjbar, M., & Kwon, S. H. (2017). Rheological Analysis of Magnetite Added Carbonyl Iron Based Magnetorheological Fluid. *Journal of Magnetism and Magnetic Materials, 444*, 161-167.

Fang, F., Jang, I., & Choi, H. (2007). Single-Walled Carbon Nanotube Added Carbonyl Iron Suspension and Its Magnetorheology. *Diamond and Related Materials, 16*(4), 1167-1169.

Farjoud, A., Cavey, R., Ahmadian, M., & Craft, M. (2009). Magneto-rheological Fluid Behavior in Squeeze Mode. *Smart Materials and Structures, 18*(9), 095001.

Farjoud, A., Craft, M., Burke, W., & Ahmadian, M. (2011). Experimental Investigation of MR Squeeze Mounts. *Journal of Intelligent Material Systems and Structures*, 1045389X11411225.

Felicia, L. J., & Philip, J. (2015). Effect of Hydrophilic Silica Nanoparticles on the Magnetorheological Properties of Ferrofluids: A Study Using Opto-Magnetorheometer. *Langmuir, 31*(11), 3343-3353.

Feng, Z., Yiping, L., & Hongjuan, R. (2015). Study of Sedimentation Stability of Magnetorheological Fluid. *Advances in Materials, 4*(1), 1-5.

Gong, X., Ruan, X., Xuan, S., Yan, Q., & Deng, H. (2014). Magnetorheological Damper Working in Squeeze Mode. *Advances in Mechanical Engineering, 2014*.

Guo, C., Gong, X., Xuan, S., Yan, Q., & Ruan, X. (2013). Squeeze Behavior of Magnetorheological Fluids Under Constant Volume and Uniform Magnetic Field. *Smart Materials and Structures, 22*(4), 045020.

Gürgen, S., Kuşhan, M. C., & Li, W. (2017). Shear Thickening Fluids in Protective Applications: A Review. *Progress in Polymer Science*.

Hajalilou, A., Mazlan, S. A., & Shila, S. T. (2016). Magnetic Carbonyl Iron Suspension With Ni-Zn Ferrite Additive and Its Magnetorheological Properties. *Materials Letters, 181*, 196-199.

Hong, K. P., Song, K. H., Cho, M. W., Kwon, S. H., & Choi, H. J. (2018). Magnetorheological Properties and Polishing Characteristics of Silica-coated Carbonyl Iron Magnetorheological Fluid. *Journal of Intelligent Material Systems and Structures, 29*(1), 137-146.

Iglesias, G., López-López, M., Duran, J., González-Caballero, F., & Delgado, A. (2012). Dynamic Characterization of Extremely Bidisperse Magnetorheological Fluids. *Journal of Colloid and Interface Science, 377*(1), 153-159.

Ismail, I., & Aqida, S. N. (2014). Fluid-Particle Separation of Magnetorheological (MR) Fluid in MR Machining Application. *Key Engineering Materials, 611*, 746-755.

Ismail, I., Mazlan, S. A., Zamzuri, H., & Olabi, A. G. (2012). Fluid–particle Separation of Magnetorheological Fluid in Squeeze Mode. *Japanese Journal of Applied Physics, 51*(6R), 067301.

Jang, D., Liu, Y., Kim, J., & Choi, H. (2015). Enhanced Magnetorheology of Soft Magnetic Carbonyl Iron Suspension with Hard Magnetic γ-Fe2O3 Nanoparticle Additive. *Colloid and Polymer Science, 293*(2), 641-647. doi: 10.1007/s00396-014-3475-6

Jang, I., Kim, H., Lee, J., You, J., Choi, H., & Jhon, M. (2005). Role of Organic Coating on Carbonyl Iron Suspended Particles in Magnetorheological Fluids. *Journal of Applied Physics, 97*(10), 10Q912.

Jeirani, Z., Jan, B. M., Ali, B. S., Noor, I. M., Hwa, S. C., & Saphanuchart, W. (2012). The Optimal Mixture Design of Experiments: Alternative Method in Optimizing the Aqueous Phase Composition of a Microemulsion. *Chemometrics and Intelligent Laboratory Systems, 112*, 1-7.

Jiang, W., Zhu, H., Guo, C., Li, J., Xue, Q., Feng, J., & Gong, X. (2010). Poly (methyl-methacrylate)-Coated Carbonyl Iron Particles and Their Magnetorheological Characteristics. *Polymer International, 59*(7), 879-883.

Kciuk, M., & Turczyn, R. (2006). Properties and Application of Magnetorheological Fluids. *Journal of Achievements in Materials and Manufacturing Engineering, 18*(1-2), 127-130.

Klingenberg, D. J. (2001). Magnetorheology: Applications and Challenges. *AIChE Journal, 47*(2), 246-249.

Kumar, S., Singh, R., & Gupta, R. (2017). Optimization of Monolayer Hydrophilic Matrix Tablets Containing Nisoldipine Solid Dispersion Using D-Optimal Design. *Indian Journal of Pharmaceutical Education and Research, 51*(2), S91-S97.

Kumbhar, B. K., & Patil, S. R. (2014). A Study on Properties and Selection Criteria for Magneto-Rheological (MR) Fluid Components. *International Journal of ChemTech Research, 6*(6).

Kumbhar, B. K., Patil, S. R., & Sawant, S. M. (2015). Synthesis and Characterization of Magneto-rheological (MR) Fluids for MR Brake Application. *Engineering Science and Technology, an International Journal, 18*(3), 432-438.

López-López, M., Zugaldía, A., González-Caballero, F., & Durán, J. (2006). Sedimentation and Redispersion Phenomena in Iron-Based Magnetorheological Fluids. *Journal of Rheology (1978-present), 50*(4), 543-560.

Machovsky, M., Mrlik, M., Kuritka, I., Pavlinek, V., & Babayan, V. (2014). Novel Synthesis of Core–Shell Urchin-Like ZnO Coated Carbonyl Iron Microparticles and Their Magnetorheological Activity. *RSC Advances, 4*(2), 996-1003.

Mangal, S., & Sharma, V. (2018). Optimization of MR fluid Yield stress using Taguchi Method and Response Surface Methodology Techniques. *IOP Conference Series: Materials Science and Engineering, 310*(1), 012008.

Mazlan, S. A., Ismail, I., Fathi, M. S., Rambat, S., & Anis, S. F. (2012). An Experimental Investigation of Magnetorheological (MR) Fluids under Quasi-Static Loadings. *Key Engineering Materials, 495*, 285-288.

Mrlík, M., Ilčíková, M., Pavlínek, V., Mosnáček, J., Peer, P., & Filip, P. (2013). Improved Thermooxidation and Sedimentation Stability of Covalently-Coated Carbonyl Iron Particles with Cholesteryl Groups and Their Influence on Magnetorheology. *Journal of Colloid and Interface Science, 396*, 146-151.

Mrlík, M., Sedlacik, M., Pavlínek, V., Peer, P., Filip, P., & Sáha, P. (2013). Magnetorheology of Carbonyl Iron Particles Coated with Polypyrrole Ribbons: The Steady Shear Study. *Journal of Physics: Conference Series, 412*(1), 012016.

Nasrollahzadeh, M., Ganji, F., Taghizadeh, S., & Vasheghani-Farahani, E. (2017). "D-optimal Experimental Design" Analysis in Preparing Optimal Polyisobutylene Based Pressure Sensitive Adhesives. *International Journal of Adhesion and Adhesives, 78*, 28-37.

Ngatu, G., Wereley, N., Karli, J., & Bell, R. (2008). Dimorphic Magnetorheological Fluids: Exploiting Partial Substitution of Microspheres By Nanowires. *Smart Materials and Structures, 17*(4), 045022.

Park, J. H., & Park, O. O. (2001). Electrorheology and Magnetorheology. *Korea-Australia Rheology Journal, 13*(1), 13-17.

Phu, D. X., & Choi, S.-B. (2019). Magnetorheological Fluid Based Devices Reported in 2013–2018: Mini-Review and Comment on Structural Configurations. *Front. Mater, 6*, 19.

Pinto, F., & Meo, M. (2017). Design and manufacturing of a novel shear thickening fluid composite (STFC) with enhanced out-of-plane properties and damage suppression. *Applied Composite Materials, 24*(3), 643-660.

Powell, L. A., Hu, W., & Wereley, N. M. (2013). Magnetorheological Fluid Composites Synthesized for Helicopter Landing Gear Applications. *Journal of Intelligent Material Systems and Structures, 24*(9), 1043–1048. doi: 10.1177/1045389X13476153

Prekas, K., Shah, T., Soin, N., Rangoussi, M., Vassiliadis, S., & Siores, E. (2013). Sedimentation Behaviour in Electrorheological Fluids Based on Suspensions of Zeolite Particles in Silicone Oil. *Journal of Colloid and Interface Science, 401*, 58-64.

Premalatha, S. E., Chokkalingam, R., & Mahendran, M. (2012). Magneto Mechanical Properties of Iron Based MR Fluids. *American Journal of Polymer Science, 2*(4), 50-55.

Rabbani, Y., Ashtiani, M., & Hashemabadi, S. H. (2015). An Experimental Study on the Effects of Temperature and Magnetic Field Strength on the Magnetorheological Fluid Stability and MR effect. *Soft Matter, 11*(22), 4453-4460.

Rashid, A. S. (2008). *Compressible Magnetorheological Fluids.* University of Nevada, Reno. ProQuest Dissertations Publishing, 2008. 1456488. database.

Roupec, J., & Mazůrek, I. (2012). Stability of Magnetorheological Effect during Long Term Operation *Mechatronics* (pp. 561-567): Springer.

Sarkar, C., & Hirani, H. (2015). Synthesis and Characterization of Nano-Copper-Powder Based Magnetorheological Fluids for Brake. *International Journal of Scientific Engineering and Technology, 4*(2), 76-82.

Shokrollahi, H. (2016). The Effect of the Volume Fraction and Viscosity on the Compression and Tension Behavior of the Cobalt-Ferrite Magneto-Rheological Fluids. *Engineering Science and Technology, an International Journal, 19*(1), 604-609.

Spaggiari, A. (2013). Properties and Applications of Magnetorheological Fluids. *Frattura ed Integrità Strutturale, 7*(23), 48-61.

Sunkara, S., Root, T., Ulicny, J., & Klingenberg, D. (2009). Iron Oxidation and Its Impact on MR Behavior. *Journal of Physics: Conference Series 149*(1), 012081. doi: 10.1088/1742-6596/149/1/012081

Triefenbach, F. (2008). *Design of Experiments: The D-Optimal Approach and Its Implementation As a Computer Algorithm.* (Bachelor's Thesis in Information and Communication Technology), Ume˚a University
Sweeden.

Truong, D., & Ahn, K. (2012). MR Fluid Damper and Its Application to Force Sensorless Damping Control System *Smart Actuation and Sensing Systems-Recent Advances and Future Challenges* (pp. 383-422): InTech.

Ulicny, J. C., Balogh, M. P., Potter, N. M., & Waldo, R. A. (2007). Magnetorheological Fluid Durability Test—Iron Analysis. *Materials science and engineering, 443*(1), 16-24.

Wang, J., & Meng, G. (2001). Magnetorheological Fluid Devices: Principles, Characteristics and Applications in Mechanical Engineering. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications, 215*(3), 165-174.

Wang, Y. (2014). *Magnetic Particles Study and Their Applications.* (MSc by Research), University of York, York.

Yang, J., Vereda, F., Morillas, J. R., & de Vicente, J. (2018). Ternary Solid-Ferrofluid-Liquid Magnetorheological Fluids. *Smart Materials and Structures, 27*(7), 075017.

Zhang, W. L., Kim, S. D., & Choi, H. J. (2014). Effect of Graphene Oxide on Carbonyl-Iron-Based Magnetorheological Fluid. *IEEE Transactions on Magnetic, 50*(1), 1-4.