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MULTIDISCIPLINARY ANALYSIS AND DEVELOPMENT METHODOLOGIES FOR TORSIONAL VIBRATION DAMPERS IN VEHICLE INDUSTRY

Booklet of Ph.D. Theses

A Dissertation submitted by:

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1. Introduction and Objectives of the Research

Continuous innovation, compliance with increasingly strict market and safety requirements, as well as cost-effective and fast R&D activities, are determining factors also in the vehicle industry. The development and serial production of today's modern vehicle industry products, as well as the preservation and increase of profit and competitiveness, are unthinkable without engineering calculations based on advanced numerical methods. This field of science provides a suitable breeding ground for the implementation of a product-specific research process, during which multidisciplinary analysis and development methods for viscous torsional vibration dampers will be developed. The research results are integrated into the design, development and production processes of the product.

The literature review reveals the fact, that high-performance but small-sized internal combustion piston engines are becoming more and more common today in order to achieve the necessary performance with the appropriate efficiency. As a result of the 'downsizing', 'downspeeding', and 'turbo-supercharging' trends appearing in the design of internal combustion engines, the engine is exposed to considerable stress. As a result, oscillations appear on the crankshaft, of which torsional oscillations are the most dangerous. [1]

The use of torsional vibration dampers (TVD) can reduce the extent of the aforementioned harmful oscillations and increase the service life of the engine. One type of vibration damper is the viscous torsional vibration damper (shortly visco-damper), the working medium of which is silicone oil. [2] Silicone oil is a pseudoplastic non-Newtonian fluid, the viscosity of that changes as a result of force (e.g. shear). The heat generated during the operation of the device has an effect on the viscosity of the damping fluid, and thus also on the damping characteristic. [3] In the design and development phase of the product, the strict market and technical requirements, as well as the geometric design and complexity of the structure, pose a challenge in the analytical solution of the flow and thermal design tasks related to the product. However, numerical tools with spatially distributed parameters, supported by modern computer technology, greatly assist the engineering calculations to be performed in this work.

The service life of the viscous damping device is determined by the lifetime of the silicone oil (also known as polydimethylsiloxane) stored in it. It is necessary to reduce the oil’s thermal load [4] to a minimum expected level both during the filling process in production and during operational use. During the filling process, it becomes necessary to optimize the dimensions of the appropriate filling hole, the geometry of the filling chamber and the damper gap, as well as the filling conditions (filling temperature and filling pressure). In addition to the operational conditions of the device, the design of the appropriate cooling fin geometry and its suitable placement also contribute to the reduction of oil’s thermal load.

In order to carry out multidisciplinary analyses and developments of viscous torsional vibration dampers, it is necessary to develop and validate models, methods, and procedures by considering the following aims:

D1 Development of an accurate and reliable temperature- and shear rate-dependent material model for silicone oil based on viscosity measurement, which can be easily implemented into CFD (Computational Fluid Dynamics) software.

D2 Development of a thermal neutron dynamic radiography measurement procedure and a result-evaluation technique that makes visible and measurable the filling process and so the effect of different damper assembly configurations. This methodology can be used for validation of the CFD simulation results also.

D3 Development of a 3-dimensional, transient, multiphase, non-Newtonian, coupled fluid dynamic and heat transfer filling model for visco-dampers which is suitable to analyze, improve and optimize the visco-damper's filling process by keeping the oil's degradation on an acceptable level.

D4 Identification and analysis of the filling time influencing factors and filling process improvement.

D5 Building a 3-dimensional, steady-state, coupled fluid dynamic and heat transfer model for visco-dampers which is suitable to study and improve the cooling efficiency and positioning of different cooling fin geometries mounted onto the housing of visco-dampers, making it possible to estimate and extending the service life of the silicone oil stored in the damper.

D6 Development of a section plane transformation method and implementing it into a visco-damper specific, 2-dimensional, thermal calculation method written in MATLAB environment to reveal the temperature distribution in visco-dampers' component during operation.

D7 The improvement of the 1-dimensional Iwamoto-equation available in the literature to provide more accurate surface temperature results on the housing of visco-dampers.

The goal of the Ph.D. research is to develop models, analysis procedures, and numerical methods which enable us the time-, capacity- and cost-effective design and development of visco-dampers, as well as maximizing their service life while the degradation of their working medium (silicone oil) is kept below the limit. The outcome of this research will be integrated into the design, development, and manufacturing processes of visco-dampers, thus must be able to apply to arbitrary visco-damper geometries, must be easy to use to any person with less experience in CFD and engineering calculations and must replace difficult, time-consuming or dangerous product tests.

The research must be supported by material and process analysis measurements which enable the verification and validation of developed numerical methods, calculation models, and procedures aimed at product development and service life extension, as well as a deeper understanding of the mechanical, thermal, and flow processes taking place in and between the product components in order to achieve further development goals in the future. To achieve these, one must perform

M1 Thorough rheological tests of AK 1 000 000 STAB high-viscosity silicone oil in the temperature and shear rate ranges valid in the filling and operation of visco-dampers.

M2 Real-time observation of the filling process of a small-sized, real visco-damper using thermal neutron dynamic imaging method [5] to analyze the process and validate the correctness of the developed silicone oil's material law and the accuracy of the visco-damper's filling model.

2. Overview of the Research Field, Applied Methods and Materials

Since visco-dampers are considered a multi-industry component of high importance from the safety point of view, they have a strong business and economical background. Regarding the internal combustion engine market, it was valued at 197,803.5 million USD in the field of piston engines in 2017 and expected to reach 271,508.6 million USD in 2026 (6.5% Compound Annual Growth Rate-CAGR between 2018-2026). [6] The worldwide market for visco-dampers is estimated to grow at a CAGR of roughly 2.0% between 2019 and 2024, and according to a new study, is expected to reach 2,360 million USD in 2024. Although these data were reported before COVID-19, forecasts indicate that there will be a recovery sometime after 2023. [7]

Few studies [8], [9], [10], [11] deal with the service life optimization, numerical flow, and thermal analysis of viscous torsional vibration dampers. The analytical relationship (Iwamoto-equation) [12] for estimating the surface temperature of the damper housing is found to be not accurate enough based on CFD calculations, thus the original Iwamoto-equation must be updated. The visco-dampers can be tested and improved in such detail only by the damper manufacturers and R&D institutes, which usually do not publish their results due to market competition.

Also, little useful information is available on the rheological analyses of high-viscosity silicone oils [13], [14]. Most of the previous articles on the rheological testing of polydimethylsiloxane examine oil samples only with a dynamic viscosity of 10 to 50 Pas or less [15] [16]. One important reason behind this is that these materials are difficult to measure with the measuring capabilities of typical rheometers in several aspects. Another reason is that silicone oils cover a fairly wide range of types, starting from a dynamic viscosity of 0.0006 Pas up to 2000 Pas, the current value of which is significantly affected not only by the current shear rate, but also by previously experienced shear rates [17], as well as temperature and pressure.

Non-Newtonian fluid models that well describe not only the viscous [18] but the viscoelastic behavior [19] of pseudoplastic fluids are already available, but it would be worthwhile to improve these models into silicone oil specific models, which can be easily implemented into Fluent CFD software used for my work, operating in the Ansys Workbench environment, capable of handling non-Newtonian and multiphase flows, operating on the finite volume principle.

In order to verify the reliability, correctness, and accuracy of the developed temperature- and shear rate-dependent material model of a high-viscosity silicone oil based on rheological measurements, as well as the developed numerical filling model, fluid front tracking measurements must be performed on the filling process of a real visco-damper. Since the damping fluid, as the subject of the current research, is enclosed inside the metal device, the dynamic neutron imaging method [20] has been selected, for which purpose this technology has not been used before.

3. Summary of the Research and the Presentation of the Theses

The working fluid of visco-dampers is a high-viscosity silicone oil since only this technical fluid is able to effectively minimize the harmful torsional vibrations in the whole frequency and operational speed ranges of a crankshaft in a high-performance internal combustion engine. Silicone oils are non-Newtonian pseudoplastic fluids and their material model must be based on rheological measurements to simulate their flow properly in a CFD calculation. Dynamic viscosity measurements have been carried out on AK 1 000 000 STAB silicone oil samples by a high-precision rotational rheometer in the operational temperature and shear-rate range of the fluid in visco-damper applications to quantify the temperature and shear rate dependence of the mentioned silicone oil’s non-Newtonian viscous behavior. Eight commonly used pseudoplastic, non-Newtonian viscosity models (Carreau, Carreau-Yasuda, Cross, Johnson, Meter, Münstedt, Powell-Eyring, and Power-Law) have been selected for nonlinear regression, model parameter estimation, and comparison to develop a reliable, accurate and easy-to-implement viscosity model for Wacker AK 1 000 000 STAB silicone oil. Different aspects (highest absolute difference to the measured values; highest relative difference to the measured values; average of relative differences with deviations and the model‘s behavior at shear rates above 1000 1/s) have been used to select the most appropriate model. As a result, the following thesis has been drawn:

Thesis 1:

The viscosity of Wacker AK 1 000 000 STAB silicone oil can be calculated by the Carreau-Yasuda viscosity model presented in Eq. (1) – (6) valid in -40 °C – 200 °C and 0 1/s – 1000 1/s ranges at atmospheric pressure.

$$\eta(\dot{\gamma},T) = \eta_\infty(T) + (\eta_0(T) - \eta_\infty(T)) \cdot \left(1 + (\dot{\gamma} \cdot \lambda(T))^{a(T)}\right)^{\frac{n(T)-1}{a(T)}} \tag{1}$$

$$\eta_\infty(T) \cong 0 \tag{2}$$

$$\begin{aligned}\eta_0(T) = 3.55208E\text{-}14 \cdot T^8 - 3.04511E\text{-}11 \cdot T^7 + 1.06686E\text{-}08 \cdot T^6 \\ - 1.98312E\text{-}06 \cdot T^5 + 2.15475E\text{-}04 \cdot T^4 - 1.48606E\text{-}02 \\ \cdot T^3 + 0.77383 \cdot T^2 - 38.54805 \cdot T + 1662.14402\end{aligned} \tag{3}$$

$$\begin{aligned}\lambda(T) = 2.97570E\text{-}19 \cdot T^8 - 3.44028E\text{-}16 \cdot T^7 + 1.49141E\text{-}13 \cdot T^6 \\ - 3.26433E\text{-}11 \cdot T^5 + 4.06031E\text{-}09 \cdot T^4 - 3.17045E\text{-}07 \\ \cdot T^3 + 1.84093E\text{-}05 \cdot T^2 - 9.51978E\text{-}04 \cdot T \\ + 3.99458E\text{-}02\end{aligned} \tag{4}$$

$$\begin{aligned}a(T) = 1.20867E\text{-}08 \cdot T^3 - 5.12543E\text{-}06 \cdot T^2 + 7.77623E\text{-}04 \cdot T \\ + 0.84655\end{aligned} \tag{5}$$

$$n(T) = 5.18491E\text{-}06 \cdot T^2 - 1.19737E\text{-}04 \cdot T - 6.35822E\text{-}03 \tag{6}$$

where η is the actual dynamic viscosity [Pas], η_∞ is the infinite-shear dynamic viscosity [Pas], η_0 is the zero-shear dynamic viscosity [Pas], λ is the relaxation time [s], a is the transition control factor [-], n is the power law index [-], $\dot{\gamma}$ is the shear rate [1/s] and T is the temperature [°C].

If the actual viscosity of the AK 1 000 000 STAB silicone oil is calculated by Carreau-Yasuda viscosity model, the highest absolute difference to the measured values is 62.483 Pas; the highest relative difference to the measured values is 10.757%; the average of relative differences is 1.105% while the deviation is 1.381% and the model shows a monotonically decreasing viscosity trend to zero above 1000 1/s.

Related publications: [I], [II]

Thermal dynamic neutron radiography experiments and related finite volume method-based calculations were completed to investigate the effect of slide bearing cut-off position on the filling process of visco-dampers. A visco-damper-specific measurement setup has been developed and applied to a test-damper filled with AK 1 000 000 STAB silicone oil. This served as a validation dataset also for the 3-dimensional, transient, multiphase, non-Newtonian, coupled fluid dynamic and heat transfer simulation model of the filling process.

In each measurement-simulation pair the spatial oil spread formation and oil layer patterns were visually compared, the propagation times were compared and the oil front velocities over time have been evaluated. The performed work includes the following steps:

I. Design modifications to a real visco-damper product to make it suitable for filling process analysis in outside-factory ambient under testing room conditions.
II. Proper material selection for the test-damper components to minimize the neutron-induced activation and improve the neutron transmission, as well as the image contrast of the dynamic radiography measurements.
III. Manufacturing the test-damper housing, cover, inertia-ring and bearings made of AlMgSi0.5.
IV. Planning the measurement procedure, the experimental arrangement, and adaptation of the equipment to the neutron radiography measurements.
V. Building up the measuring setup and performing pilot measurements.
VI. Performing measurements and evaluating the results.

As a result, the following thesis and its application have been established:

<u>Thesis 2:</u>

A thermal-neutron-based dynamic radiography measurement protocol has been developed for visco-dampers which is suitable (i) to visualize and quantify the front propagation of the silicone oil during the filling process (ii) to study the effect of different damper assembly configurations on the filling process and (iii) to validate the developed simulation methodology. The measurement procedure consists of the following main steps (see Figure 1. for the test setup):

1. ***Assembling the test-damper with a given bearing cut-off position and placing it into the support frame (5.) at a 30-mm distance from the scintillator screen (Detector).***
2. ***Connecting the filling hose to the inlet hole.***
3. ***Pumping up the hydraulic manual pump (1.) to 500 bar (generating 90 bar supply pressure at the closed ball valve tap (3.)) and leaving the testing room.***
4. ***Initializing the measurement system remotely.***

5. ***Opening the neutron beam shutter and recording “dry” images without silicone oil in the damper gap.***
6. ***Lifting the counterweight (6.) by letting the spring to open the ball valve tap (3.) and to start the filling process.***
7. ***Monitoring the oil spread in real-time in form of 2-dimensional shadow images till the oil front reaches the outlet hole.***
8. ***Sinking the counterweight (6.) against the spring to close the ball valve tap (3.) and finish the filling process.***
9. ***Regularly checking the level of the radiation in the bunker and waiting until it reaches a safe level.***
10. ***Disconnecting the filling hose from the test-damper and removing it from the support frame (5.).***
11. ***Disassembling the test-damper and removing silicone oil from each component by using detergent (Ultraderm) solved in fresh water and paper-based wipes soaked in acetone.***

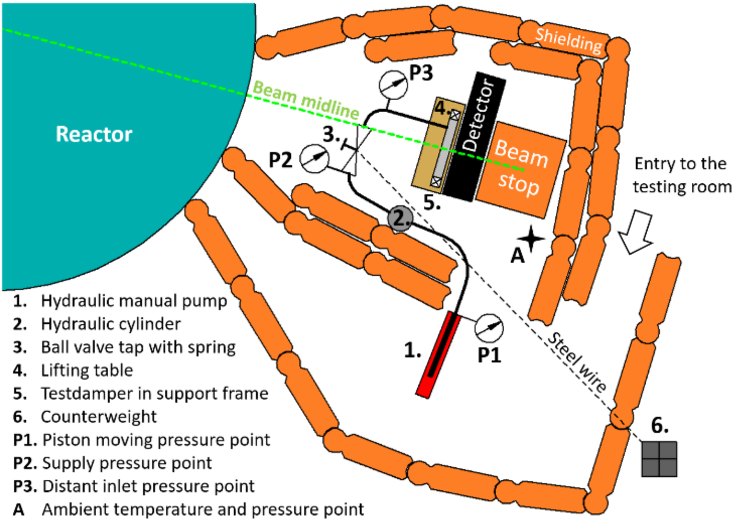


Figure 1. Arrangement of the measurement setup for the neutron radiography tests

Application:

Based on the processing of the real-time raw images into binarized imaging sequences, two different installations were compared: when the visco-damper is assembled in a way that the bearing cut-off is close (i) to the inlet, and to (ii) where it is placed far from the inlet. It was found that in the first case the filling process lasts longer by 11 seconds due to the tapping effect of the bearing cut-off.

Related publication: [III]

Silicone oil in the visco-damper is allowed to undergo minimal degradation from the thermal point of view during the damper's filling process to provide maximum service life under operating conditions. For this reason, it is necessary to know the maximum allowable oil inlet temperature value at a given oil inlet pressure, at which the oil still can be used safely under operation. Estimating the filling time for a given filling condition (at the applied oil inlet temperature and oil inlet pressure) is also an important aspect when the shortening of the damper production process is planned. Because of these facts, a 3-dimensional, transient, multiphase, finite volume method-based, coupled fluid dynamic and heat transfer simulation model has been developed in Ansys Fluent 2021 R2 based on rheological measurements and neutron radiography validation to numerically analyse and improve the filling process of a small-sized visco-damper. The filling process is calculated at four different filling inlet overpressures (1 bar, 5 bar, 10 bar, and 20 bar) and the maximum allowed filling inlet temperature of the oil is determined for all pressure cases so that during the filling process the oil's temperature did not exceed in any point of the fluid the 150 °C (maximally allowed temperature of Wacker silicone fluids AK according to the oil's product catalogue) and the minimal degradation of the oil is ensured. As a result, the following thesis and its applications have been established:

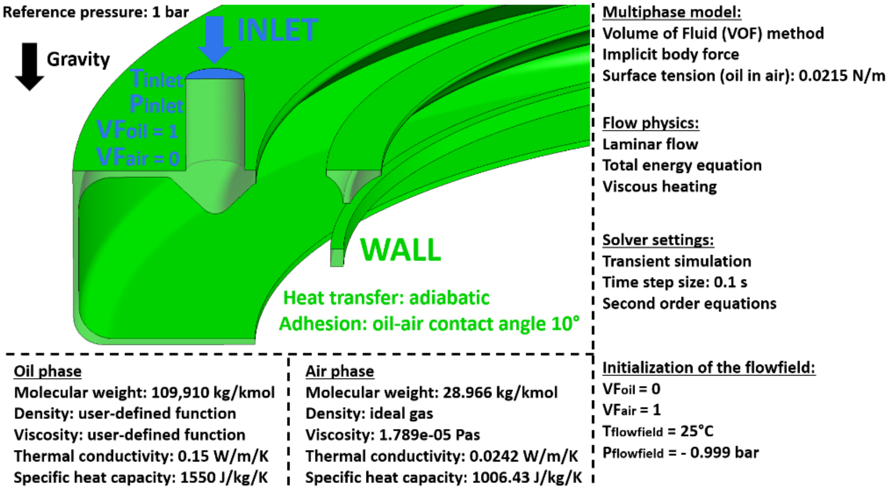
Thesis 3:

Novel, 3-dimensional, transient, multiphase, non-Newtonian, finite volume method-based, coupled fluid dynamic and heat transfer simulation setup is developed in Ansys Fluent, which contains only the geometry of oil-cavity of the damper with an inlet tube at the filling hole, as illustrated in Figure 2 to analyze and improve the filling process of a visco-damper following the measurement-based validation.

Features of the filling model:

- ***The "Oil phase" data refers to AK 1 000 000 STAB silicone oil and the temperature and shear rate dependent viscosity model of the oil, while the temperature dependent density model is expressed by equation found in the product catalogue.***

- *The Volume of Fluid (VOF) multiphase method is used with Implicit Volume Fraction Formulation (Volume Fraction Cutoff is set for 10^{-6}) and the Interface Modelling Type is set to Sharp.*
- *The heat transfer coefficient of the walls is set to adiabatic for worst-case study with highest possible oil temperature values during the filling process or set to 8 W/m^2/K for standard thermal conditions.*
- *Further solver settings and applied solution methods are next:*
  - *Scheme of pressure-velocity coupling is set to Pressure-Implicit with Splitting of Operators (PISO).*
  - *Density, Momentum, Energy and Transient Formulation of Spatial Discretisation is set to Second Order Upwind.*
  - *Volume Fraction of Spatial Discretisation is set to Compressive.*
  - *Pressure of Spatial Discretisation is set to Body Force Weighted.*
  - *Under relaxation factor for Density, Body Forces and for Energy is set to 1, for Momentum is set to 0.7, for Volume Fraction is set to 0.5 and for Pressure is set to 0.3.*
  - *Minimum-phase-averaged is used for Operating Density Method.*



Multiphase model:
Volume of Fluid (VOF) method
Implicit body force
Surface tension (oil in air): 0.0215 N/m

Flow physics:
Laminar flow
Total energy equation
Viscous heating

Solver settings:
Transient simulation
Time step size: 0.1 s
Second order equations

Oil phase
Molecular weight: 109,910 kg/kmol
Density: user-defined function
Viscosity: user-defined function
Thermal conductivity: 0.15 W/m/K
Specific heat capacity: 1550 J/kg/K

Air phase
Molecular weight: 28.966 kg/kmol
Density: ideal gas
Viscosity: 1.789e-05 Pas
Thermal conductivity: 0.0242 W/m/K
Specific heat capacity: 1006.43 J/kg/K

Initialization of the flowfield:
$VF_{oil} = 0$
$VF_{air} = 1$
$T_{flowfield} = 25°C$
$P_{flowfield} = -0.999$ bar

Figure 2. CFD model for analysing the filling process of visco-dampers

The accuracy of the developed CFD filling process calculation method has been validated by thermal neutron dynamic radiography measurements and the visual comparison of the spatial oil spread formation and oil layer patterns of the measurement results and the CFD results show a good agreement. In terms of propagation time, the highest relative difference between the measurement results and the CFD results is found to be 3.55%. As regards oil front velocity, the highest average of the relative differences between the measurement-velocity values and the CFD-velocity values is found to be 17.28%.

Application 1:

As illustrated in Figure 3., in case of visco-dampers with $D_0/D_i \approx 1.62$ and $D_0/s \approx 340$ geometrical ratios (where D_0 is the outer diameter of the damper's housing, D_i is the inner diameter of the inertia-ring and s is the gap-size), if AK 1 000 000 STAB silicone oil is used to fill into the damper gap, the following maximal allowable oil inlet temperatures must be applied during the filling process to avoid the permanent oil degradation by exceeding the maximal allowed fluid temperature (150 °C):

- at 1 bar inlet overpressure: 119.4 °C
- at 5 bar inlet overpressure: 107.7 °C
- at 10 bar inlet overpressure: 104 °C
- at 20 bar inlet overpressure: 102 °C.

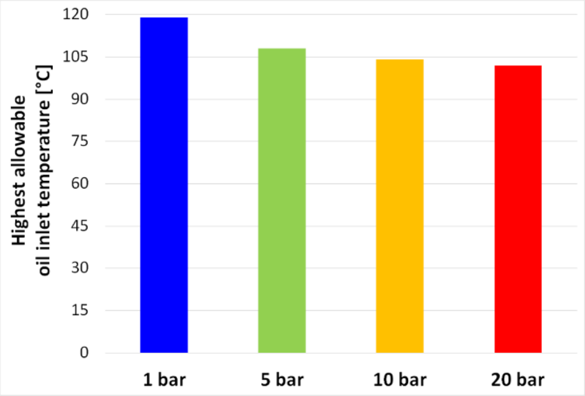


Figure 3. Maximal allowable oil inlet temperatures at different inlet overpressures

Application 2:

As illustrated in Figure 4., in the case of visco-dampers with $D_0/D_i \approx 1.62$ and $D_0/s \approx 340$ geometrical ratios (where D_0 is the outer diameter of the damper's housing, D_i is the inner diameter of the inertia-ring and s is the gap-size), if AK 1 000 000 STAB silicone oil is used to fill into the damper gap at highest allowable inlet oil temperature (instead of 25 °C), the filling time can be shortened:

- at 1 bar inlet overpressure by 61.6%
- at 5 bar inlet overpressure by 56.5% (by 87.1% related to 1 bar – 25 °C case)
- at 10 bar inlet overpressure by 51.1% (by 93.4% related to 1 bar – 25 °C case)
- at 20 bar inlet overpressure by 20.7% (by 94.3% related to 1 bar – 25 °C case).

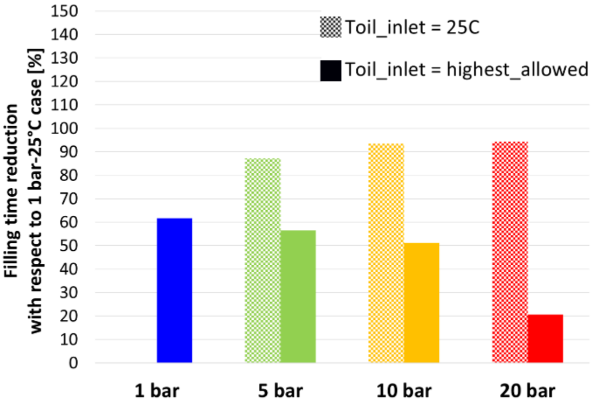


Figure 4. Filling time reduction at different inlet overpressures and inlet temperatures (solid bars) compared to the 1 bar – 25 °C filling case (perforated bars)

Related publications: [II], [III]

The reduction of manufacturing time is a key factor in increasing productivity. One of the possible solutions in this regard is to reduce the time frame required for the silicone oil to be filled into the narrow damper gap channels of a visco-damper. 3-dimensional, transient, multiphase, non-Newtonian, coupled fluid dynamic and heat transfer simulations have been used to analyse the impact of the applied inlet overpressure, oil temperature, and the slope of pressure ramp-up onto the filling time. The parameter sensitivity analyses have been performed with six different inlet overpressures (1 atm, 5 atm, 10 atm, 15 atm, 20 atm, 30 atm), four different oil temperatures (25 °C, 40 °C, 60 °C, 80 °C) and four different slopes of inlet pressure ramp (0.0066 s/atm, 0.0033 s/atm, 0.0016 s/atm, 0.0011 s/atm) such a way that only one parameter has been changed (taking roughly the half and roughly the third parts of the reference value) at each investigated scenario. As a result, the following thesis has been drawn:

Thesis 4:

Based on the parameter sensitivity analysis of visco-dampers' filling process, inlet overpressure is found to be the most influencing parameter, which effect on the filling time is approximately three times compared to the influence of oil temperature and approximately five times compared to the influence of slope of pressure ramp.

The outcome of the parameter sensitivity analysis is presented in Figure 5. with normalized values.

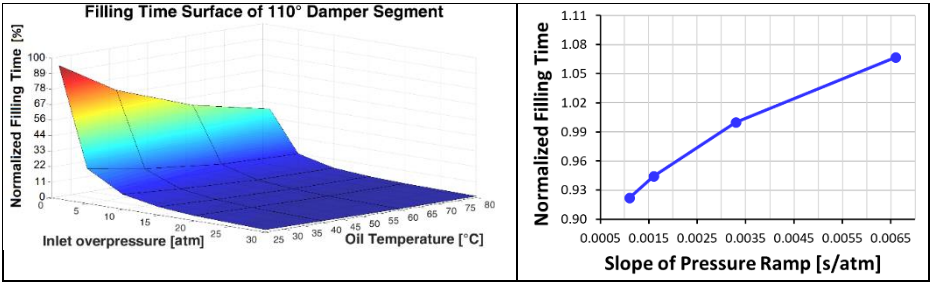


Figure 5. Parameter sensitivity analysis of the inlet overpressure, oil temperature and slope of pressure ramp on the filling time

Related publication: [IV]

The service life of a visco-damper is determined by the service life of the silicone oil stored in the damper. During operation, the silicone oil is exposed to a significant amount of thermal load that influences permanently the oil's viscosity, damping characteristics, and lifetime. In order to maintain the operating temperature of the silicone oil at a regulated value, the visco-damper must be equipped with cooling fins assembled on the housing in a properly defined position. The effect of the side-positions of the cooling fin geometries has been analysed with help of 3-dimensional coupled fluid dynamic and heat transfer simulations. The lifetime curves of silicone oil have been used to identify damper design modifications that can extend the silicone oil's service life and the visco-dampers' durability. As a result, the following thesis has been drawn:

Thesis 5:

The cooling of the visco-damper's housing can be improved by assembling the cooling fins not on the engine side of the damper's housing but on the free-end away from the engine.

In this case, at the closest point of the cooling fins measured from the axis of rotation (where the radius-dependent heat transfer coefficient is the smallest), the heat flow in the direction of the ambient is 3.78 times higher than at the same point of the cooling fins assembled on the engine side.

If the 'tunnel type' cooling fins are assembled onto the free-side of the damper housing instead of the motor-side, the silicone oil's lifetime can be prolonged by 2.33 times (133.2%).

Related publication: [V], [VI]

The thermal analysis of visco-dampers under operational conditions is an indispensable act in the design and development phases of the dampers considering the lifetime increase of the silicone oil and the prolongation of the service life of the product. Since carrying out thermal measurements on a visco-damper in operation is a dangerous and difficult task, numerical calculation methods must be applied to perform thermal analyses. To reveal the temperature field in the damper components and to estimate the degradation level of silicone oil in given operational conditions, a 2-dimensional verified numerical calculation method has been developed and implemented in MATLAB environment.

A half empirical analytical expression, developed by S. Iwamoto, is available in the literature and can be used for preliminary thermal analysis of visco-dampers to estimate the outer surface temperature of the damper housing under operation. This expression is described by Eq. (7) [12].

$$\dot{Q}_{damp} = 1121 \cdot \theta \cdot \omega^{0.8} \cdot A^{1.3} \cdot (T_s - T_{ambient}) \cdot e^{-0.00176 \cdot T_s} \tag{7}$$

The equation has been tested in numerical way on three different geometries under three different operational conditions for each geometry and found to provide different results than the numerical investigations meanwhile the testing geometry range covers the validity range of the equation. Hence, a possibility is found to increase the accuracy of the equation in the investigated cases. Nonlinear regression and parameter identification has been applied in order to increase the accuracy of the model. As an outcome, the following thesis and its application has been established:

Thesis 6:

A visco-damper specific section plane transformation method has been developed and implemented into a finite-difference method-based thermal calculation script written in MATLAB environment to estimate the steady-state temperature distribution of each visco-damper component and so to estimate the degradation level of silicone oil at given operational conditions in a radial section plane.

The workflow and the calculation mechanism of the developed script is the following:

1. ***Taking input parameters from the real 3-dimensional damper geometry and initialization.***
2. ***Calculating the radial cross-section of the simplified damper geometry (in 2-dimensions).***

3. ***Calculating heat transfer coefficient and heat source.***
4. ***Converting the simplified damper geometry into an equivalent damper geometry by applying the developed section plane transformation method.***
5. ***Creating coefficient matrix*** $[\bar{\bar{A}}]$**.**
6. ***Creating constant-term vector*** $[\bar{C}]$**.**
7. ***Creating solution vector*** $[\bar{T}]$ ***by solving the matrix equation expressed by Eq. (8)***
8. ***Generating the temperature-field matrix*** $[\bar{\bar{T}}]$ ***from the solution vector.***
9. ***Plotting the temperature-field matrix on the equivalent damper geometry.***

$$\left(\bar{\boldsymbol{T}} = \bar{\bar{\boldsymbol{A}}}^{-\mathbf{1}} \cdot \bar{\boldsymbol{C}}\right) \tag{8}$$

The accuracy of the developed thermal calculation method has been tested in a 3-dimensional – 2-dimensional two-step verification process by finite element and finite volume-based advanced engineering software in ANSYS Workbench environment and the highest relative deviation in verification points remained under 10% and the average of the relative deviations remained under 5%.

Advantages of the developed 2-dimensional thermal calculation method:

- Fast, accurate, and best solution with utilizing all advantages of the finite difference method including the option for parallelization,
- Goal-oriented and cost-effective procedure,
- There is no need for knowledge in the field of simulation engineering,
- User-friendly, easy to use, and automatic,
- Fast preparation: there is no need for detailed pre- and postprocessing,
- Best approach for concept analyses and checking preliminary designs.

Application:

The updated Iwamoto-equation expressed in Eq. (9) can be used to gain more accurate surface temperature estimation on the housing of a visco-damper in operation at the investigated conditions. The validity range of the equation is $D_0/D_i = 1.67 \div 2.0$ (where D_0 is the outer diameter of the damper's housing and D_i is the inner diameter of the inertia-ring).

$$\dot{Q}_{damp} = 109.8594625502 \cdot \theta \cdot \omega^{0.7553085697} \cdot A^{1.3707718782} \cdot (T_s - T_{ambient}) \cdot e^{-0.0017649324 \cdot T_s} \tag{9}$$

where $\dot{Q}_{damp}$ is the damping power [W], θ is the Iwamoto-coefficient [-], ω is the angular velocity of the housing [rad/s], A is the outer surface of the housing [m^2], T_s is the surface temperature of the housing [°C], $T_{ambient}$ is the ambient temperature [°C] and e is the mathematical constant, which is also known as Euler's number and it is approximately equal to 2.71828.

By comparing the accuracy of the original Iwamoto-equation to the updated one, the highest relative deviation is reduced from 33.93% to 9.32% and the average of the relative deviations is reduced from 23.02% to 5.44%.

Related publication: [VII], [VIII]

4. Utilization Possibilities of the Achieved Results

The outcome of the current research will be integrated into the design, development, and production processes of viscous torsional vibration dampers. With their help, the time and cost required for engineering calculations can be significantly reduced, and the difficult, time-consuming, and several difficult, time consuming and dangerous product testing can be omitted.

The developed calculation methods and models make it possible to accurately calculate the operational temperature distribution of visco-dampers and especially of the silicone oil stored in them, which can be important input data for estimating the thermal degradation of the silicone oil and thus the service life of the damping device, as well as the safe operating time of high-performance internal combustion engines.

By parametrizing the inputs of geometry and boundary conditions used in the calculations, case studies and genetic algorithm-based parametric optimization can be performed for product improvement in the future.

By applying the developed and measurement-validated filling simulation model, the production time of the damping product can be shortened, production can be enhanced and thus the profit and competitiveness of the device manufacturer can be increased.

The measurement procedures developed during the research provide an opportunity for materials science investigation of new types of damping fluids and for the implementation of their new material models, as well as for a deeper understanding and optimization of the filling and operating processes of visco-dampers.

Since silicone oils are a widely used technical fluids, the methods, models, and procedures developed during the research can be applied to test and develop any device, equipment, product, or process, apart from visco-dampers where silicone oil is used as a working medium.

The details of the research work carried out and the formulated theses highlight the versatile and complex nature of silicone oil, as well as provide a basis for further materials science, fluid dynamic, damping, and safety technology investigations, research, and developments, which will lead to the design of even more efficient and even more reliable non-Newtonian fluid-based devices and systems available in the future.

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