1 Introduction

At the Institute of Product Development and Engineering Design (PKT) at the Hamburg University of Technology a mechanical test procedure for the determination of the lubricating capability of hydraulic fluids is developed, which should close a gap in the range of available standardized tests. In particular it is planed to replace the vane cell pump test according to DIN 51389 /1/ (or DIN EN ISO 20763) by the new procedure and test apparatus which is developed within the research projects "Mechanical Testing of Hydraulic Fluids I+II (DGMK-projects 514 und 514-1) /2/, /4/. The new test procedure is characterized by low costs for specimen, great flexibility because of the simple shape of the specimen, low test time, low material and energy costs and normal requirements for the measurement technique /3/. The MPH test procedure is suitable for automation, so that influences from handling can be excluded.

The paper presents the results of new test series with 9 mineral oil based hydraulic fluids, 2 motor oils and one gear oil. The PKT was commissioned by an oil supplier to test the fluids within a blind test regarding to their lubricating and wear protection capabilities. The multigrade motor oil and the gear oil were tested at various concentrations of a commercially available "additive" in the MPH test apparatus to determine changes in the lubricating and wear protection capability. There was measured a significant influence of the "additive", particularly in the characteristic of the friction coefficient within the endurance test.

Figure 1 show the test rig in the institute own test field and a CAD model of the main assembly to realize a dynamically loaded rolling/sliding line contact, consisting of an excentric rotating cylinder and the test specimen "slider".
2 MPH test rig parameters

Figure 2 show the load conditions of the tribocontact and the defined test rig parameters.

- speed of the cylinder \( n_{\text{EX}} = 650 \) 1/min
- eccentricity of the cylinder \( e = 2.5 \) mm
- sliding speed \( v_{\text{EX}} = 3 \) m/s
- load of the tribocontact \( F_{\text{EX,av}} = 0-14 \) kN (\( p_{\text{HD}} = 0-200 \) bar)
- Hertzian stress (endurance test) \( p_{\text{Hertz}} = 1200 \) N/mm\(^2\)
- Hertzian stress (short time test) \( p_{\text{Hertz}} = 0-3000 \) N/mm\(^2\)
- range of oil temperature (controlled) \( \vartheta_{\text{tank}} = 20-100 \) °C

Figure 2: Load conditions of the tribocontact and the defined test rig parameters
The material combination of the tribocontact can be chosen regarding to the requirements of the test. For example, also specimen of ceramic materials (coated or full-ceramics) or even sliding bearing materials can be used. By default all oils are tested at a reference viscosity of 20 mm²/s; the tank temperature of the MPH test rig will be controlled to keep the reference viscosity of the oil constant.

3 Description of the MPH test rig and the defined test conditions

For statistical validation of the MPH test results the necessary short-term and endurance tests were 2 times repeated (see Figure 3). The MPH test takes a total of approximately 125 hours (3 short-term tests á 1.5 h and 3 endurance tests á 40 h), this is only the half of test time that the vane cell pump needs /1/. Moreover, the 2-times repetition of the MPH test makes a statement to the spreading of the measured test result parameters, whereby the significance of the results in comparison with other testing methods, such as the gear rig tester /11/ or the vane cell pump test, is significantly increasing. In these test procedures a repetition of the test is not mandatory and is usually also for cost reasons not performed.

![Diagram showing the MPH test rig and test conditions](image)

**Figure 3**: Measured test rig parameters and deduced test results

The representation of the evaluated test series takes place on the one hand in tabular form, with the measured and calculated fluid specific result parameters critical pressure \( p_{HD, crit} \), average coefficient of friction \( \mu_{EX, av} \) and wear volume \( V_{line} \) and on the
other hand by an 3-dimensional graphical representation with relative values. In this presentation, all result parameters are related to the results of one fluid, which is defined as a reference for all tested fluids within one test series. These three result parameters (absolute or relative) describe the lubricating and wear protecting capability of the tested hydraulic fluids, gear and motor oils.

3.1 Test conditions within the short-term test run

Short-time tests are used to determine the fluid specific critical high-pressure pHD,crit where spontaneously and intensive, adhesive material transfer ("seizing") between the specimen slider and the cylinder occur. Figure 4 show the characteristic of the short time test parameters.

Figure 4: Characteristic of the test rig parameters – short-term test
This critical pressure $p_{HD,\text{crit}}$ leads to a critical load (crit. Hertzian stress) in the tribocontact, where the lubricating film between the specimen collapses and the area of mixed friction is left into solid friction. This value is one of the three result parameters of the MPH test. Figure 4 shows the characteristic of the test parameters during a short-time test with a mineral oil based hydraulic fluid with anti wear and extreme pressure additives (HLP). The clear identification of the critical pressure at which the tribocontact begins "seizing" takes place by the determination of the gradient of the mean friction torque $\text{grad } T_{EX}$ of the excentric (cylinder). The critical pressure $p_{HD,\text{crit}}$ at which the torque exceeds the limit of 0.2 Nm/s, is used as the result parameter of the short-time test.

3.2 Test conditions within the endurance test run

The endurance test is used for the determination of the two other result parameters average coefficient of friction $\mu_{EX,\text{av}}$ and wear volume $V_{\text{line}}$. Figure 5 shows the typical characteristic of the test rig parameters within a endurance test run. After a defined start procedure the pressure $p_{HD}$ is linear increased to the endurance test pressure.

![Figure 5: Characteristic of the test rig parameters – endurance test](image)

The level for the average pressure $p_{HD,\text{av}}$ for the endurance test run is directly influencing the fluid specific coefficient of friction and the fluid specific wear volume of
the specimen. Therefore it is not aloud to compare test results of oils directly with each other, if the test has not taken place under the same load conditions (pressure p_{HD,av}). Various test series with different oils with different additive formulations and concentrations have shown that a pressure of p_{HD,av} = 60 bar (approx. 1200 N/mm² Hertzian stress) during the endurance test period for most not wear protected oils is not critical, so they don’t start "seizing" and the amount of wear volume of good lubricating fluids is still so large that this can be reproducibly measured. The load level of p_{HD,av} = 60 bar within the endurance test was therefore defined as a standard.

4. MPH test results with hydraulic fluids

Table 1 shows typical results of 9 MPH test series with different mineral oil based hydraulic fluid with different additive packages; the table shows mean values each generated by 3 short-term and 3 endurance tests. The view on these absolute result parameters allow an assessment of the lubricating and wear protecting capability of the tested fluids.

<table>
<thead>
<tr>
<th>tested hydraulic fluids</th>
<th>crit. high pressure pH_{HD,crit} [bar]</th>
<th>crit. Hertzian Stress p_{Hertz,crit} [bar]</th>
<th>av. friction coefficient ( \mu_{EX,av} ) [-]</th>
<th>max. friction coefficient ( \mu_{EX,max} ) [-]</th>
<th>wear volume V_{line} [mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil-1 (HVLP - Zn)</td>
<td>79</td>
<td>1348</td>
<td>0,069</td>
<td>0,075</td>
<td>0,056</td>
</tr>
<tr>
<td>Oil-2 (HVLP - Zn)</td>
<td>83</td>
<td>1381</td>
<td>0,069</td>
<td>0,074</td>
<td>0,059</td>
</tr>
<tr>
<td>Oil-3 (HLP - Zn)</td>
<td>103</td>
<td>1539</td>
<td>0,057</td>
<td>0,068</td>
<td>0,065</td>
</tr>
<tr>
<td>Oil-4 (HLP - Zn)</td>
<td>94</td>
<td>1470</td>
<td>0,053</td>
<td>0,064</td>
<td>0,136</td>
</tr>
<tr>
<td>Oil-5 (HVLP - Zn)</td>
<td>89</td>
<td>1430</td>
<td>0,070</td>
<td>0,075</td>
<td>0,232</td>
</tr>
<tr>
<td>Oil-6 (HVLP - Zn)</td>
<td>99</td>
<td>1514</td>
<td>0,071</td>
<td>0,075</td>
<td>0,351</td>
</tr>
<tr>
<td>Oil-7 (HL - Zn free)</td>
<td>65</td>
<td>1226</td>
<td>0,049</td>
<td>0,051</td>
<td>0,043</td>
</tr>
<tr>
<td>Oil-8 (HLP - Zn)</td>
<td>121</td>
<td>1674</td>
<td>0,049</td>
<td>0,055</td>
<td>0,125</td>
</tr>
<tr>
<td>Oil-9 (HLP - Zn)</td>
<td>71</td>
<td>1280</td>
<td>0,048</td>
<td>0,066</td>
<td>0,123</td>
</tr>
</tbody>
</table>

Table 1: Tabular representation of test results – mineral oil based hydraulic fluids

A direct comparison of the lubricating capability of the oils on basis of the tabular results representation is possible, but comparatively difficult. Only the common view of all three fluid specific result parameters enables a suitable differentiation of the tested fluids. Figure 6 shows the results of 9 MPH test series in a three-dimensional result room.
The coordinates of each fluid within this result room is determined by the mean values of the result parameters (see Figure 6). A result coordinate is defined by the three parameters relative critical pressure $p_{HD,crit,rel}$, relative coefficient of friction $\mu_{EX,av,rel}$ and rel. wear volume $V_{line,rel}$. The result coordinates of each tested fluid are placed relative to the coordinates of the selected reference oil. In the result room the hydraulic fluid “Oil 5” was selected as reference fluid. The reference fluid determines the position of 100% coordinate, relative to this reference all the other fluids are positioned. The decision which of the fluids is defined as the reference fluid has no effect on the result of comparison, but only affects the clarity of the presentation. The maximum spread of the results of a tested fluid limit in the three main axes relative critical pressure $p_{HD,crit,rel}$, relative coefficient of friction $\mu_{EX,av,rel}$ and rel. wear volume $V_{line,rel}$ the “spread room”. The “spread room is a indication of the reproducibility of the test results, the smaller the enclosed volume, the higher was the reproducibility of the considered test runs.

Figure 6: Three-dimensional representation of the MPH test results
Besides these absolute and relative representations of the result parameters in Table 1 and Figure 6, the characteristic of the coefficient of friction is also suitable to differentiate between the tested fluids and to make suitable statements for their lubricating capability. Figure 7 shows four typical characteristics of the coefficient of friction depending on different base oils and additive packages.

![Image showing four typical characteristics of the coefficient of friction](image)

**Figure 7**: Typical characteristics of the measured coefficient of friction
5. MPH test results with motor and gear oils

Table 2 show the tabular presentation of the results of 5 MPH test series with two different multigrade motor oils and one gear oil. The oils were tested without and with a commercial “additive” in various concentrations. This commercial “additive”, according to manufacturer’s specifications, improves the positive features (lubricating and wear protection capability) of motor and gear oils; the table shows mean values each generated by 3 short-term and 3 endurance tests.

<table>
<thead>
<tr>
<th>tested motor and gear oils</th>
<th>motor/gear “additive” [vol %]</th>
<th>crit. high pressure $P_{Hertz, crit}$ [bar]</th>
<th>crit. Hertzian Stress $P_{Hertz, crit}$ [bar]</th>
<th>av. friction coefficient $\mu_{EX, av}$ [-]</th>
<th>max. friction coefficient $\mu_{EX, max}$ [-]</th>
<th>wear volume $V_{Line}$ [mm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) motor oil 15W40</td>
<td>-</td>
<td>151</td>
<td>2410</td>
<td>0,053</td>
<td>0,067</td>
<td>0,256</td>
</tr>
<tr>
<td>(2) motor oil 15W40</td>
<td>10 %</td>
<td>111</td>
<td>2066</td>
<td>0,050</td>
<td>0,057</td>
<td>0,208</td>
</tr>
<tr>
<td>(3) motor oil 15W40</td>
<td>15 %</td>
<td>67</td>
<td>1605</td>
<td>0,047</td>
<td>0,053</td>
<td>0,146</td>
</tr>
<tr>
<td>(4) motor oil 5W40</td>
<td>-</td>
<td>115</td>
<td>2103</td>
<td>0,060</td>
<td>0,081</td>
<td>0,510</td>
</tr>
<tr>
<td>(5) motor oil 5W40</td>
<td>10 %</td>
<td>76</td>
<td>1710</td>
<td>0,051</td>
<td>0,061</td>
<td>0,422</td>
</tr>
<tr>
<td>(6) gear oil - ISO VG 320</td>
<td>-</td>
<td>140</td>
<td>2320</td>
<td>0,074</td>
<td>0,078</td>
<td>0,278</td>
</tr>
<tr>
<td>(7) gear oil - ISO VG 320</td>
<td>20 %</td>
<td>179</td>
<td>2624</td>
<td>0,076</td>
<td>0,078</td>
<td>0,055</td>
</tr>
</tbody>
</table>

Table 2: MPH test results with motor and gear oils with a commercial “additive”

![Figure 8: 3D-representation of the MPH test results – motor and gear oils](image)

(reference fluid: (2))

(1) motor oil 15W40 (without „additive“)
(2) motor oil 15W40 (+10% „additive“)
(3) motor oil 15W40 (+15% „additive“)
(4) motor oil 5W40 (without „additive“)
(5) motor oil 5W40 (+10% „additive“)
(6) gear oil ISO VG 320 (without „additive“)
(7) gear oil ISO VG 320 (+20% „additive“)
Figure 8 shows the isometric view of the results of the 5 MPH tests with “oil-2” as the reference. The three-dimensional representation of the relative test results allows a clear differentiation of the motor and gear oils with different concentrations of the commercial “additive”.

The two projections of the result room to the plains of relative critical pressure $p_{HD, crit, rel}$ and relative coefficient of friction $\mu_{EX, av, rel}$ (see Figure 9) with inclusion of the rel. wear volume $V_{line, rel}$ shows the strong influence of the “additive”. The MPH test procedure enables a clear differentiation between the oils without and with “additives” and enables suitable statements of the lubricating and wear protecting capabilities of the tested fluids.

Figure 9: Projections of the result room to the plains of relative critical pressure $p_{HD, crit, rel}$ and relative coefficient of friction $\mu_{EX, av, rel}$ with inclusion of the rel. wear volume $V_{line, rel}$.
Besides these absolute and relative representations of the result parameters in Table 2 and Figures 8 and 9, also the within the endurance test determined characteristic of the coefficient of friction is suitable to differentiate between the tested oils and to make suitable statements for their lubricating capability.

Figure 10 demonstrate that the addition of the “additive” leads to a significant decrease of the friction coefficient at the beginning of the endurance test run, particularly in the pressure increasing period during the start procedure (see also Figure 5). The oil without additional “additive” causes at the beginning of the endurance test a much higher coefficient of friction. After about 25 h the very different characteristics at the beginning of the test become more and more similar and are almost identical at the end of the endurance test.

Figure 10: Changing of the characteristic of the measured coefficient of friction after addition of different amounts of commercial “additive”

The motor oil with the viscosity range 5W40 shows a similar behaviour to the 15W40 (not illustrated in the paper), but the reduction of the coefficient of friction after adding the additive is less distinct.
Conclusion

The analysis of hydraulic fluids, gear and motor oils in the MPH test apparatus has shown that the determination of the coefficient of friction, the wear volume and the critical pressure ("seizing" load) is suitable to differentiate lubricants very clearly and that suitable statements regarding lubricating and wear protecting capability of the fluids can be made /5/, /6/. The high accuracy of compliance with the defined test conditions was achieved by design optimisations of the MPH test apparatus; these further development of the test rig was an essential part of the DGMK research project 610 /7/ (see also /8/, /9/, /10/).

The Institute of Product Development and Engineering Design (PKT) is currently developing a new generation of the MPH test apparatus to bring the new test procedure into application, at first with round robin tests at the company sites of oil deliverers, additive developers and component developers from the propulsion technology. Within the further development of the MPH test apparatus, the test procedures, the geometry of the tribocontact and the load conditions remain unchanged, but the complexity and size of the test rig will be significantly reduced. In particular, a reduction of the required amount of test fluid from currently 60 l to 10 l is intended.

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