Journal of KONBiN 48(2018)
e-ISSN 2083-4608
DOI 10.2478/jok-2018-0061

Leszek UŁANOWICZ, Grzegorz JASTRZĘBSKI, Michał JÓŹKO,
Ryszard SABAK, Paweł SZCZEPANIAK
Air Force Institute of Technology (Instytut Techniczny Wojsk Lotniczych)

HYDRAULIC PLUNGER PUMP CONTAMINATION SENSITIVITY EVALUATION

Szacowanie wrażliwości zanieczyszczeniowej pomp hydraulicznych

Abstract: *The correct operation of the hydraulic pump and achieving the assumed durability depends on the purity of the used working fluid. The research paper discusses a method for evaluating the contamination sensitivity of a hydraulic plunger pump. The theoretical grounds for evaluating the contamination sensitivity of hydraulic plunger pumps of a hydraulic drive based on the contamination sensitivity factor were presented. An example of evaluating contamination sensitivity of an NP-34M hydraulic plunger pump was discussed.*
Keywords: hydraulic drive, hydraulic pump, working fluid, impurities in the liquid

Streszczenie: *Poprawne działanie pompy hydraulicznej i jej trwałość zależy od czystości użytkowanej cieczy roboczej. W artykule przedstawiono metodę szacowanie wrażliwości zanieczyszczeniowej nurnikowej pompy hydraulicznej. Zaprezentowano podstawy teoretyczne szacowania wrażliwości zanieczyszczeniowej nurnikowych par hydraulicznych napędu hydraulicznego oparte o współczynnik wrażliwości zanieczyszczeniowej. Przedstawiono przykład szacowania wrażliwości zanieczyszczeniowej nurnikowej pompy hydraulicznej typu NP-34M.*
Słowa kluczowe: napęd hydrauliczny, pompa hydrauliczna, ciecz robocza, zanieczyszczenia w cieczy roboczej

1. Introduction

An avionic hydraulic drive is a technical object, consisting of hydraulic assemblies connected via hydraulic lines, used to transfer streams of energy through a working fluid, from a hydraulic pump to a power consumer. Therefore, the working fluid is an integral part of a hydraulic drive. The operational effectiveness and reliability of hydraulic plunger pumps largely depends on the content of contamination in the working fluid. The presence of impurities in working fluids leads to abrasive wear, seizing and stalling of moving parts of the pumps, e.g. plungers in rotor cylinders [1, 4, 8, 9, 12, 13]. Using a working fluid containing certain concentration of impurities causes a change of the basic characteristics of the hydraulic pump, such as required linearity, assumed hysteresis, operation stability. Contamination of hydraulic drives originate mainly from [1, 4, 5, 9] manufacturing and mounting of hydraulic assemblies, improper distribution of the working fluid and drive filling, wear of the assemblies or abrasion of the seals.

When analysing individual phases of one working fluid circulation cycle within a hydraulic drive, one can track the displacement of solid particles within the drive and their impact on individual drive assemblies, especially hydraulic plunger pumps. A working fluid in a hydraulic tank, with an output condition depending on the cleanliness of the tank and the working fluid it is filled with, is sucked in by a hydraulic plunger pump and supplied to hydraulic drive assemblies. Firstly, the working fluid works with hydraulic plunger pairs of the hydraulic pump. The hydraulic pump sucks all contamination destructively acting on its hydraulic plunger pairs from the hydraulic tank. Next, the working fluid usually flows through a filter, which stops the impurities of appropriate size. This increases the cleanliness of the working fluid flowing to the control and actuating assemblies of the hydraulic drive. This brief analysis indicates that the operation of a hydraulic plunger pump and its reliability is largely affected by the cleanliness of the working fluid in the hydraulic tank.

In the light of the above, there is a need to develop a method to assess the contamination sensitivity of hydraulic plunger pairs of a hydraulic pump. The term "contamination sensitivity" refers to the deterioration of the most important parameters of a hydraulic pump resulting from the impact of a specific level of contamination within a working fluid. Therefore, the degree of deterioration of the most important parameters of a hydraulic pump depends on the size of solid particles and their concentration in the working fluid, as well as the hardness of solid impurities. It can be assumed that the degree of deterioration of the most important parameters of a hydraulic pump, affected by the working fluid with a determined level of contamination, depends on the contamination sensitivity of hydraulic plunger pairs of the pump to each range of particle sizes and the degree, to which the particles of all size ranges impact the plunger pairs.

One of the basic difficulties encountered by designers, manufacturers and users of hydraulic pumps is determining what cleanliness of the working fluid to allow, in order to ensure the pump's correct operation and its assumed durability [3-7]. This issue has not yet been solved, despite the growing complexity and miniaturization of hydraulic pump designs, as well as the piling difficulties associated with securing their reliability. Very few studies had been published up to date, which concentrate on contamination sensitivity of hydraulic plunger pairs of a hydraulic pump. The authors mostly attempt to explain the studies of hydraulic filters or the phenomenon of gradual reduction of the micro-gap active cross-section as a result of absorbing dispergated particles in the fluid through its wall, which is a phenomenon associated with cavitational generation of contamination in hydraulic systems [1, 8, 10, 13]. The analysis of the literature indicates that studying the contamination sensitivity of hydraulic drives is a novel subject.

2. Operating conditions and loads of a hydraulic plunger pair

A hydraulic plunger pair acts as a displacement element of a hydraulic pump. It consists of moving plungers, a pump rotor with plunger operation chambers and an angled keep plate. A hydraulic plunger pair has an operating cycle consisting of three stages: filling of the working chamber with fluid, transferring the fluid in the working chamber from the suction area (low pressure) to the supply area (high pressure), forcing the fluid out of the working chamber. Plunger diameter is usually from 10 mm to 20 mm and the plunger stroke from 10 mm to 30 mm. Plunger length is selected taking into account its stroke and the maximum permissible contact pressures between the plunger and the surface of the angled keep plate.

A characteristic of a plunger pair is the simultaneous interaction of the plunger and two elements: seat surface of the rotor, in relation to which the plunger moves with a reciprocating motion and the surface of the angled keep plate, in the relation to which rolling, rotating and sliding of a spherical surface of the plunger face takes place. The plungers of the supply node perform a complex movement in the course of the hydraulic pump operating process. Under the impact of working fluid pressure and the components of rotational centrifugal forces and elastic spring forces from one side, and the reaction of the angle keep plate surface from the other, the plungers displace in a reciprocating manner within the rotor sleeves. Together with the pump rotor, the plungers rotate around the rotor axis, achieving a specified displacement relative to the angled keep plate surface. The plunger, besides a reciprocating motion, rotates in relation to the rotor sleeve, with a variable speed depending on the rotor rotation angle. The diagram of the forces acting on the plunger within the operating process of a plunger pair is shown in fig. 1.

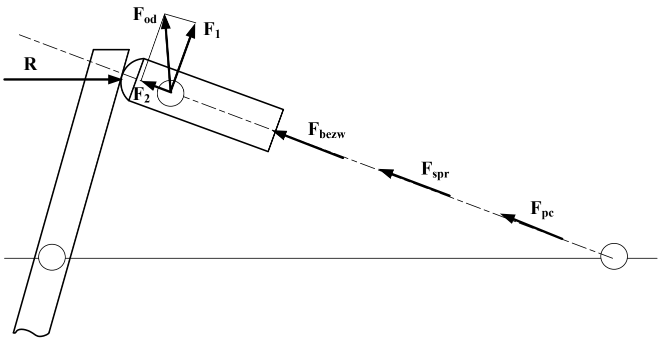

Fig. 1. Plunger pump load diagram F_{pc} – working fluid pressure force; F_{bezw} – force of inertia upon a relative movement; F_{spr} – spring force; F_{od} – centrifugal force; R – plunger face reactive force; F_1 and F_2 – centrifugal force components

When the plunger supplies the fluid, it is impacted, along the axis, by: working fluid pressure force F_{pc}, inertial force upon relative motion F_{bezw}, spring force F_{spr}. Centrifugal force F_{od} acts in the radial direction from the axis of rotation through the plunger centre of gravity. At the point of contact between the plunger face spherical surface and the keep place surface, the reactive force *R* acts towards the radius of the plunger ball. The fluid pressure force acting on the plungers represents a force resulting from fluid pressures, acting from the supply mains side and from angled keep plate space opposite to the plunger. The centrifugal force can be broken down into two components: F_1 and F_2. Force F_1 acts on the plunger in a radial direction and presses it to the angled keep plate surface. The magnitude of that force determines the friction force within the plunger pair. The reactive force component R causes a lateral pressure of the plunger to the sleeve surface. The centrifugal force component F_2 act in the direction of the plunger axis, and together with the spring, presses it to the angled plate. This force contributes to overcoming friction in the plunger pair during displacement of the plunger from the bottom to the top dead centre.

The hydraulic plunger pairs used in pumps or rotating hydraulic motors are characterised by the following features:

1) constant reciprocating motion of plungers relative to the cylinder, with a stroke from several millimetres to several centimetres, and the speed resulting from the multiplicity of the lift system (drive shaft) rotating speed,

2) high radial pressure between the plunger and cylinder surface,
3) high contact loads of the plunger face surface and the control element surface,
4) operation in conditions of complex coupling of acting loads and mutual displacement of cooperating friction surfaces, with relative slide, at a rapidly changing sliding speed, depending on the rotor angle of rotation,
5) high sensitivity to the presence of solid particles in the working fluid, which cause increase friction in the plunger-cylinder pair or blockage of the plunger,

3. Theoretical grounds for the contamination sensitivity evaluation of hydraulic drive hydraulic plunger pairs

The capacity of a hydraulic plunger pump changes (degrades) due to the impact of contamination within a working fluid on a hydraulic plunger pair. The change (degradation) of the hydraulic plunger pump capacity results from damage to the surface of side plungers and increasing backlash within the hydraulic plunger pair.

Utilizing the assumptions similar to compressibility and the bulk modulus of elasticity of the working fluid, it is possible to describe the rate of change over time in the capacity of a hydraulic plunger pump, due to the solid particle contaminants in the working fluid impacting the hydraulic plunger pair of this pump [2]. The change (degradation degree) in the capacity of a hydraulic plunger pair can be described by the equation:

$$\frac{dQ_W(t)}{dt} = -\Gamma(z)\,\frac{dN(t)}{dt} \tag{1}$$

where:

$\Gamma(z)$ – contamination sensitivity factor of a hydraulic pump plunger pair,
N – number of particles in the i size range found in the hydraulic drive working fluid volume.

Contamination sensitivity factor $\Gamma(z)$ of a hydraulic plunger pair depends on the resistance of that pair to factor-determined wear α and on the sizes and concentration of solid particles in the working fluid. This can be expressed as follows:

$$\Gamma(z) = \alpha \cdot z(t) \tag{2}$$

where:

α – wear factor as a result of contamination impact on the hydraulic plunger pair,
$z(t)$ – contamination concentration within a hydraulic drive.

Hydraulic drives operate within a closed working fluid circulation and, as a result, should the liquid contain or have introduced a certain amount of contamination with an initial concentration of N_o within a given size range i, the particles will be destroyed due to the impact of a hydraulic pump destructive activity, as per the formula:

$$z(t) = z \cdot e^{-\frac{t}{T}} \tag{3}$$

where:

z – initial concentration of contamination in a working fluid,

T – contamination particle destruction time constant in a working fluid.

Substituting the relationships (2) and (3) to the equation (1), we get a modified equation describing a change in the hydraulic plunger pump capacity Q_w over time:

$$\frac{dQ_w(t)}{dt} = -\alpha \cdot z \cdot e^{-\frac{t}{T}} \cdot \frac{dN(t)}{dt} \tag{4}$$

The change in the hydraulic plunger pump capacity can be determined from the equation of the working fluid flow intensity balance equation – principle of mass conservation. This equation has the following notation [2]:

$$Q_w = \frac{dV}{dt} + \frac{V}{\rho}\frac{d\rho}{dt} \tag{5}$$

where:

$\frac{dV}{dt}$ – volume change resulting from adjusted geometrical dimensions,

$\frac{V}{\rho}\frac{d\rho}{dt}$ – volume change induced by working fluid compressibility,

V – working fluid volume,

ρ – working fluid density.

Due to the fact the flow induced by working fluid compressibility is minor compared to the flow induced by a change in the volume, this component is omitted in further considerations. Therefore, the hydraulic plunger pump capacity balance equation has the following notation:

$$Q_w(t) = \frac{dV}{dt} \tag{6}$$

The following relationship arises from the definition of contamination concentration [2]:

$$z(t) = \frac{N(T)}{V(T)} \tag{7}$$

where:

$N(T)$ – number of particles within the volume of a hydraulic drive working fluid,

$V(T)$ – the volume of contaminated working fluid in a hydraulic drive.

Taking the relationship (7) into account, we can note:

$$\frac{dN(t)}{dt} = z(t)\frac{dV(t)}{dt} \tag{8}$$

Substituting the relationship (3) to the equation (8), we get:

$$\frac{dN(t)}{dt} = z \cdot e^{-\frac{t}{T}} \cdot \frac{dV(t)}{dt} \tag{9}$$

Substituting the equation (6) to the equation (9), we get:

$$\frac{dN(t)}{dt} = z \cdot e^{-\frac{t}{T}} \cdot Q(t) \tag{10}$$

Ultimately, the equation describing the rate of change of the hydraulic plunger pump capacity Q_w takes the form:

$$\frac{dQ_w(t)}{dt} = -\alpha \cdot z \cdot e^{-\frac{2t}{T}} \cdot Q_w(t) \tag{11}$$

After separating the variables, equation (11) can be transformed to the form:

$$\int_{Q_{w_0}}^{Q_w(t)} \frac{dQ_w(t)}{Q_w(t)} = -\int_0^t \alpha \cdot z \cdot e^{-\frac{2t}{T}} dt \tag{12}$$

where:

Q_{wo} – hydraulic plunger pump capacity initial value.

As a result of integration (12) and omitting the component $\left(1-e^{-\frac{2t}{T}}\right)$, in the case of large values of time t, we obtain the relationship for the capacity of a hydraulic plunger pump:

$$Q_w\,(t) = Q_{w_0} exp\left[-\frac{\alpha\cdot T\cdot z^2}{2}\right] \tag{13}$$

or

$$\frac{Q_w(t)}{Q_{w_0}} = exp\left[-\frac{\alpha\cdot T\cdot z^2}{2}\right] \tag{14}$$

where:

$Q_w(t)$ – hydraulic plunger pump capacity after time t,
Q_{wo} – hydraulic plunger pump capacity initial value.

In the practical aspect, contamination sensitivity of a hydraulic plunger pump is studied not for selected particle size ranges but for selected working fluid cleanliness classes. Therefore, it is more convenient to use a working fluid cleanliness class number *K* than the concentration of contaminations *z* in a given size range.

The relationship between the concentration of contamination *z* in a given size range and the working fluid cleanliness class number *K* has the form:

$$z = 2^{K+1}\cdot\frac{M}{V}\left[\frac{particle\ number}{unit\ of\ volume}\right] \tag{15}$$

where:

K – working fluid cleanliness class as the adopted standard [14-18],
M – number of particles in 100 cm^3 of the working fluid for a cleanliness class number zero, as per the adopted standard [14-18],
V – volume of contaminated working fluid [14-18].

Equation (14) enables to determine a wear factor resulting from the impact of contaminants on hydraulic plunger pair of the pump, in the following form:

$$\alpha = -\frac{2}{z^2\cdot T}\cdot ln\frac{Q_w}{Q_{w_0}} = \frac{2}{z^2\cdot T}\cdot ln\frac{Q_{w_0}}{Q_w} \tag{16}$$

Using relationship (15) and (16) we obtain a relationship for the contamination sensitivity factor *Γ(z)* of a hydraulic plunger pump, in the following form:

$$\Gamma(z) = \frac{V}{2^K \cdot T \cdot M} \cdot ln\frac{Q_{w_0}}{Q_w} \quad (17)$$

4. An example of contamination sensitivity evaluation of a hydraulic plunger pump

In order to determine a hydraulic plunger pump contamination sensitivity factor as per relationship (17), one should experimentally determine a particle destruction time constant *T* for each particle size range. Tests involving an NP-34M hydraulic plunger pump generating a flow of a working fluid with test powder within a given particle size range and a periodic capacity measurement for this pump during the tests were conducted for this purpose. AC test powder was used for the test. Powder concentration in the working fluid was selected so that the number of particles from given size ranges was in conformity with standard NAS 1638 [14]. The tests were conducted for working fluid cleanliness classes 8 to 12 as per NAS 1638. The tests were executed until achieving the NP-34M pump capacity of $Q_w/Q_{w_0} = 0{,}7$ for a given working fluid cleanliness class.

Using the test data and the relationship:

$$T = -\frac{t}{ln\frac{Q_w(t)}{Q_{w_0}}} = \frac{t}{ln\frac{Q_{w_0}}{Q_w}}$$

we calculate the working fluid particle destruction time *T*. Based on individual measurements, it is possible to calculate the time constant as an average of *j* measurement of the hydraulic pump capacity value, i.e. $T = \frac{\sum T_j}{j}$.

The results of calculations regarding the destruction of contaminant particles within a working fluid for cleanliness classes 8 to 12 as per NAS 1638 are shown in table 1.

Table 1

Contamination particle destruction times within a working fluid

	UoM	Working fluid cleanliness class number as per NAS 1638				
		8	9	10	11	12
Contamination particle destruction time within a working fluid	[h]	25600	6400	1600	400	100

By adopting the standardization of working fluid cleanliness classes as per NAS 1638 [2], it should be assumed that for a cleanliness class 00, the cleanliness class number will be K = -1, while formula (15) will adopt the following forms for individual particle size ranges:

– for particle size 5–15 µm: $z = 2^{K+1}\frac{125}{100}$;
– for particle size 15–25 µm: $z = 2^{K+1}\frac{22}{100}$;
– for particle size 25–50 µm: $z = 2^{K+1}\frac{4}{100}$;
– for particle size 50–100 µm: $z = 2^{K+1}\frac{0{,}703}{100}$;
– for particle size > 100 µm: $z = 2^{K+1}\frac{0{,}125}{100}$.

For all particles bigger than µm contained in a volume of 100 cm^3, relationship (15) can be generalized to the form: $z = 2^{K+1}\frac{152}{100}$ or in a volume of 1 dm^3 to the form: $z = 1520 \cdot 2^{K+1}$.

The wear factor resulting from the impact of contamination on a hydraulic plunger pair of a pump will have the following form:

$$\alpha = \frac{1}{1520^2 \cdot T \cdot 2^{(2K+1)}}$$

Whereas, the contamination sensitivity factor will have the form:

$$\Gamma(z) = \frac{1}{1520 \cdot T \cdot 2^{K}}$$

The dependence of the contamination sensitivity factor of the NP-34M hydraulic plunger pump operating with a working fluid with test powder, on working fluid cleanliness classes as per NAS 1638 is shown in fig. 2. The graph indicates that the NP-34M hydraulic plunger pump is insensitive to contaminations up to working fluid cleanliness class 6, as per NAS 1638. The operation of the

NP-34M pump with a working fluid above cleanliness class 8 may decrease its reliability and operational stability.

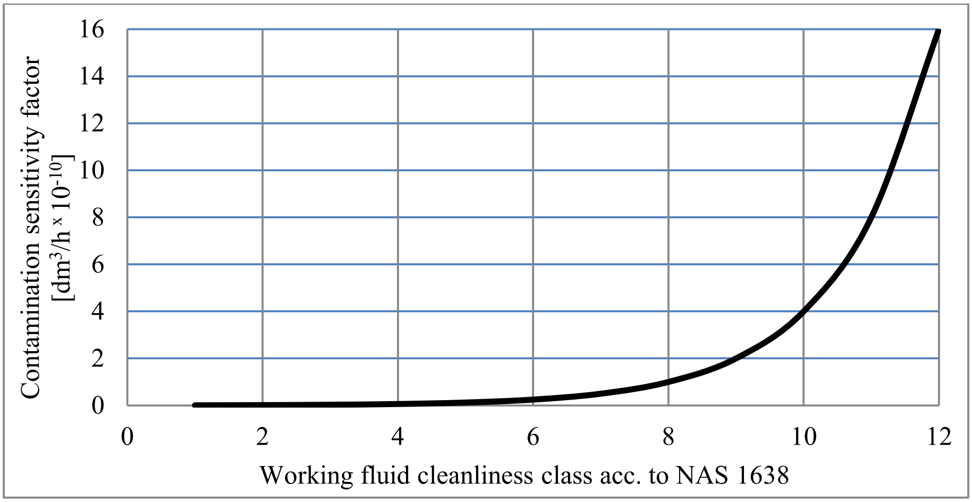

Fig. 2. Dependence of the NP-34M hydraulic plunger pump contamination sensitivity factor on working fluid cleanliness classes acc. to NAS 1638

5. Conclusions

A contamination sensitivity model for plunger hydraulic pumps presented in the research paper is a generic and rather complex model. The presented method for evaluating the contamination sensitivity of hydraulic plunger pumps adopts certain simplifications, which in addition brings the test conditions closer to the actual operating conditions of plunger pumps. The first assumption of this method is the performance of hydraulic pump tests with a working fluid containing a test powder with particles from 0 μm to ones present in a given class of working fluid cleanliness, as per the adopted standard. Furthermore, contamination sensitivity of a hydraulic pump is studied not for the selected particle size ranges, but for the selected working fluid cleanliness classes, as per the adopted standard. The second assumption of the method is assuming that the concentration of particles with sizes from a selected size range is constant over the course of pump activities.

The presented model also enables to determine the wear factor due to the impact of impurities α and is a particle destruction time constant T for a given particle size range. The product of a contamination-related wear factor α and the particle destruction time constant *T* for each particle size range enables to predict the durability of hydraulic pumps.

The contamination sensitivity factor proposed in the article can be a convenient parameter used to compare hydraulic pumps and other hydraulic assemblies operating in the same conditions.

The awareness of hydraulic plunger pair behaviour under the impact of contamination contained in the working fluid can be helpful in their correct design, manufacturing and operation.

6. References

1. Day M.J., Rinkinen J.: Contaminant monitoring of hydraulic systems - the need for reliable data, Presented at 10th International Congress and Exhibition on Condition Monitoring and Diagnostic Engineering Management, Helsinki, June 1997.
2. Gullion M.: Theory and calculations of hydraulic systems, Scientific and Technical Publishers, Warszawa, 1966.
3. Nie S.L., Huang G.H., Zhu Y.Q., Li Z.Y., Li Y. P.: SEWHAPM: development of a water hydraulic axial piston motor for underwater tool systems, Journal of Mechanical Engineering Science, vol. 219, no. 7/2005.
4. Nie S.L., Li Y.P., Shi X.Y., Huang G.H., Hu B.: An IPINP model for the assessment of filter allocation and replacement strategies in a hydraulic contamination control system under uncertainty, Journal of Mechanical Engineering Science, vol. 223, no. 4/2009.
5. Nie S.L., Hu Z., Li Y.P., Huang G.H.: Non-linear programming for filter management in a fluid power system with uncertainty, Journal of Power and Energy, vol. 224, no. 2/2010.
6. Nie S.L., Li Y.P., Xiong Z.B., Huang G.H., Hu B., IFQP: a hybrid optimization method for filter management in fluid power systems under uncertainty, Engineering Optimization, vol. 42, no. 1/2010.
7. Nie S.L., Zheng Y.L., Li Y.P., Peng S., Huang G.H.: IFCIP: an integrated optimization method for planning filters in fluid power systems under uncertainty, Engineering Optimization, vol. 43, no. 3/2011.
8. Poeth B.: Proactive maintenance, Fluid Power Journal, vol. 12, no. 1/2005.
9. Stecki S.J.: Modeling of contamination control system. First Annual Workshop on Total Contamination Control, Monash University, Fluid Power Net Publications, Melbourne 1998.
10. Tomasiak E.: Hydraulic and pneumatic drives and controls, Wydawnictwo Politechniki Śląskiej, Gliwice 2001.

11. Yao C.Y., Zhao J.Y.: Application of silting principle to online monitoring oil contamination in hydraulic system, China Mechanical Engineering, vol. 17, no. 2/2006.
12. Zboiński M, Spychała J., Deliś M.: The reliability analysis of hydraulic systems supporting aircraft control systems, Problemy eksploatacji, vol. 1/2011.
13. HYDAC Filtration Handbook no E70.000.0/02.08 www.hydac.com.au.
14. NAS 1638, Cleanliness requirements of parts used in Hydraulic systems, Aerospace Industries of America, Washington D.C., USA, 2001.
15. ARP 598, The determination of particulate contamination in liquids by the particle count method, SAE, Warrendale, Pa., USA, December 1986.
16. ISO 4406, Hydraulic fluid power - Fluids - Method for coding level of contamination by solid particles, International Organization for Standardization, Geneva, Switzerland, 1999.
17. AS4059, Aerospace fluid power - cleanliness classification for hydraulic fluids, SAE, Warrendale, Pa., USA, April 2001.
18. ISO TR16386, Hydraulic fluid power - Impact of changes in ISO fluid power particle counter, contamination control and filter test standards, International Organization for Standardization, Geneva, Switzerland, 1999.