

## USING SIMILARITY NUMBERS FOR THE DIAGNOSTICS OF AIRCRAFT HYDROGENERATOR

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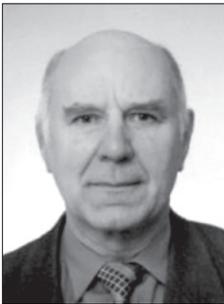


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**Abstract.** In aviation, great emphasis is placed on aircraft safety. The current technical condition of the aircraft and its systems is an important parameter for its airworthiness. In this respect, the usage of diagnostics without disassembly is considered an advantage. This method provides information on the technical condition of the aircraft or its parts throughout their operational and technical life. The technical condition of the elements measured during a flight should be compared to parameters specified by the manufacturer and measured in laboratory conditions. This article deals with the possibility of the use of dimensionless numbers for the diagnostics of the hydro generator.

**Keywords:** Aircraft, hydro generator, diagnostics, dimensionless numbers, hydraulic system.

### 1. Introduction

Experiments in the field of hydraulic systems offer the possibility of determining the operational impact and characterizing the links between the technical condition and the corresponding symptoms. From a practical point of view, emphasis is placed on keeping only the information that has the greatest information value for the technical condition assessment. The parameters, which do not require additional conversions or corrections with respect to the operating conditions under which they were meas-

ured, are preferred. Such parameters allow us to compare the diagnosed component with a standard component.

In the case of hydraulic systems, it is difficult to determine the actual technical condition, since the sensing values of diagnostic parameters during a flight are not assessed under the same conditions as the measurements in the manufacturer's laboratory. This article is focused on the possibility to compare parameters measured during a flight with the parameters measured in the laboratory by using similarity numbers.

**2. The means for aircraft control and diagnostics**

Diagnostic methods have different operation principles and degree of automation. There are two basic options for aircraft diagnostics. The diagnostics of object may be performed on the ground, in which case the condition of the object is assessed regardless of ambient conditions. Diagnostics may also be performed using sensors installed on board of an aircraft: the data is evaluated and analyzed on a mobile checkpoint. The diagnostic system KL-39 was based on the principle which was used to diagnose the L-39 Albatros and was conceived as a land evaluation center located in the car UAZ 452A (Fig.) (KL-39 2013).

The second possibility for monitoring the technical condition of an aircraft is the diagnostic system AMOS, which is designed for the aircraft L-159 ALCA and is currently used. The AMOS monitoring system measures and evaluates aircraft parameters in real time, and the selected parameters of aircraft onboard systems are stored in fixed memory. During a flight, the pilot is informed, about major events related to on-board systems and flight safety via the multifunction display. In the case of an aviation emergency event, it allows to carry out the necessary technical analysis of the emergency recorder's records.

It is clear from the comparison that the present monitoring systems for airplanes are moving towards onboard diagnostics. Sensor signals are permanently placed in the diagnosed element of the airplane and record the scanned data into the recording and evaluation units located in the airplane. Measurement and evaluation systems increase the cost of the system and place increased demands on sensors and devices that must have high reliability and durability (Nechval *et al.* 2004). With this type of diagnosis, the data is gathered directly from the service during the whole period of a reference system's operation and is subsequently evaluated by the onboard computer. In terms of diagnosis, it is necessary

to find the parameters that characterize the condition of an object and its wear. On the basis of diagnostics the maintenance of the system or its components is performed afterwards.

**3. Dimensionless numbers**

Experimental work is an important conjunction of theory and practice. The laws of similarity between the model and the final product are basis for this connection (Tab.). Three types of mechanical similarities are usually applied in fluid mechanics (Sob 2002):

- 1) geometric similarity: the lines of objects are proportional and the angles between them are equal;
- 2) kinematic similarity: this means that the observed geometry of vector field rate is similar;
- 3) dynamic similarity: dynamic similarity indicates that the observed geometry of vector field forces is similar.

Similarity solution is possible in three ways:

- 1) using the geometric, kinematic and dynamic similarity;
- 2) employing differential equations describing the status monitoring;
- 3) using algebraic dimensional analysis.

Table. The most widely used similarity numbers (Noskievic *et al.* 1987)

The ratio of inertial force and other force types	frictional	gravity	pressure
	$Re = \frac{vl}{\nu}$	$Fr = \frac{v^2}{gl}$	$\frac{1}{Eu} = \frac{\rho v^2}{p}$
	O. Reynolds	W. Froude	L. Euler
	elastic	capillary	
	$Ca = \frac{v^2}{a^2}$	$We = \frac{\rho v^2 l}{\sigma}$	
	A. I. Cauchy	M. Weber	

**4. Using similarity numbers on the hydro generator**

A hydro generator is a converter of mechanical energy into pressure energy. Efficiency is the most important parameter characterizing the condition of a hydro generator. The efficiency of a hydro-generator depends on the pump design, operation, input and output parameters (Zborník... 1988):

$$\eta = f(Q, V_g, n, p, M_k, c_v, \rho, T, \nu, E_k), \tag{1}$$

where  $Q$  [ $m^3s^{-1}$ ] indicates the rate of flow;  $V_g$  [ $m^3$ ] – the geometric volume of a hydro generator;  $n$  [ $s^{-1}$ ] – rotation speed;  $p$  [ $kgm^{-1}s^{-2}$ ] – the pressure gradient between the inlet and output pressure;  $M_k$  [ $kg m^{-2} s^{-2}$ ] – torque moment;  $c_v$  [ $m^2 K^{-1} s^{-1}$ ] – the mean specific heat of oil;  $\rho$  [ $kg m^{-3}$ ] – oil density;  $T$  [K] oil temperature;  $\nu$  [ $m^2$ ]

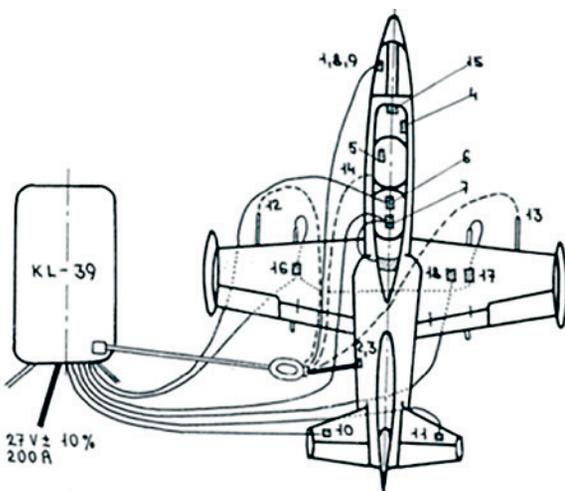


Fig. Scheme of KL-39 connection to an aircraft (Kral *et al.* 1985)

s<sup>-1</sup>] kinematic viscosity; and  $E_k$  [kgm<sup>-1</sup>s<sup>-2</sup>] – the oil modulus of elasticity.

The estimated dependence (1) can be expressed in the following exponential form:

$$\eta = CQ^a V_g^b n^c p^d M_k^e c_v^f \rho^g \Delta T^h \nu^i E_k^k. \quad (2)$$

Constant  $C$  and exponents (from  $a$  to  $k$ ) can be determined from the results of active experiments and measurements. The similarity theory ( $\pi$  – theorem) and dimensional analysis can be used. Unknown numbers can be reduced in this way.

$$\eta = f(\pi_1, \pi_2, \dots, \pi_n), \quad (3)$$

where  $\pi_1$  to  $\pi_n$  are the dimensionless arguments. The numbers of arguments from the original ten are reduced by four (the number of basic parameters, namely weight, length, time and temperature). The homogeneous systems of algebraic equations from equation (2) for each of the basic variables are:

$$\begin{aligned} kg: 0 &= d + e + g + k; \\ m: 0 &= 3a + 3b - d + 2e + 2f - 3g + 2i - k; \\ s: 0 &= -a - c - 2d - 2e - 2f - i - 2k; \\ K: 0 &= -f + h. \end{aligned} \quad (4)$$

It is possible to express the four exponents with reference to the remaining six exponents. The choice of the exponent is generally arbitrary. Exponents  $b$ ,  $c$ ,  $d$  and  $h$ , are selected with respect to the already known similarity numbers and ease of measurement of their arguments.

$$\begin{aligned} b &= -a - e - \frac{2}{3}f + \frac{2}{3}g - \frac{2}{3}i; \\ c &= 2g - 2f - a - i; \\ d &= -e - g - k; \\ h &= f. \end{aligned} \quad (5)$$

Substitution of the exponent in equation (2) results in:

$$\eta = C \left( \frac{Q}{V_g n} \right)^a \left( \frac{M_k}{V_g p} \right)^e \left( \frac{c_v T}{V_g^{2/3} n^2} \right)^f \left( \frac{V_g^{2/3} n^2 \rho}{p} \right)^g \left( \frac{\nu}{V_g^{2/3} n} \right)^i \left( \frac{E_k}{p} \right)^k, \quad (6)$$

after adjustment:

$$\eta = C \pi_1^a \pi_2^e \pi_3^f \pi_4^g \pi_5^i \pi_6^k, \quad (7)$$

where:

$$\begin{aligned} \pi_1 &= \left( \frac{Q}{V_g n} \right) = \eta_Q, \quad \pi_2 = \left( \frac{M_k}{V_g p} \right) = \frac{1}{\eta_p}; \\ \pi_3 &= \left( \frac{c_v T}{V_g^{2/3} n^2} \right) = \frac{1}{Ec}, \quad \pi_4 = \left( \frac{V_g^{2/3} n^2 \rho}{p} \right) = \frac{1}{Eu}; \\ \pi_5 &= \left( \frac{\nu}{V_g^{2/3} n} \right) = \frac{1}{Re}, \quad \pi_6 = \left( \frac{E_k}{p} \right). \\ \eta &= f(\eta_Q, \eta_p, Ec, Eu, Re, \pi_6), \end{aligned} \quad (8)$$

where  $Re$  indicates Reynolds' number;  $Eu$  – Euler's number;  $Ec$  – Eckert's number;  $\eta_Q$  – the flow efficiency and  $\eta_p$  – the pressure efficiency of the hydro generator.

It is possible to use an arbitrary combination of  $\pi_1$  to  $\pi_6$  for the description of the similarity of the examined phenomena. However the total count of  $\pi$  – numbers must correspond with the count of dimensionless numbers.

For  $G\ddot{u}$  – Gumbels number the following is true:

$$G\ddot{u} = \frac{p}{\nu \rho n} = \frac{V_g^{2/3} n}{\nu} \frac{p}{V_g^{2/3} n^2 \rho} = Re Eu. \quad (9)$$

And the Cauchy number is as follows:

$$Ca = \frac{V_g^{2/3} n^2 \rho}{E_k} = \frac{V_g^{2/3} n^2 \rho}{p} \frac{p}{E_k} = Eu \pi_6. \quad (10)$$

Equation (8) can then be expressed in the form:

$$\eta = f(\eta_Q, \eta_p, Re, Ec, G\ddot{u}, Ca). \quad (11)$$

During a flight, the waveforms of all variables in equation (2) are changing except for the geometric volume pump  $V_g$ . The effectiveness of the hydro generator is determined for each set (standard) measurement condition in the laboratory. These conditions are not the same as during a flight or in the case of on-ground measurement. The different parameters are described above. It is necessary to convert the efficiency measurement of the hydro generator during a flight to (standard) operating conditions in the laboratory. It is necessary to keep similarity numbers constant and, thereby, ensure similarity phenomena.

During a flight the efficiency of the hydro generator (Paciga 1985), (Nevrlý 2005) can be detected according to equation (8):

$$\eta_L = \frac{P_2}{P_1} = \frac{Q p}{M_k \omega} = \frac{Q}{V_g n} \frac{p V_g}{2\pi M_k} = \eta_Q \eta_p, \quad (12)$$

where  $P_1$  and  $P_2$  indicate the performance measured during a flight. The technical condition of the pump is determined by coefficient  $\eta$  according to equation (11). It is necessary to observe the similarity numbers ( $Re$ ,  $Ec$ ,  $Eu$ ,  $Ca$ ) at the same values that were determined by measuring the standard conditions. Therefore, equation (8) can be expressed in the following form:

$$\eta = \eta_L Re^\alpha Ec^\beta G\ddot{u}^\chi Ca^\delta, \quad (13)$$

exponents ( $\alpha$ ,  $\beta$ ,  $\chi$ ,  $\delta$ ) are determined from the results of experimental measurements.

## 5. Determination of the technical state of the hydro generator

The development of aircraft diagnostics is heading towards on-board diagnostics. In such a case, the parameters are measured and evaluated during a flight. It is necessary to determine a method for the recalculation of the obtained parameters to determine the values

under laboratory conditions. The calculated data can be compared with the data specified by the manufacturer or aircraft operator and the current technical condition of the diagnosed element can be determined. The efficiency of the hydro generator under standard conditions is determined from:

$$\eta = \eta_S \text{Re}_S^\alpha \text{Ec}_S^\beta \text{Gü}_S^\chi \text{Ca}_S^\delta. \quad (14)$$

The efficiency of the hydro generator under in-flight conditions is determined according to:

$$\eta = \eta_L \text{Re}_L^\alpha \text{Ec}_L^\beta \text{Gü}_L^\chi \text{Ca}_L^\delta. \quad (15)$$

The efficiency of the hydro generator can be recalculated from the flight conditions to the standard laboratory conditions according to equations (14) and (15):

$$\frac{\eta}{\eta} = 1 = \frac{\eta_L \text{Re}_L^\alpha \text{Ec}_L^\beta \text{Gü}_L^\chi \text{Ca}_L^\delta}{\eta_S \text{Re}_S^\alpha \text{Ec}_S^\beta \text{Gü}_S^\chi \text{Ca}_S^\delta} = \frac{\eta_L}{\eta_S} \left( \frac{\text{Re}_L}{\text{Re}_S} \right)^\alpha \left( \frac{\text{Ec}_L}{\text{Ec}_S} \right)^\beta \left( \frac{\text{Gü}_L}{\text{Gü}_S} \right)^\chi \left( \frac{\text{Ca}_L}{\text{Ca}_S} \right)^\delta. \quad (16)$$

If the flight conditions for the operation of the hydro generator are the same as standard conditions, the proportions of the various similarity numbers are equal to 1.

The efficiency of the hydro generator under flight conditions will equal the efficiency under standard conditions.

If the conditions differ, it is necessary to make a correction. The efficiency of the hydro generator is generally determined according to equation (12) for both standard and flight parameters.

If the parameters  $(v, \rho, E_K, c_v, T, n)$  measured during a flight are not the same as standard ones, the cern efficiency must be recalculated. The range and type of maintenance work depends on the recalculated efficiency.

This article assumes that a hydro generator with fixed displacement ( $V_g = \text{const.}$ ) is used, because it is the most widespread hydro generator in smaller aircraft.

### 5.1. Correction of oil temperature change

The conversion of the efficiency measured during a flight to the standard laboratory efficiency with a change of hydraulic oil viscosity is based on the similarity ratio of the Reynolds' number.

Kinematic viscosity of oil  $\nu[\text{m}^2\text{s}^{-1}]$ , which is a polymeric substance, depends primarily on its temperature. However, it is necessary to monitor the thermal, oxidative and pressurized degradation due to operation and load.

For the conversion of efficiency of the hydro generator with a fixed displacement  $V_g$  during flight conditions into the value under standard conditions and taking into account changes in the temperature of hy-

draulic oil, it is possible to simplify the structure of equation (16):

$$\eta_S = \eta_L \left( \frac{\text{Re}_L}{\text{Re}_S} \right)^\alpha = \eta_L \left( \frac{n_L v_S}{v_L n_S} \right)^\alpha = \frac{Qp}{2\pi M_k n_L} \left( \frac{n_L v_S}{v_L n_S} \right)^\alpha = \frac{Qp}{2\pi M_k n_E}, \quad (17)$$

where the equivalent rotation speeds are:

$$n_E = n_L \left( \frac{n_S v_L}{v_S n_L} \right)^\alpha. \quad (18)$$

### 5.2. The correction of oil compressibility changes

Compressibility of oil is reflected in the change of elastic modulus  $E_K$ , which affects the dynamic properties of the hydro generator. Dangerous pressure pulsations can be caused by reducing the value of the modulus of elasticity. The modulus of elasticity is affected by the content of free gas (air, nitrogen). The air is getting into the oil primarily during maintenance, such as replacing filters, filter cartridges. Equation (16) can be simplified, for correcting the changes in the modulus of oil elasticity, in the form:

$$\eta_S = \eta_L \left( \frac{\text{Ca}_L}{\text{Ca}_S} \right)^\delta = \eta_L \left( \frac{n_L^2 \rho_L E_{KS}}{n_S^2 \rho_S E_{KL}} \right)^\delta = \frac{Qp}{2\pi M_k n_L} \left( \frac{n_L^2 \rho_L E_{KS}}{n_S^2 \rho_S E_{KL}} \right)^\delta = \frac{Qp}{2\pi M_k n_E}, \quad (19)$$

where the equivalent rotation speeds are:

$$n_E = n_L \left( \frac{n_S^2 \rho_S E_{KL}}{n_L^2 \rho_L E_{KS}} \right)^\delta. \quad (20)$$

### 5.3. The correction of pressure and dynamic viscosity changes

Currently, aircraft hydraulic systems are divided into two groups (Nepraž 2002). The first group includes the system with a hydro generator with a constant flow rate at constant rotation ( $V_g = \text{const.}$ ). The second group includes the system with the hydro generator which observes the output pressure at a specific value  $V_g \neq \text{const.}$  at various flow rates. The change of pressure depends on the hydraulic motor consumption. There is a slight increase or decrease in the outlet pressure at the outlet of the hydro generator. The assessment of the technical condition of the hydro generator is affected by changes in the output pressure and it is again corrected by changing rotation speeds  $n_E$ , which are obtained according to equation (22).

$$\eta_S = \eta_L \left( \frac{\text{Gü}_L}{\text{Gü}_S} \right)^\chi = \eta_L \left( \frac{p_L \mu_S n_S}{\mu_L n_L p_S} \right)^\chi = \frac{Qp}{2\pi M_k n_L} \left( \frac{p_L \mu_S n_S}{\mu_L n_L p_S} \right)^\chi = \frac{Qp}{2\pi M_k n_E}, \quad (21)$$

where the equivalent rotation speeds are:

$$n_E = n_L \left( \frac{p_S \mu_L n_L}{p_L \mu_S n_S} \right)^\chi. \quad (22)$$

#### 5.4. The correction of oil temperature by increasing flow through the hydro generator

Hydraulic oil is heated by the flow through the hydro generator, which is caused by the compression and friction of oil at a certain flow rate.

$$\eta_S = \eta_L \left( \frac{Ec_L}{Ec_S} \right)^\beta = \eta_L \left( \frac{V_{gL}^{2/3} n_L c_p T_S}{c_p T_L V_{gS}^{2/3} n_S} \right)^\beta = \quad (23)$$

$$\frac{Qp}{2\pi M_k n_L} \left( \frac{n_L c_p T_S}{c_p T_L n_S} \right)^\beta = \frac{Qp}{2\pi M_k n_E},$$

where the equivalent rotation speeds are:

$$n_E = n_L \left( \frac{n_S c_p T_L}{n_L c_p T_S} \right)^\beta. \quad (24)$$

In this equation,  $T_L$  and  $T_S$  indicate the difference between oil temperature, exiting and entering the hydro generator during the flight measurement, and the measurement under standard conditions. Equation (24) shows the theoretical and practical possibility to assess the change of hydro generator efficiency by measuring the difference between the enthalpy of oil output of and input to the hydro generator. Assuming that the specific heat of the oil is not dependent on temperature, it is possible to assess the efficiency of the hydro generator's temperature difference between the hydro generator's oil inlet and outlet.

## 6. Conclusion

In aviation, the basic flight performance parameters (speed, climb, glide, etc.) are always applied to flights under standard flight conditions such as air temperature at 15 °C, atmospheric pressure of 1013.25 hPa and the acceleration of gravity at 9.81 ms<sup>-2</sup>. Flight performance measurements are usually carried out under conditions different from standard flight conditions. The achieved performance is recalculated for standard conditions. Then it is possible to compare the quality of individual aircraft. The same applies when considering the diagnostics of hydraulic components and systems. The manufacturer and operator specify operational parameters for individual components and systems. Their values are valid for the agreed operational standard conditions.

For example, the efficiency of the hydro generator, booster and actuator is provided for operational elements of the value of 0.8 at a 40 °C temperature of the hydraulic fluid, the speed at 6000 rpm, a pressure of 21 MPa, etc. The operator measures the efficiency of elements under different conditions rather than standard ones. For the

decision on the serviceability of an element or system, it is necessary to convert the acquired diagnostic data to standard conditions.

The present article proposes the possibility of using similarity numbers for the conversion of hydro generator efficiency measured under the operating conditions during a flight into the standard conditions in a laboratory. It would then be possible to assess the serviceability or inconvenient technical condition of the hydro generator. The described procedure can also be applied to other elements of hydraulic and pneumatic aircraft systems.

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