

Advancing methodology to specify cavitation characteristic of screw-type centrifugal pumps

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Abstract. The research proposes a methodology of high-rate cavitation tests significantly decreasing testing period as well as increasing the accuracy of specifying a cavitation characteristic. To specify it, the tests without holding up consumption are conducted; however, at the pump inlet the rate to minimize pressure is increased. To decrease a test discrepancy, the data logging system is introduced. The research determines the high-rate pressure decreases without holding up consumption; it does not impact the accuracy to specify the cavitation characteristic and minimizes pump operation under the cavitation conditions diminishing erosive action. Automation significantly minimizes labour intensity during tests and improves the accuracy.

1. Introduction

Cavitation means a process of flow continuity disruption in a depression zone; the process involves caving, filling in with vapours and gases released from liquid [1-3]. The appearance and development of cavitation are determined by cavitation cores in the working fluid, the cores being undissolved entrapped gases. In the liquid-propellant engine pumps, when input pressure P_1 decreases below certain critical pressure P_{cr} , cavitation appears: a phenomenon that may result in disrupting a pump operation mode is followed by decreasing head, efficiency and consuming liquid by a pump [4]. Therefore, determining anti-cavitation characteristics of a pump becomes a necessity. The characteristics are specified by the value of the critical input head Δh_{cr} [5], practically determined for every pump empirically while cavitation tests are performed [6, 7]. The head value is calculated using critical input pressure based on the formula (1):

$$\Delta h_{cr} = \frac{P_{1cr} + P_a - P_s}{\rho} + 0.5v_{imp}^2, \quad (1)$$

where P_{1cr} – critical input pressure, Pa; P_a – atmospheric pressure, Pa; P_s – liquid saturation vapour pressure, Pa; v_{imp} – liquid velocity at the pump input, m/s.

2. The description of the existing methodology

Due to the existing methodology [8, 9], cavitation tests are conducted in the following way: the input pressure decreases gradually after putting a pump into operation mode by setting up the nominal values of rotation rate and fluid consumption. The main pump parameters are measured at every pressure decrease after setting up the mode: the input and output pump pressure is P_1 , P_2 , Pa; the



rotation rate of the rotor spin ω , rad/s.; pump flow \dot{m} , m³/s. These data specify a dynamic head based on the formula (2) [10], then a head capacity curve is built – formula $H_i = f(P_1)$ where \dot{m} , $\omega = \text{const}$.

$$H_i = \frac{P_{2i} - P_{1i}}{\rho} \quad (2)$$

The next stage is to specify the critical input pressure P_{1cr} , related to the beginning of operation mode stall. The value is determined by two methods:

- using an approximating line intersection point of an unstall and stall part of the cavitation characteristic;
- using a point of head decrease to the value set up within specifications.

Obtaining P_{1cr} values, Δh_{cr} is calculated by the formula (1).

While building the stall curve of the cavitation characteristic, the pump operates in the mode specified by the decrease of the pump head, decrease in fluid and general instability in the processes. Therefore, due to the specifications to the cavitation tests of the centrifugal pumps, there could be a stall curve of the characteristic, if the fluid consumption is lower than nominal one. The experimental data demonstrate the divergence of test results are up to 6,3%, however, due to the research data [11], the divergence of Δh_{cr} can be up to 10%. The divergence values are calculated by the methodology [12].

In addition, the cavitation process is dangerous not only for the pumps operating as an element of the item (their operation cycle is short), but for the pumps tested, as the test duration can exceed the assembly operation time within the in-flight rocket [13].

Therefore, due to the information above there are the following main failures of the methodology:

- the significant labour intensity to eliminate cavitation characteristic, consequently, the prolonged operation of the pump within cavitation conditions and decrease of its reliability in general;
- insufficient accuracy in specifying input critical pressure;
- impact of the subjective factors on the test results;
- long test duration.

3. Description of the proposed methodology

The article proposes a test procedure, according to it, the pump characteristics are proposed to specify under the continuous and rather high-rate change of P_1 , this allows to decrease the cavitation test time and significantly decrease cavitation damage of rotor wheels. Currently the test duration is from 3 to 6 minutes that equals 50-80% of the entire time spent on specifying the main pump characteristics and parameters. In this occasion if the cavitation damage is intensive, the pump operation duration is approximately 60 s., it compares with the pump operation duration as an item element.

To exclude the subjective factors, the research proposes not to support \dot{m} as a constant value during the stall mode; it allows not to use insufficiently reliable fluid control valves. Fluid control valves off increases the sustainability of pump operation in the stall mode.

The process can be automated after setting up the critical pressure at the point of the head decrease during the cavitation stall up to the given value.

The structural circuit of the parameter logging functions in the following way: an independent parameter in the cavitation test is the input pump pressure.

The input pressure decreases after setting up the nominal fluid consumption and angular spin rate of a rotor and the input pressure P_1 is higher than nominal pressure P_{nom} . In this case the information of current value of the input pressure P_{1i} is compared to the given nominal one. The information about the current head value H_i is compared to the given nominal one. When the head value equals (0,75-0,97) H_{nom} , the engine shutdown is initiated. Simultaneously with engine shutdown, the value P_{cr} corresponding to H_{nom} is set up.

4. Analysis of the system operation under the unsteady conditions

Under the continues and rather fast decreasing input pressure, determining the cavitation parameters of a pump, results in the processes becoming non-stationary. Therefore, the impact of the process unsteadiness on the test results was analysed.

While determining the cavitation parameters of a pump in the unsteady mode, there are two cases to identify:

- (I) a pump functions without head stall ($P_2, \dot{m}, \omega \approx const$), only input pressure P_1 changes. The change rate P_1 is characterized by the value dP_1/dt .
- (II) the pump operates in dramatic pressure decrease P_2 , as well as decrease in consumption m and increase in the rate of rotation ω . Under these conditions, the consumption and the rate of rotation are not registered, therefore, the measurement system operation is not analysed in the occasion. The change rate P_2 is determined as dP_2/dt .

The pump operation in field I is characterized by relative parameter stability. Under these conditions, the divergence of the test results in the non-stable and stable mode can be expected only if the input pressure is indicated.

If a pump operates in field II, the divergence of the results will be identified by the transient processes not only in the pump cavities, test transit lines, but in the measure systems P_2 and P_1 .

The transient process time according to [14] is not more than 0,3-0,5 s. Consequently, the pump impact with joined transit lines will be visible in case of high rates when input pressure decreases.

The value of the dynamic divergence will be identified by the constant delay time of pressure measurement T_{P1} and the rate of decrease in input pressure dP_1/dt :

$$\delta P_{cr.dyn} = T_{P1} \cdot \frac{dP_1}{dt} \cdot \frac{1}{P_{1cr}} \quad (3)$$

This implies that if the input pressure rate increases, the value of dynamic divergence increases ($\approx 20-60\%$). To decrease it up to (1-2) %, P_1 needs to decrease with rate of ≈ 100 Pa/s, that is time $t \approx 10$ min. In addition, to decrease the dynamic divergence, the measurement system performance P_1 can be increased, that implies decreasing T_{P1} . If a vibration isolator is excluded, the response time value is specified by the length of the impulse tube.

We should highlight, that rate decrease limit of the input pressure imposes if the pump operates in the stall zone, in the unstill mode the rate can be increased, therefore, the tests can be conducted in the following way.

The stable zone of the pump output parameters P_2, \dot{m}, ω occurs when the input pump pressure is decreased fast; close to the stall area, the decrease rate P_1 decreases up to the value providing a low dynamic discrepancy determining the input pressure.

During the cavitation tests, analysing the system operation to measure input and output pressure results in the following outcomes:

- to estimate a discrepancy of critical input pressure determination requires to take into account the process dynamics and the response speed of the measuring systems;
- to decrease the dynamic discrepancy constituent while measuring P_{1cr} requires to agree the dynamic characteristics of measurement systems of input and output pressures providing the equality of time constants (3). Herewith, the dynamic characteristics should be determined for pressures P_2 and P_1 close to the corresponding parameters belonging to a pump operating in the critical zone.

In operation the experimental research was conducted; the goal was in the following:

- to determine experimentally the impact of input pressure decrease rate on the cavitation test results;
- to determine the impact of the time constants of the input and output pressure measurement systems on the cavitation test results.

To exclude the impact of technological and geometrical factors on the research results, all tests were conducted for the pumps of the same specification. The pump was overhauled to replace the life-expired bearings.

To get information about the tests, the cavitation characteristics were obtained during the continuous decrease of the input pressure with the continuous parameter monitoring.

To realize the possibilities of continuous decrease of the input pressure at various rates, the minor structural modifications were required: two additional drain lines were installed.

The test bench is structurally designed that the surge tank is located 5 meters below the pump; the pressure in the pneumatic cushion determines the input pump pressure, therefore, complete cavitation tests could be performed without a vacuum pump.

Table 1 demonstrates the data processing results for the tests and compares the results of the theoretical calculations of the impact of the input pressure decrease rate and measurement system response rate based on the proposed process model.

Table 1. Data processing results.

		Sensor at the end of the long line behind the damper			Sensor is connected to the pump input with a flexible line of high pressure		
		T_{P1}, s	$P_{cr} 10^5 Pa$	$\delta P_{cr.dyn}, \%$	T_{P1}, s	$P_{cr} 10^5 Pa$	$\delta P_{cr.dyn}, \%$
$\frac{dP_1}{dt} = 790 Pa/s$	Experimental	10	0,605	12,2	0,65	0,55	0
	Calculated	10	0,625	13,6	-	-	-
$\frac{dP_1}{dt} = 790 Pa/s$	Experimental	10	0,725	31,8	0,65	0,555	1,1
	Calculated	10	0,738	34,2	0,65	0,557	1,33
$\frac{dP_1}{dt} = 2080 Pa/s$	Experimental	-	-	-	0,65	0,565	3,3
	Calculated	10	0,748	36,9	0,65	0,559	1,5

As a whole, the experimental results satisfactorily agree with the theoretical calculations and completely prove the adopted process model occurring in the system “pump - hydro test bench - measurement system” while determining cavitation characteristics of the centrifugal pumps at the transient conditions.

Moreover, the dynamic characteristics of the system of the input pressure measurements are not taken into consideration in some cases during the cavitation tests; as a result, anti-cavitation pump parameters determined experimentally are worse than actual parameters.

The theoretical analysis of operation conditions to determine anti-cavitation pump properties under the transient conditions allows to elaborate the requirements for the test bench measurement system to meet, to minimize the dynamic discrepancy of specifying the pump parameters. The conducted experiments proved the correctness of the suppositions and demonstrated the convergence of the calculation and the experiment at the decrease rate of P_I up to 2000 Pa/s and allowed to develop the methodology to conduct the accelerated cavitation pump tests.

To examine experimentally the possibility to determine the input pump critical pressure during the tests, a prototype device of automatic monitoring was constructed. The discrepancy to determine P_{1cr} was 1,63%, the time of three test trials was ~17 min.

5. Conclusion

Based on the data, we come to the conclusion that in full-scale production the high-rate testing method allows to solve the problems:

- to decrease the probability of erosion destruction, decreasing the test time;
- to decrease labour intensity for the test result processing;
- to eliminate the impact of subjective factor on the test results;

- to improve the accuracy of specifying cavitation pump parameters at the expense of automating the critical input pressure determination process.

The developed data logging system by means of some transformations can be used to specify cavitation parameters practically for the vane pumps of all types.

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