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X-Ray Measurements in a Cavitating Centrifugal Pump During Fast Start-ups

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ABSTRACT

The start-up of rocket engine turbopumps is generally performed in a few seconds or even less. It implies that these pumps reach their nominal operating conditions after a few rotations only. During the start-up, the flow evolution within the pump is governed by transient phenomena, based mainly on the flow rate and rotation speed increase. Significant pressure fluctuations, which may result in the development of cavitation, are observed. A centrifugal impeller whose transient behaviour during start-ups has been detailed in a previous publication is considered. Three different cases of fast start-ups have been identified according the final operating point (Duplaa et al. 2010 [1]). The aim of this paper is to analyse the evolution during the start-ups of the local amount of vapor in the blade to blade channels of the pump by fast X-ray imaging. This technique has enabled to calculate the time-evolution of the fluid density within the pump, which appears to be correlated with pressure time-evolutions. For each investigated start-up, X-ray measurements have been performed at three different sections of the impeller height. For each investigated start-up and section tested, measurements have been performed for several initial positions of the impeller, to estimate the measurement uncertainty, and to obtain records from different beam angles, like in tomography.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>A</td>
<td>area</td>
<td>(m²)</td>
</tr>
<tr>
<td>b</td>
<td>blade width</td>
<td>(m)</td>
</tr>
<tr>
<td>Cₜ</td>
<td>tangential component of the velocity</td>
<td>(m/s)</td>
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</table>
\[ C_r = \frac{Q}{2\pi rb} \] radial component of the velocity (m/s)

\[ C \] torque (Nm)

\[ H \] total head (m)

\[ I \] moment of inertia (kg.m^2)

\[ L \] equivalent length (m)

\[ Nb \] Number of blades (-)

\[ P_s \] static pressure in the pump suction pipe (Pa)

\[ P_d \] static pressure in the pump delivery pipe (Pa)

\[ P_{vs} \] vapor pressure (Pa)

\[ Q \] inlet volume flow rate (m^3/s)

\[ r \] impeller radius (m)

\[ S \] limit of the fluid volume in the channels (m^3)

\[ t \] time (s)

\[ u \] tip impeller velocity \( \omega \times r_2 \) (m/s)

\[ v \] inlet pipe velocity (m/s)

\[ V \] volume (m^3)

\[ \beta_t \] relative flow angle (-)

\[ \alpha \] length (m)

\[ \beta \] volume fraction \( V/V_w \) (-)

\[ \Delta P \] pressure elevation in the impeller (Pa)

\[ \phi \] flow rate coefficient \( Q/2\pi rb_2u_2 \) (-)

\[ \Psi \] pressure coefficient \( \Delta P/\rho u_2^2 \) (-)

\[ \omega \] rotation speed (s^{-1})

\[ \omega_s \] specific speed \( \omega \cdot Q^{1/2}/(gH)^{3/4} \) (-)

\[ \tau \] cavitation number \( \left( P_s + \frac{1}{2} \rho v^2 - P_{vs}\right)/\frac{1}{2} \rho u_2^2 \), shear stress (-), (N/m^2)

\[ \rho \] density (kg/m^3)
Subscripts:

1 impeller inlet
2 impeller outlet
cav cavitating conditions
f final (steady part of the fast start up)
m average value
n nominal
sh front/rear shroud
st steady
tr transient
v vapor
w liquid water

1. Introduction

Turbopumps of space launchers are characterized by fast start-ups: actually, the time delay between the inception of shaft rotation and the achievement of the nominal flow conditions is usually close to one second. It means that the rotation speed increases from zero up to several tens of thousands of rotations per minute during a single second. Such fast start-up results in severe transient effects that are mainly governed by the rotation speed acceleration \( \frac{\text{d}\omega}{\text{dt}} \) and the flow rate increase \( \frac{\text{d}Q}{\text{dt}} \) \[2\].

Transient effects in centrifugal pumps have been studied experimentally by several means for about 25 years: fast opening or closure of valves (See Tanaka and Tsukamoto \[3\]), fast start-up and shutdown sequences (Tanaka and Tsukamoto \[4, 5\], Picavet and Barrand \[6\], Bolpaire et al. \[7\], Lefevbre and Barker \[8\]), and/or rotation speed fluctuations (Tsukamoto et al. \[9\]). It has been found in these previous studies that fast transients result in pronounced unsteady effects involving large pressure and flow rate fluctuations, which may be preponderant in front of the quasi-steady flow evolution. So, the understanding and the prediction of these transient behaviors are of primary importance for the design of the feed pumps of rocket engines.

Investigations of fast start-ups of pumps have been also conducted in the LML laboratory for 20 years, using an original test rig that enables to increase the rotation speed of a centrifugal pump from zero up to 3000 rpm in about 0.4s, which corresponds to a few rotations of the impeller. Such rapid fast start-up is responsible for transient effects that influence the pump performance evolution. These transient effects have been investigated in non cavitating
conditions [9,10] and recently in cavitating conditions. Indeed, pressure fluctuations observed during fast start-ups may be responsible for the development of cavitation in the blade to blade channels and in the inlet pipe as well. Such pressure variations have been also reported by Tanaka and Tsukamoto [4] during start-up or shut down sequences of a centrifugal pump: they have found strong fluctuations of both flow rates and pressures at inlet and outlet. While some of these fluctuations, which occur simultaneously at pump suction and delivery, are attributed by the authors to water hammer phenomenon, other oscillations, only detected at pump outlet, are due to unsteady cavitation.

Cavitation may be very prejudicial for the pump performance at stabilized operating conditions. It is also expected that fluctuations of the vaporized areas in the impeller should affect significantly the transient flow behavior. In the recent experiments conducted in the LML laboratory, Duplaa et al. [1] have identified three different types of fast start-ups involving cavitation, triggered mainly by the flow conditions (flow rate and cavitation number) of the stabilized operating point. Several competitive effects due to mass flow and rotation speed increase have been discussed, for the three different cases.

The present work focuses on high frequency X-rays imaging performed in collaboration with the French Atomic Commission (CEA). These experiments are based on the technique developed in simpler flow configurations by Stutz and Legoupil [10] and later by Coutier-Delgosha et al [11] to derive the instantaneous global and local values of the volume fraction of the vapor phase from X-ray attenuation measurements. In these two previous works, cavitation on a fixed geometry (Venturi type section and 2D foil section, respectively) was considered, and flow conditions were steady. Some tests have also been performed by Walid [12] in a configuration of rotating machinery, in stabilized rotation and flow rate conditions. The objective was to identify dissymmetric arrangements of vapor within a rocket engine pump inducer. The authors have taken advantage of the stabilized flow conditions to record X-ray data at numerous angular positions of the inducer, in order to reconstruct the local volume fraction of vapor in the inducer with an algorithm derived from tomography. In the present case, complexity of the process is increased because of the transient character of the flow and because of the presence of the pump casing.

2. General experimental device

The test rig has been initially constructed in 1993 for the study of fast start-up of centrifugal pumps. It has been used since that time for the investigation of fast transients in various situations of non-cavitating flows [6-7-15]. For the purpose of the present study, the set-up has been significantly modified in order to improve its capabilities of measurement and also to enable different types of initial conditions.

Two different configurations are available (Figure 1):

- Configuration #1: suction pipe and delivery pipe of the pump are connected to a single tank, so that the test rig is
closed. In this situation, the flow velocity in the rig before the pump start-up is zero.

- Configuration #2: delivery pipe is connected to a second tank, which means that the inlet and outlet initial pressures can be set independently. So an initial flow can be performed before the pump start up.

The switch between the two configurations is controlled with a valve located on the pump delivery pipe (Figure 1). In the present study, configuration #1 is systematically used. In order to achieve fast starting periods, a special conception of the line of shafts is required: the pump is driven by an asynchronous electric motor through an electromagnetic clutch. The fast start-ups are obtained by engaging the clutch, once the motor is running at its final rotation speed. Slower start-ups can also be obtained by engaging the clutch before the motor is started.

A single stage vaned diffuser single volute type radial flow pump is used for the experiments. The main specifications of the impeller are summarized in Table 1.

Several high frequency measurements (few thousands of hertz) are available on the installation, in order to characterize the flow evolution during the pump fast start-up. A Meiri 0170MS torquemeter is included between the pump and the electromagnetic clutch in order to obtain the instantaneous rotation speed and torque. Four Kistler 701A piezoelectric pressure transducers are located on the inlet and delivery pipes. The transducer which is the nearest from the impeller on the suction pipe is located 50mm upstream from the pump, while the first one on the delivery pipe is located 100 mm downstream from the pump. Their signals are used to obtain as well the high frequency inlet and outlet pressure evolutions as the inlet flow rate, according to the method initially proposed by Ghelici [15]. More details can be found in Duplaa et al [1] regarding this method and its accuracy. Moreover, the motor shaft rotation speed is measured by a photoelectric cell, and an accelerometer located on the pump casing is used to obtain the radial vibrations.

Supplementary low frequency instrumentation (few tens of hertz) is also available in order to control the final flow conditions after the transients or to characterize the stabilized flow conditions. For this purpose, two Krohne Optiflux 4300 flow meters are used at the pump suction and delivery, respectively, and two Rosemount pressure sensors are devoted to the measurements of the inlet static pressure and pump static pressure elevation, respectively. These sensors are not used for unsteady measurements because their acquisition frequency is too small: 25 Hz for the flow meters and less than 1Hz for the Rosemount pressure sensors. Such values do not enable to detect the flow rate and pump performance variations during a fast start-up.

The pressure and torque high frequency measurements are acquired simultaneously by a National Instrument PXI-PCI system. The sampling frequency is 10 kHz, and the acquisition duration is 5s. In the case of fast start-ups, acquisition is triggered by a Transistor-Transistor Logical (TTL) signal emitted at the engagement of the electromagnetic clutch, so that all experiments have the same reference time.
3. Specific X-rays Experimental setup

3.1 Overview

The principle of these non intrusive measurements is based on the variations of X-ray absorption between liquid and vapor. The X-ray attenuation is more important crossing the liquid than the vapor. So, the amount of vapour crossed by the X-ray beam can be derived from the signal intensity received by the detectors.

To perform X-ray measurements, modifications have been applied to the test rig. Actually, the X-ray beam absorption by the casing must be reduced as much as possible in order to maximise the beam intensity as it crosses the flow. For that reason the bronze casing has been replaced by a material with a lower density. It has been developed in polyamide by laser sintering. Laser sintering is used to obtain a polyamide part by successive layering, polymerized by a laser.

The main disadvantage of this process is a waterproof lack for pressure above 1 bar. Consequently, composite fibre-glass materials, impregnated with resin, have been laid down all around the casing, in order to avoid any leakage by porosity, and also at the same time to improve its mechanical properties. For the same reason, the aluminium impeller has been replaced by a Plexiglas impeller whose density is lower (Figure 2). The impeller has been manufactured with a 5 axis machine as an open configuration. The front shroud of the impeller is machined in Plexiglas too. The two parts are glued together with a specific cyanoacrylate “Loctite 401” glue.

3.2 Specific mechanical requirements

The repetition of fast start-ups induces significant efforts on the impeller shaft. As the impeller and the shroud are both manufactured in Plexiglas, a special attention must be paid to their mechanical resistance. Therefore, a preliminary study has been carried out for the dimensioning of i) the fixation of the shroud on the impeller, ii) the fixation of the impeller on hub.

3.2.1 Fixation impeller/ front shroud

During the fast starts-up, the fixation of the shroud on the impeller is submitted to shear and normal stresses applied on the blades surface. The estimation of these stresses is thus of primary importance.

The shear stress applied on one blade is defined as \( \tau = C \cdot r / (N_b \cdot J) \) where \( C = I_{sh} * \partial \omega / \partial t \) is the torsional moment, \( N_b \) is the number of blades, and \( J = \int_0^\infty r^4 (\vartheta) dr d\vartheta \) the blade quadratic moment. \( J \) is estimated equal to \( 7,14 \cdot 10^{-7} \text{ m}^4 \). For a fast start-up with a final rotation speed of 3000 rpm, the torque applied is estimated equal to \( C = I_{sh} * \partial \omega / \partial t = 29 \text{ N.m} \).

So, the shear stress applied on each blade, at the impeller tip radius \( (r=0.1 \text{ m}) \) is \( \tau_{app} = 29 \cdot 0.1 / (5 \cdot 7,14 \cdot 10^{-7}) = 8,1 \cdot 10^5 \)
N/m² = 0.8 N/mm². Note that the stresses due to the fluid are neglected here.

The normal stress applied on the shroud, which is related to the pressure difference between both sides of the shroud, is estimated equal to maximum 2.8 N/m² and 2 N/m² for a fast start-up with a final rotation speed equal to 3000 rpm and 2500 rpm, respectively. The normal stress applied on each blade is thus equal to \( \sigma_{\text{app}} = 2.8 \times 10^5 \frac{S_{\text{sh}}}{5 \times S_{\text{blade}}} = 5.6 \) N/mm² and 4N/mm², respectively.

The fixation between the impeller and the shroud link is obtained by sticking with cyanoacrylate « Loctite 401 ». Stick mechanical resistance estimations have been performed at the laboratory in static conditions. The maximum shear and normal stresses supported by sticking have been respectively evaluated to 3.3 N/mm² and 4 N/mm². So, it appears that the value of the maximum normal stress during fast start-ups may be very close to the limit value. Consequently, two screws are positioned on each blade in order to increase the mechanical strength and a maximum final rotating speed of 3000 rpm has been applied in all experiments.

3.2.2 fixation between the impeller and the hub

The impeller/hub fixation must ensure the impeller drive by the shaft and also withstand the torque due to fast start-ups, which can be expressed as \( C = I_{\text{hub}} \frac{\dot{\omega}}{\dot{t}} \approx 150 \) N.m. An aluminium grooved hub with circular striations is machined in order to fulfill these conditions (Figure 3).

The applied force on each striation at radius R₁ equals \( F = \frac{150}{(X \times R₁)} \) Newton where \( X \) is the number of striations. Each striation is supposed to keep its shape and results in a normal stress on the Plexiglas as \( \sigma_{\text{n,app}} = \frac{150}{(X \times R₁)} / S \), where \( S = \pi R₁ L \) is the surface where the force is applied. Normal stress on the Plexiglas due to one striation is presented on Table 2, according to the number, the diameter and the length of striations.

Regarding the rupture mechanical strength of the Plexiglas, which equals 80 N/mm², the last configuration presented in table 2 has been chosen. This choice enables to guarantee a significant safety margin.

4. Experimental characterization of the pump in cavitating conditions

Experiments have been performed with tap water whose temperature is close to 298K. Before each set of experiments, a flow circulation was applied in the test rig during half an hour, in order to stabilize the amount of cavitation nuclei in the test rig.

Transient behaviours have been investigated by performing fast start-ups of the pump at several flow rates and cavitation numbers. All data are obtained for a final rotation speed equal to 3000 rpm. The whole tests have been classified into three different categories according to the trend of pressure evolutions: “high frequency fluctuations” (case 1), “low frequency oscillations” (case 2), and “water hammer” (case 3). For each case, pressure evolutions of a ref-
ference fast start-up are presented hereafter. The final operating points of these fast star-up-ups are given in Table 3.

In most of the cases, pressure evolutions are similar to the one drawn in Figure 4a (case 1). The pressure at pump suction, after the initial drop, remains completely stable during most of the start-up \((0.25s < t < 0.45s)\). The pressure at delivery is characterized by a significant drop at the end of the start-up, which may be related to the temporary decrease of the pump head because of cavitation on the blades. The delivery pressure signal also exhibits high frequency fluctuations whose maximum amplitude is about 50% of the pump head. This may be due to vapour collapse at the pump outlet.

For high flow rates (at least 1.1 Qn) slightly different pressure signals are obtained (Figure 4b). Low frequency oscillations of the delivery pressure can be observed at the end and after the transient period. This particular behaviour (case 2), may be due to the obstruction generated by pressure side cavitation on the blades: such blockage results in a significant decrease of the pump head. Low amplitude pressure oscillations can also be observed on the inlet pressure signal, which suggests that this phenomenon is related to a surge type instability that affects the whole pump.

A third typical pattern of the pressure signals is obtained for intermediate and high values of the cavitation number and lower flow rates. In such conditions of moderate cavitation, a pressure peak is obtained at the pump suction at the end of the transient (Figure 4c). It can be noticed that a peak of similar magnitude occurs also at the same time at delivery, although it is not so visible because of high frequency pressure fluctuations. Such simultaneous pressure jumps can be associated with a water hammer phenomenon, as it was previously stated by Tanaka et al. [4]. This configuration corresponds to the case 3.

The tests performed in cavitating conditions have been classified into these three different categories of transients, and the resulting map is drawn in Figure 5. It confirms that large scale oscillations systematically occur at high flow rate and in conditions of developed cavitation, while water hammer phenomena are detected at lower flow rate and for a moderate development of cavitation.

For cases 1 to 3, a physical analysis has been proposed by Duplaa et al [1] to explain the evolution of the pump head during the start-up. It has been shown that low final flow rates usually enable to reach at the end of the start-up low cavitating conditions, whereas increasing the final flow rate results in more developed cavitating conditions, leading to progressive head drop of the pump. Conversely, low final flow rates result in the occurrence of water hammer phenomena that may be related to the complete sudden collapse of the vapour in the pump and/or the inlet pipe.

5. X-ray measurements

The X-ray experimental setup consists of a X-ray generator (Philips MG 161) located on one side of the pump, and 1024 detectors (whose dimensions are 0.6 mm*0.3 mm) vertically positioned on the other side (Figure 6). The X-ray
beam emitted by the generator crosses the casing and the impeller and finally reaches the detectors. The distance from generator to detectors is about 550 mm. The acquisition frequency of detectors is set to 2 kHz and the record time duration equals 1.5s. As the other high-frequency sensors, the detectors are triggered by the electromagnetic clutch. The X-ray beam is sufficiently large in x-axis direction to include the entire pump, while the width of the X-ray beam in the y-axis direction equals 0.3 mm (Figure 7). The generator and detectors device is positioned on a motorized plate in order to enable the movement of the whole setup in the axial direction (y-axis). In order to reconstruct the axial density evolution along the 7 mm width of the impeller, the X-ray device is positioned at three stations in the axial (y axis) direction (Figure 7): the middle of the blade to blade channels (section 1), 2 mm on the left (section 0 disclose to the shroud) and 2 mm on the right (section 2 close to the hub). For safety reasons, the X-ray device and the pump are confined into a lead structure. This last one protects the operators from the X-ray radiations and guarantees for the maximal power of the source(120 kV, 25 mA) an irradiation dose lower than 2.5µSv/h at a distance of 5 meters from the emission location. The commands of the test rig have thus been moved 10 meters away.

X-ray measurements have been performed for different fast start-ups corresponding to the three different cases (high frequency fluctuations, low frequency oscillations and water hammer). The aim is to determinate the density evolution within the impeller during fast start-up in cavitating conditions. As it has been explained previously, the intensity of the signal received by the detectors depends on the density crossed by the X-rays in the pump. In order to obtain the volume fraction of the vapor phase $\beta_i$ crossed by the beam section that reach each detector, the following relation is used [10]:

$$\beta_i = 1 - \frac{\ln \left( \frac{I_0}{I_i} \right)}{\ln \left( \frac{I_0}{I_1} \right)}$$

Equation 1

Where:

- $I_0$ is the signal intensity when the pump is full of air.
- $I_1$ is the signal intensity when the pump is full of water.
- $I_i$ is the signal intensity during measurements with the pump operating in cavitating conditions.

The intensity of the measurement is expressed by the Beer-Lambert law [12] :

$$I_i = I_0 e^{-\alpha \mu}$$

Equation 2

Where $\mu_0$ is the linear attenuation coefficient and $\alpha$ is the material thickness crossed by the beam (Figure 8).

For each detector, the volume fraction crossed by the beam is defined as :

$$\beta_i = \frac{V_i}{V_T} = A_m * \frac{e}{\alpha}$$

Equation 3
with \( A_m \) is the measurement surface and \( \epsilon/\alpha \) the relative vapour length crossed by each X-ray, i.e. the vapor thickness divided by the total thickness of material (Figure 8).

A calibration of the setup is first performed. It consists in measurements with i) air only inside the pump, ii) liquid water only inside the pump. Note that air is preferred to vapor for calibration by simplicity. The error related to this simplification is negligible:

\[
\Delta = \left| \frac{\rho_{\text{air}} - \rho_{\text{v}}}{\rho_{\text{w}}} \right| \approx 10^{-3}
\]

Measurements have been performed at three stations of the blade to blade channels, in the axial direction. Figure 9 shows relative vapour length obtained in section 1 for each case of fast start-up. The relative vapour length is plotted for the 1024 sensors during the duration of the start-up (1.5s). These data enable estimating the life time and the radial position of the cavitation structures in the impeller during the start-up. Indeed, the vertical axis qualitatively indicates the radial position of the vapour, while the horizontal axis gives its temporal evolution. The grey level stands for the amount of vapour: from black (pure liquid) to white (pure vapour). The very dark band located at the middle of the pictures corresponds to the aluminium hub, which absorbs almost completely the X-rays.

From these relative lengths of vapour, the evolution of the mean density within the impeller during the start-up can be reconstructed. At each time, the mean fluid density \( \rho_T \) can be derived from \( \beta_i \) and \( V_i \), volume of the impeller crossed by the X-rays that reach detector i:

\[
\rho_T = \frac{\sum_i [\beta_i (V_i (\rho_{\text{w}} - \rho_{\text{v}}) + \rho_{\text{w}} V_i)]}{V_T}
\]

Equation 4

where \( \beta_i \) is the volume fraction of vapor seen by detector i (i=1…1024).

So, the density evolution obtained at station 1 (middle of the blade to blade channel) are displayed in Figure 9 for the three different types of start-ups. It can be observed that the density profiles are correlated with the pressure evolutions (see Figure 4).

Figure 10 presents the density evolutions obtained at stations 1 to 3 for the three cases of fast start-up. An interpolation in the axial direction of the density distribution within the impeller is shown in Figure 11. The eye of the impeller is located at the front of the picture. On the same figure are plotted the iso-density curves.

Different conclusions can be drawn from these two representations:

i) The cavitation inception takes place first at the impeller inlet. It is principally verified for the case 3, the “water hammer” case, where the density in section 0 decreases earlier than the one in the two others sections.
ii) The cavitation is more developed in section 0. Indeed, the minimum value of density is measured in this section for all cases of fast start-up.

iii) Globally, it can be noticed that cavitation starts at the impeller inlet and develops towards the hub. Conversely, cavitation collapse occurs in the opposite direction.

iv) Whereas the final density value (it means the stabilized value reached at the end of the start-up) is the same in the three sections in cases 1 and 3 (close to the water density), it clearly appears in case 2 that the cavitation is still present between the impeller inlet and mid-chord of the blades. The largest amount of vapour is observed at the the impeller inlet.

In order to estimate the uncertainty related to the repeatability of the cavitation development during fast start up, X-ray measurements have been performed 12 times for each final operating point and section tested. The standard deviation $\sigma(t)$ at time $t$, based on these 12 tests, is defined as:

$$
\sigma(t) = \sqrt{\frac{1}{12} \sum_{j=1}^{12} (\rho_{Tj}(t) - \rho_{Tm}(t))^2}
$$

Equation 5

Where $\rho_{Tm}(t)$ is the average value of the mean density at time $t$. The relative deviation is defined as the standard deviation $\sigma(t)$ divided by $\rho_{Tm}(t)$:

$$
\sigma_r(t) = \frac{\sigma(t)}{\rho_{Tm}(t)}
$$

Equation 6

The evolution of $\sigma_r(t)$ is plotted in Figure 12. It can be observed that the relative uncertainty due to the repeatability on the density is lower than 0.5% during stabilized period and lower than 3% during fast start-up.

Summary

Three different cases of fast start-ups in cavitating conditions have been presented. The aim of this paper is to show the high frequency X-ray measurement feasibility in a volute casing pump during fast start-ups. An important adaptation of the test rig has been performed with a Plexiglas impeller and a pump casing manufactured in polyamide by means of laser sintering process. X-ray measurements enable determining the time evolution of the global fluid density in the pump and showing different cavitation behaviors depending on the considered case of fast start-up. These different vapor evolutions are correlated with the pressure evolutions. The axial distribution of vapor has also been obtained. The local fluid density has not been obtained, yet. In the future, these informations regarding the density evolution within the impeller will be included in a 1D model devoted to the prediction of pump performance during
fast start-ups operated in cavitating conditions.

Acknowledgements

The present work was performed in the scope of a research grant from the CNES (French Space Agency) and SNECMA Moteurs. The authors wish to express their gratitude to SNECMA Moteurs and the CNES for their continuous support.

REFERENCES


**Figures and tables:**

Figure 1: Photography and scheme of the test rig: a) Configuration 2, b) Configuration 1

Figure 2: Photography of the Plexiglas impeller

Figure 3: Scheme of the hub conception

Figure 4: Pressure evolutions :a) case 1 - b) case 2- c) case3

Figure 5: Classification of the start-ups

Figure 6: X-rays device

Figure 7: Location of test sections and definition of the frame x-y axis

Figure 8: Relative vapour length in the pump

Figure 9: Relative vapour length and density profile in the pump during fast start-ups (Section1) :

   a) case 1 - b) case 2- c) case3

Figure 10: Density profiles for the three sections :

   a) case 1 - b) case 2- c) case3

Figure 11: Axial density distribution and iso-density curves during fast start-up :

   a) case 1 - b) case 2- c) case3

Figure 12: Relative Uncertainty profiles due to the repeatability for the three sections :

   a) case 1 - b) case 2- c) case3
Table 1: Impeller specifications

Table 2: Normal stress applied by each striation

Table 3: Final operating point for the three reference cases of fast start-ups
Figure 1
Figure 2

Aluminium grooved hub

Striation
Figure 3
Figure 4
Figure 5
Figure 6
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Figure 9
Figure 10
Figure 11
Figure 12
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<tr>
<th>Geometric specifications</th>
<th>Hydraulic parameters</th>
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<tr>
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<td>$\omega_n$ 2900 rpm</td>
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<tr>
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<td>$\Delta P_n$ 4.9$\times$10$^5$ Pa</td>
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Table 1:
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<thead>
<tr>
<th>Length L (m)</th>
<th>Radius r (m)</th>
<th>Number X</th>
<th>Normal stress $\tau_{n,\text{app}}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>0.002</td>
<td>3</td>
<td>184</td>
</tr>
<tr>
<td>0.012</td>
<td>0.002</td>
<td>3</td>
<td>123</td>
</tr>
<tr>
<td>0.012</td>
<td>0.004</td>
<td>3</td>
<td>61</td>
</tr>
<tr>
<td>0.012</td>
<td>0.004</td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>0.016</td>
<td>0.004</td>
<td>8</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 2
Table 3

<table>
<thead>
<tr>
<th>$\omega_0$ (tr/min)</th>
<th>$\tau_f$</th>
<th>$Q/Q_a$</th>
<th>Pressure evolution</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>0.091</td>
<td>0.9</td>
<td>Fig. 5a</td>
<td>case 1</td>
</tr>
<tr>
<td>3000</td>
<td>0.091</td>
<td>1.2</td>
<td>Fig. 5b</td>
<td>case 2</td>
</tr>
<tr>
<td>3000</td>
<td>0.111</td>
<td>0.7</td>
<td>Fig. 5c</td>
<td>case 3</td>
</tr>
</tbody>
</table>