Comparison of rotodynamic fluid forces in axial inducers and centrifugal turbopump impellers

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Abstract. The paper illustrates and compares the results of the experimental campaigns carried out in the Cavitating Pump Rotodynamic Test Facility (CPRTF) at Alta, Italy, under ESA funding for the characterization of the lateral rotodynamic fluid forces acting on high-head axial inducers and centrifugal turbopump impellers for space propulsion applications. The configurations presented here refer to a three-bladed tapered-hub, variable-pitch, inducer (DAPROT3) and a single-stage centrifugal pump (VAMPIRE) with vaneless diffuser and single spiral volute. Both the centrifugal pump and the inducer have been designed by means of reduced order models specifically developed by the author and his collaborators for the geometric definition and performance prediction of this kind of hydraulic turbomachinery. Continuous spectra of the rotodynamic forces acting on the impellers as functions of the whirl frequency have been obtained by means of the novel technique recently developed and demonstrated at Alta. The influence of the rotor whirl motion, flow rate, cavitating conditions, and liquid temperature (thermal cavitation effects) on the rotodynamic fluid forces is illustrated and the observed differences in their behavior in axial inducers and centrifugal turbopumps are discussed and interpreted in the light of the outcome of recent cavitation visualization experiments carried out by the Chemical Propulsion Team at Alta.

Introduction

Liquid-fed rocket engines still play a crucial role in primary space propulsion systems. In these applications propellant feed turbopumps are one of the most important components, whose design and operation are critical for the success of the mission. In order to minimize the total weight of the propulsion system, propellant feed turbopumps must be designed for high head and suction performance. This objective is invariably achieved by reducing the dimensions of the machine, increasing its rotational speed and by operating it under “controlled cavitation” conditions. The drawbacks of this choice consists in the performance degradation effects of cavitation, and more so in the possible development of fluid dynamic and rotodynamic instabilities, which can easily responsible for catastrophic failures of the machine.

Current rocket propellant feed turbopumps often employ an inducer in order to improve the suction performance and avoid unacceptable cavitation levels in the main centrifugal stage(s), thus allowing for the reduction of the propellant tank pressure and weight. This is typically achieved by
proper hydrodynamic design of the inducer, which is characterized by fewer blades than centrifugal pump impellers, large stagger angles with respect to the axial direction, and significantly high blade solidities. Long blades and small incidence angles allow for the reduction of the blade loading, and consequently for significant improvements of the suction performance. Radial and mixed-flow pumps, conversely, exploit the work developed by centrifugal forces on the fluid for generating most of the required pressure rise. Hence, their blades must be sturdier (i.e. thicker) than those of inducers in order to sustain the higher loads exerted by the liquid. With respect to centrifugal compressors, radial turbopump impellers usually have a smaller number of blades (typically six or eight) in order to avoid excessive flow blockage.

According to Brennen ([1]), flow instabilities in turbopumps can be divided in system, global and local oscillations (respectively involving the entire pumping line, the whole pump and a more limited region of the pump flow), as well as instabilities caused by radial or rotordynamic forces. Rotordynamic forces, together with flow instabilities whether or not generated by cavitation, are one of the most recognized and dangerous sources of vibrations in turbomachines. These forces can affect all of the components of the machine, including its bearings, seals and, obviously, the impeller itself ([2]). Even if the rotordynamic fluid forces acting on noncavitating centrifugal pump impellers and inducers have been extensively investigated (see for example [3], [4], [5], [6], [7], [8]), the experimental information on the influence of cavitation on these forces is still very limited. Available data mainly come from the work carried out in the 1980’s at the California Institute of Technology, Pasadena, California, ([9] [10], [11], [11] and [12]). More recently, Yoshida and his coworkers have investigated the relationship between the size of the bubble in the uneven rotating cavitation and the associated vibration ([13] and [14]). On the other hand, not so many numerical approaches have been proposed so far (see, for example, [15], [16] and [17]), probably due to the complexity of the flowfield. In general, the lack of data is particularly evident for unshrouded inducers under cavitating condition, which is a common operating condition in space rockets applications. Finally, in the last five years more extensive experimental investigations of rotordynamic impeller forces on unshrouded inducers and centrifugal turbopump impellers under cavitating conditions have been presented by the Chemical Propulsion Team at Alta, Pisa, Italy (see, for instance, [18], [19] and [20]). In their experiments, just like as the pioneering ones carried out at Caltech in the 1980’s, the impeller is subject to a whirl motion of given constant eccentricity and angular velocity. A special procedure ([21]) has been used to measure the continuous spectrum (behavior) of rotordynamic forces as functions of the whirl-to-rotational speed ratio.

Experimental Apparatus

The experimental activity reported in the present paper has been carried out in Alta’s CPRTF, which is illustrated in Figure 1 and specifically designed for characterizing the performance of cavitating and/or noncavitating turbopumps in a wide variety of alternative configurations (axial, radial, or mixed flow, with or without an inducer ([22], [23]). The facility uses water as working fluid at temperatures up to 90 °C and is intended as a flexible apparatus readily adaptable to conduct experimental investigations on virtually any kind of fluid dynamic phenomena relevant to the design of high performance turbopumps under fluid dynamic and cavitation similarity conditions. The pump housing and the inlet section can easily be configured to host machines and inducers with actual geometries of different sizes. Unsteady pressure sensors can be flush-mounted on the casing walls of the pump to detect, identify, and monitor the occurrence of flow instabilities developing in the machine.
For this campaign, the facility has been instrumented in order to measure:

- the inducer inlet pressure (Druck, model PMP 1400, 0–1.5 bar operating range, and 0.25% precision class);
- the inducer static pressure rise (Druck, model PMP 4170, 0–1 bar operating range, and 0.08% precision class);
- the volumetric flow rate on the suction and on the discharge lines (model 8732E by Fisher-Rosemount, range 0–100 l/s, 0.5% precision);
- the water temperature inside the main tank;
- the absolute angular position of the driving shaft;
- the absolute angular position of the eccentric shaft that generates the whirl motion.

A rotating dynamometer in the test section allows for the measurement of the forces and moments acting on the impeller. The eccentricity generation is realized by means of a dual-shaft mechanism. The shafts are assembled one inside the other by means of a double eccentric mount and their eccentricity can be finely adjusted from 0 to 2 mm ±0.05 mm by changing the relative angular position of the double eccentric mount before each test. A brushless motor driving the outer shaft generates the whirl motion, while the impeller rotation is imparted by connecting the inner shaft to the main motor by means of an omokinetic coupling. The rotating dynamometer is realized in a solid piece of phase hardening steel AISI 630 H1025 and consists of two flanges connected by four pillars, acting as flexing elements.

The deformation of the dynamometer is measured by 40 semiconductor strain gages suitably installed on the sensing pillars and arranged in ten full Wheatstone bridges, which provide redundant measurements of the forces and moments acting on the impeller ([9]). Each bridge is temperature self-compensated, with separate bipolar excitation and read-out for better reduction of electrical cross-talking. The sizing of the sensing pillars is the result of a trade-off between sensitivity and structural resistance, operational stability, and position control (stiffness). The current design of the dynamometer is optimized for a suspended mass of 4 kg with 70 mm gyration radius, an added mass of about 2 kg (based on the expected magnitude of the rotordynamic forces), a rotational speed of 3000 rpm without eccentricity, and maximum rotational and whirl speeds up to 2000 rpm with 2mm shaft eccentricity. Under these conditions the first torsional mode of the dynamometer has a frequency of about 169 Hz, whereas the first flexural frequency is about 192 Hz, well above the excitation frequency generated by the impeller rotation. The maximum absolute error of the dynamometric force measurements is 1.4 N on the lateral forces and 0.1 N m on the axial torque.
Present experiments have been conducted on the DAPROT3 axial flow inducer and on the VAMPIRE radial turbopump in order to highlight how impeller rotodynamic fluid forces depend on the machine configuration. The VAMPIRE pump is a six-bladed unshrouded centrifugal pump manufactured in 7075-T6 aluminum alloy, with vaneless diffuser and single-spiral volute. The DAPROT3 inducer is a three-bladed, tapered-hub, and variable-pitch inducer, also manufactured in 7075-T6 aluminum alloy. Both the VAMPIRE pump ([24] and [25]) and the DAPROT3 inducer ([26], [27] and [28]) have been designed by means of the reduced order models developed at Alta for preliminary geometric definition and performance prediction of inducers and centrifugal pumps. Their main characteristics are summarized in Table 1 and pictures of their impellers are shown in Figure 2. A moderate value of the blade loading, with a diffusion factor $D = 0.47$ and solidity $\sigma_T = 1.68$, has been chosen for the DAPROT3 inducer in order to reduce the leading-edge cavity and improve the suction performance. The value of the tip incidence-to-blade angle ratio $\alpha/\beta_b < 0.5$ has been selected with the aim of controlling the danger of surge instabilities at design flow under cavitating conditions.

### Table 1. Main characteristics of the DAPROT3 inducer and the VAMPIRE pump.

|                     | DAPROT3 | VAMPIRE |
|---------------------|---------|---------|
| Design Flow Coefficient [\text{--}] | $\Phi_D$ | 0.065 $^a$ | 0.092 $^b$ |
| Number of Blades [\text{--}] | $N$ | 3 | 6 |
| Inlet Tip Radius [\text{mm}] | $r_{T1}$ | 81.0 | 57.2 |
| Outlet Tip Radius [\text{mm}] | $r_{T2}$ | 81.0 | 105.0 |
| Axial Length [\text{mm}] | $c_a$ | 90.0 | 46.4 |
| Mean Blade Height [\text{mm}] | $h_b$ | 25.95 | 17.95 |
| Tip Solidity [\text{--}] | $\sigma_T$ | 1.68 | 2.26 |
| Material [\text{--}] | | Anodized AL 7075 T6 | Anodized AL 7075 T6 |

$^a \Phi = Q/\pi \Omega r_T^3$

$^b \Phi = Q/\Omega r_T^3$

**Figure 2.** Renderings of the DAPROT3 inducer (left) and the centrifugal impeller of the VAMPIRE pump (right).

Figure 3 shows the test chamber configurations for the experiments on the DAPROT3 inducer and the VAMPIRE pump. The rotating dynamometer is placed between the driving shaft and the impellers. The DAPROT3 inducer has been recessed with respect to the optical access of the test section inlet in order to reduce cantilever effects on the impeller shaft. A nominal radial clearance of 2 mm has been
selected for accommodating the imposed whirl eccentricities. It corresponds to nondimensional clearances \( c_n = 7.7\% \) for the DAPROT3 inducer and 11.2\% for the VAMPIRE pump when referred to the respective mean blade heights. Though relatively large, previous experience ([29]) indicated that this choice of the radial clearance represents an acceptable compromise for generating measurable rotordynamic forces without excessively increasing tip leakage effects.

**Figure 3.** Test configurations of DAPROT3 inducer (left) and the VAMPIRE pump (right).

**Experimental Procedure**

A circular whirl orbit with constant eccentricity \( \varepsilon \) has been imposed to the test impellers in order to determine the corresponding fluid-induced rotodynamic forces. The resulting instantaneous fluid force \( F \) acting on the impellers can be expressed as the sum of a steady component \( F_0 \), not depending on the rotor eccentricity, and an unsteady contribution generated by the whirl motion. The latter is the rotordynamic force \( F_R \) and is usually a linear function of the eccentricity, which represents small perturbation of the impeller flow.

A schematic of the whirl trajectory in a plane orthogonal to the axis of the machine, together with the decomposition of the total force acting on the impeller into the steady and the rotodynamic forces, are depicted in Figure 4. In the same figure the projections of the rotordynamic force \( F_R \) along the normal (\( F_N \)) and tangential (\( F_T \)) directions to the whirl orbit are also shown. The normal force is assumed positive if directed outward. The tangential force is assumed positive if it has the same direction of the impeller rotational speed \( \Omega \). Therefore, with reference to Figure 5 the normal force is destabilizing when positive (tending to increase the eccentricity) and stabilizing when negative. Similarly, the tangential force is destabilizing when has the same sign as the whirl speed (promoting the whirling motion) and stabilizing in the opposite case.

It is worth noting once more that the rotordynamic forces presented in this paper only refer to the fluid forces induced by the eccentricity of the rotors. The effects of gravity, buoyancy, and tare forces (the submerged weight and the centrifugal force generated by the whirl motion on the rotor mass), as well as the steady fluid force on the impeller (like those induced by azimuthal asymmetries of the flow), have been subtracted from the total force read by the dynamometer. This is typically obtained by performing suitable experiments in air and then under fully-wetted flow conditions, as already shown in [1] and more recently in [30]. The rotordynamic forces have been normalized as follows ([1], [11]):
\[ F^*_r = \frac{F_r}{\rho c_a \varepsilon \Omega^2 r_T^2} \]

where \( \rho \) is the liquid density, \( c_a \) is the axial length of the inducer blades, \( \varepsilon \) is the radius of the whirl orbit (eccentricity), \( \Omega \) is the inducer rotational speed, and \( r_T \) is the impeller tip radius.

**Figure 4.** Schematic representation of the rotordynamic forces in the laboratory and rotating reference frames.

**Figure 5.** Schematic diagram of the stability/instability regions of the normal and tangential components of the rotordynamic force for positive (left) and negative (right) whirl frequency ratios.

Two different approaches have been used to evaluate the spectral dependence of rotordynamic fluid forces on the whirl speed. The first “traditional” approach consists in the evaluation of the rotordynamic forces from separate experiments carried out at discrete values of the whirl ratio \( \omega/\Omega \) ([20], [31]). The second procedure, illustrated in detail in [21] and [32], yields a continuous measurement of the rotordynamic force spectrum as a function of the whirl ratio from the data obtained in a single experiment by progressively shifting the observation time window throughout the imposed variation of the whirl speed, thus greatly simplifying and speeding up the acquisition and reduction of the experimental data.
The experimental campaign carried out on the DAPROT3 inducer has been aimed at understanding how the rotodynamic forces are influenced by:

- the flow rate (flow coefficient $\Phi$);
- the cavitation regime (cavitation number $\sigma$);
- the fluid temperature (inertial/thermal cavitation).

All tests have been carried out with a whirl eccentricity $\varepsilon = 1.13 \pm 0.05$ mm and an impeller rotational speed $\Omega = 1750$ rpm, whose choice represents a suitable compromise between the generation of measurable rotodynamic forces and the structural integrity of the rotating dynamometer under the resulting centrifugal forces on the test impellers. Only subsynchronous whirl ratios have been investigated, with both positive and negative values up to $\pm 0.7$ ($\omega/\Omega = \pm 0.1, \pm 0.3, \pm 0.5, \pm 0.7$ for the discrete approach). The combinations of flow rate, cavitating conditions, and water temperature have been considered, as summarized in the test matrix of Table 2.

### Table 2. Test matrix for the DAPROT3 and the VAMPIRE pump.

| Flow Coefficient $\Phi/\Phi_D$ | Flow Rate $\Omega/\Omega$ | Temperature $T[\degree C]$ | DAPROT3 | VAMPIRE |
|-------------------------------|--------------------------|-----------------------------|---------|---------|
| 80%                           | $-0.7 \leq \omega/\Omega \leq 0.7$ | 19                          | 0.052   | 1.015*  |
| 100%                          | $-0.7 \leq \omega/\Omega \leq 0.7$ | 70                          | 0.065   | 0.143b  |
| 120%                          | $-0.7 \leq \omega/\Omega \leq 0.7$ | 70                          | 0.078   | 0.088c  |

* No cavitation

b Limited cavitation

b Developed cavitation

### Results and Discussion

A series of tests has been conducted on the DAPROT3 inducer in order to characterize its noncavitating pumping performance and hydraulic efficiency at 20 °C in the same nominal configuration used in rotodynamic tests but with zero eccentricity. Figure 6 shows the noncavitating experimental curves in terms of the head coefficient $\psi = \Delta p/\rho \Omega^2 r_i^2$ and hydraulic efficiency $\eta = \Delta p/\rho \Omega^2 r_i^2$ as functions of the flow coefficient $\Phi = Q/\pi \Omega^2 r_i^2$. The volumetric flow rate $Q$ has been measured by means of an electromagnetic flowmeter mounted on the discharge line, the static pressure increase ($\Delta p$) by means of a differential pressure transducer. The low pressure tap has been located on the suction line about six inducer diameters upstream of the blade leading edges, in order to reduce the effect of inlet flow prerotation. The high pressure tap has been mounted on the discharge line at about 2.5 duct diameters downstream of the test chamber connection, because of the uncertainties in compensating for the influence of exit flow swirl if mounted on the inducer discharge casing. Hence, head measurements include the (negligible) viscous losses from the upstream pressure tap to the inducer inlet, as well as the diffusion losses from the inducer outlet into the test section and the entrance losses in the discharge line. In order to evaluate the total pressure rise, two main assumptions have been made according to the model explained in detail in a previous paper [31]:

- the static pressure in the discharge line is equal to the bulk static pressure at the exit of the inducer;
- the azimuthal velocity at the inducer exit can be evaluated by means of the Carter’s rule.

The torque $\tau$ has been directly measured by means of the rotating dynamometer, thereby by-passing the uncertainties associated with seal friction on the inducer shaft. The maximum measured efficiency
(about 82%) corresponds to a flow rate close to the design flow coefficient $\Phi_D = 0.065$ that is in good agreement with the typical optimization made for this kind of machine.

![Graph](image)

**Figure 6.** Noncavitating pumping performance and hydraulic efficiency curves of the DAPROT3 inducer with zero imposed eccentricity and whirl motion.

![Graph](image)

**Figure 7.** Noncavitating pumping performance and hydraulic efficiency of the VAMPIRE pump with zero imposed eccentricity and whirl motion. The arrows indicate the operating points corresponding to the three values of the flow coefficient tested in the experiments.

The corresponding results for the VAMPIRE pump are presented in Figure 7, which illustrates the noncavitating pumping performance and the hydraulic efficiency characteristics of the machine. The arrows indicate the three flow coefficients used in the experiments.

**Rotordynamic Forces on the DAPROT3 Inducer**

In the following Figures from 8 to 12 representative results for the rotordynamic forces measured on the DAPROT3 inducer under the conditions indicated in Table 2 are presented in terms of their nondimensional normal and tangential components as functions of the whirl speed ratio $\omega/\Omega$. Lines and markers indicate the results of continuous and discrete tests, respectively. The latter approach is likely to be more accurate because the whirl speed is constant over the observation time, while it slowly drifts in continuous tests. On the other hand, the spectral resolution of continuous tests is of special interest as it provides more accurate information on the dependence of rotordynamic forces on the whirl ratio in the regions where they undergo rapid changes and allows for clear identification of the maxima and minima of the curves. As shown in the figures, the results of the two approaches agree
almost perfectly, thus confirming the validity of the technique used for the continuous measurement of the rotordynamic force spectra.

Figure 8. Effect of the flow rate on the rotordynamic force spectra of the DAPROT3 inducer in water tests under fully-wetted flow conditions. Nondimensional normal and tangential components $F_N^*$ and $F_T^*$ as functions of the whirl ratio at 80%, 100% and 120% of the design flow ($\Phi = 0.052$, 0.065, 0.078), $T = 20 °C$ and $\sigma = 0.98$.

Figure 8 illustrates the effect of the flow coefficient under noncavitating flow conditions. The results are in a very good agreement with the effects detected in similar inducers tested in previous experiments [19], [32]. The first effect manifest at negative whirl ratios consists in the increase of the rotordynamic force intensity at lower flow coefficients, consistently with the parallel increase of the blade loading. A second effect evident at positive subsynchronous whirl ratios is the presence of maxima and minima in the force spectra, with the tendency to shift towards higher values of the whirl ratio as the flow coefficient decreases.

Previous flow visualizations experiments first conducted at Alta in 2010 ([19], [33]) clearly demonstrated that such peaks in the rotordynamic force spectra for moderately positive whirl ratio are generated by the matching of the impeller whirl speed with the inlet flow prerotation. Under these conditions, the disturbance introduced by the rotor whirl effectively modulates the inlet flow, as especially manifest in cavitation experiments where the cavities tend to concentrate in a single azimuthal lobe co-rotating with the average flow in the inducer eye (see Figure 9). The resulting flow distortion induces more intense lateral forces at the frequency corresponding to the common angular speed of the inlet flow prerotation and the whirl motion. In general, the average rotation of the flow in the inducer eye increases with the load, the azimuthal stagger angle, the leading edge backsweep and the tip leakage of the impeller blades. In particular, for fixed geometry of the inducer, the average prerotation of the inlet flow increases at high blade loads and therefore at lower flow coefficients, consistently with the behavior of the rotordynamic force spectra observed in present and previous experiments both at Alta and Caltech.

For negative whirl speeds, when the interaction with the inlet flow prerotation is weak, the spectral behavior of both components of the rotordynamic forces on the DAPROT3 inducer under fully-wetted flow conditions is rather smooth and regular (Figure 8). In particular, in this range of whirl speeds the normal component is nearly parabolic with upper concavity and the tangential one nearly linear with negative slope, consistently with typical findings in centrifugal impellers ([11] and later Figures 14 – 17). On the other hand, for positive subsynchronous whirl ratios the rotordynamic force spectra are more complex and irregular as a consequence of the interaction with the prerotating inlet flow.
Figure 9. Single-lobed azimuthal cavitation in the eye of the DAPAMITO3 inducer operating in water at whirl speed synchronous with inlet flow prerotation. From left to right and top to bottom the frames correspond to a complete whirl orbit. The flow conditions are: $\Phi = 0.044$, $\sigma = 0.094$, $T = 19.8 ^\circ C$, $\omega/\Omega = 0.3$ (from [19]).

At all flow rates, the normal component of the rotodynamic force becomes destabilizing for whirl ratios $\omega/\Omega < 0.3$, is stable for moderate intermediate whirl ratios, and tends to become again destabilizing at higher whirl ratios. The tangential force is significantly less intense than the normal one and is stabilizing at all flow rates for negative whirl, while it exhibits multiple zero crossings in the positive portion of the frequency spectrum. The lowest flow coefficient (higher blade load) is associated to a more stabilizing behavior of both the normal and tangential components of the rotodynamic force. The influence of the flow coefficient on the rotodynamic forces observed in fully-wetted flow conditions has also been confirmed under both limited and more intense cavitation (at $\sigma \approx 0.14$ and 0.09, respectively), whose results are not shown here for conciseness.

Figure 10. Effect of the cavitation number on the rotodynamic force spectra of the DAPROT3 inducer in cold water tests at 80% of the design flow. Nondimensional normal and tangential components $F_N^* \text{ and } F_T^*$ as functions of the whirl ratio at $\Phi = 0.052$, $T = 20 ^\circ C$ (inertial cavitation) and $\sigma = 0.98$, 0.14, 0.09, respectively corresponding to fully-wetted flow, limited cavitation and developed cavitation conditions.
Figure 11. Effect of the cavitation number on the rotordynamic force spectra of the DAPROT3 inducer in cold water tests at 100% of the design flow. Nondimensional normal and tangential components $F^*_N$ and $F^*_T$ as functions of the whirl ratio at $\Phi = 0.065$, $T = 20 \, ^\circ C$ (inertial cavitation) and $\sigma = 0.98, 0.14, 0.09$, respectively corresponding to fully-wetted flow, limited cavitation and developed cavitation conditions.

Figure 12. Effect of the cavitation number on the rotordynamic force spectra of the DAPROT3 inducer in cold water tests at 120% of the design flow. Nondimensional normal and tangential components $F^*_N$ and $F^*_T$ as functions of the whirl ratio at $\Phi = 0.078$, $T = 20 \, ^\circ C$ (inertial cavitation) and $\sigma = 0.98, 0.14, 0.09$, respectively corresponding to fully-wetted flow, limited cavitation and developed cavitation conditions.

Figures 10, 11 and 12 illustrate the effects of varying the conditions of cavitation in cold water tests at $T = 20 \, ^\circ C$ and 80%, 100% and 120% of the design flow coefficient ($\Phi = 0.052, 0.065$ and 0.078). The impact of cavitation on the rotodynamic force is relatively limited, especially at the lowest flow coefficients, and tends to increase only slightly at higher flow rates. In general, the occurrence of cavitation reduces the intensity of the rotodynamic force and delays the destabilizing behavior of the normal force component in the range of whirl ratios from $\omega/\Omega = -0.3$ to $\omega/\Omega = -0.5$ (Fig. 12). The influence of cavitation is most likely the consequence of the general modifications it induces on the impeller blade loading, both steady and unsteady. In fact when cavitation is strong enough to appreciably degrade the pumping performance of the machine, the blade loading is also reduced, and so is the rotodynamic force acting on the impeller.
Figure 13. Effect of the water temperature on the rotordynamic force spectra of the DAPROT3 inducer at 100% of the design flow. Nondimensional normal and tangential components $F_N^*$ and $F_T^*$ as functions of the whirl ratio at $\Phi = 0.065$, $\sigma = 0.14$, corresponding to limited cavitation conditions, and $T = 20 \, ^\circ C$ (inertial cavitation) and 70 °C (incipient thermal cavitation).

Finally, Figure 13 highlights the effect of the water temperature at design flow rate under slightly cavitating conditions. The occurrence of incipient thermal cavitation in the tests at 70 °C has just a minor influence on the rotordynamic force spectra at the levels of cavitation tested in present experiments. The tangential component is less affected than the normal one which, together with the overall amplitude of the rotordynamic force, tends in general to increase when the whirl ratio is higher than $\omega / \Omega > 0.5$ or lower than $\omega / \Omega < -0.2$. As before, this finding can be readily interpreted if rotordynamic forces are assumed to respond to thermal cavitation like the hydrodynamic loads on the impeller blades. Then the observed effect of the water temperature on the rotordynamic force spectra in the DAPROT3 inducer is coherent with the well-known delay of the pumping performance degradation of hydraulic turbomachinery in the presence of thermal cavitation effects because of the resulting increase of the dynamic actions on the impeller blades.

Rotordynamic Forces on the VAMPIRE Impeller

Representative measurements of the rotordynamic forces acting on the impeller of the VAMPIRE pump under the conditions indicated in Table 2 are presented in the Figures from 14 to 17 for comparison with the results for the DAPROT3 inducer.

The effect of the flow rate on the normal and tangential components of the rotordynamic force in cold-water tests under noncavitating conditions is shown in Figure 14. The influence of the flow rate is larger for the normal force and almost insignificant for the tangential one. In both cases the minimum of the rotordynamic force intensity depends on the flow rate and tends to shift from right to left as the flow rate increases. Besides, the normal force is typically destabilizing at higher whirl speeds, while the tangential force is stabilizing for counter-rotating whirl speeds and typically destabilizing or neutral at positive for $\omega / \Omega > 0$.

However, the most striking difference of the rotordynamic force spectra in the VAMPIRE pump with respect to the results for DAPROT3 inducer is the more regular behavior and the virtual absence of maxima and minima at positive subsynchronous whirl speeds. In particular, the normal force is nearly quadratic and the tangential one roughly linear over the entire frequency spectrum of the experiments, as first documented in earlier investigations ([10]).
Figure 14. Effect of the flow rate on the rotordynamic force spectra of the VAMPIRE impeller in cold water tests under noncavitating conditions. Nondimensional normal and tangential components $F^*_N$ and $F^*_T$ as functions of the whirl ratio at 80%, 100% and 120% of the design flow ($\Phi = 0.074, 0.093$ and $0.111$) at $\sigma \approx 0.081$ and $T = 20 ^\circ C$ (incipient thermal cavitation).

As explained earlier, the more complex behavior of the rotordynamic force spectra at moderate subsynchronous whirl speeds is due to the resonant interaction between the inlet flow prerotation and the motion of the impeller eccentricity. This interaction is also occurring in the eye of mixed-flow centrifugal machines like the VAMPIRE pump, whose inlet geometry and physical phenomena responsible for inlet flow prerotation are rather similar to those of inducers. However, the coupling between the inlet flow prerotation and the impeller whirl is proportionally more pronounced in axial machines than in centrifugal impellers, where the inlet radius is comparably smaller. In particular, when (as in the present work) rotordynamic forces are nondimensionalized inversely with the cube of the impeller tip radius, the normalized intensity of the impeller whirl interaction with the inlet flow appears to be greatly reduced in radial machines with respect to axial inducers. This consideration justifies the different behavior observed in present experiments on the VAMPIRE pump and the DAPROT3 inducer.

Figure 15. Effect of the cavitation number on the rotordynamic force spectra of the VAMPIRE impeller in cold water tests at 100% of the design flow. Nondimensional normal and tangential components $F^*_N$ and $F^*_T$ as functions of the whirl ratio at $\Phi = 0.111$, $T = 20 ^\circ C$ and $\sigma = 0.60, 0.11, 0.08$, respectively corresponding to fully-wetted flow, limited cavitation and developed cavitation conditions.

The effect of cavitation intensity on the rotordynamic forces in the VAMPIRE pump is illustrated in Figure 15. Its impact on the impeller forces is relatively small, as for the DAPROT3 inducer. The
occurrence of cavitation is seen to slightly reduce the intensity of the rotordynamic force, especially at lower negative whirl ratios, and in general acts in favor of the impeller stability with respect to rotordynamic lateral motions. These effects are more pronounced at higher-than-design flow conditions (not shown in the figures) and for the normal force component with respect to the tangential one.

The effects of (incipient) thermal cavitation are shown in Figure 16, where the results of tests at room conditions and elevated water temperature are compared. The normal component is more strongly affected, especially at moderate whirl ratios, while the tangential one is almost unchanged. In terms of rotordynamic stability, thermal effects broaden and slightly shift the range of stable whirl frequencies of the normal force component, but have virtually no influence on the stability of the tangential force. In general, therefore, thermal effects tend to have a favorable influence on the rotordynamic stability of the pump impeller.

Finally, it is worth noting that also the components of the rotordynamic force illustrated in Figures 14, 15 and 16 tend to be smooth functions of the whirl ratio over the whole spectrum covered by the experiments. This result indicates that the effects of the whirl interaction with the inlet flow in the

Figure 16. Effect of the water temperature on the rotordynamic force spectra of the VAMPIRE impeller in tests at 100% of the design flow. Nondimensional normal and tangential components $F_N^*$ and $F_T^*$ as functions of the whirl ratio at $\Phi = 0.111$, $\sigma = 0.11$ (limited cavitation) and $T = 20 \, ^\circ C$ (inertial cavitation) and 70 °C (incipient thermal cavitation).

Figure 17. Effect of the cavitation intensity on the rotordynamic force spectra of the VAMPIRE impeller in hot water tests at 120% of the design flow. Nondimensional normal and tangential components $F_N^*$ and $F_T^*$ as functions of the whirl ratio at $\Phi = 0.111$, $T = 70 \, ^\circ C$ (incipient thermal cavitation) and $\sigma = 0.60$ (no cavitation), 0.11 and 0.081 (developed cavitation).
impeller eye of the VAMPIRE pump remain relatively weak also under cavitating conditions. Some evidence of the residual influence of the dynamic coupling between the inlet flow prerotation and the eccentric motion of the impeller can still be recognized in the small subsynchronous irregularities of the rotordynamic force spectra shown in Figure 17, which illustrates the results of hot water tests at 120% of the design flow rate and three values of the cavitation number corresponding to fully-wetted flow, limited cavitation and developed cavitation conditions.

Conclusions
The present series of comparative tests on the DAPRO T3 axial inducer and the centrifugal impeller of the VAMPIRE pump confirms in the first place the validity of the procedure recently developed at Alta for the continuous characterization of the spectral dependence of the rotordynamic fluid forces acting on the impellers as functions of the frequency of their eccentric whirl motion. This procedure greatly simplifies and speeds up the acquisition and reduction of the experimental data and proved to be very effective in a) providing accurate, frequency-resolved information on the dependence of these forces on the whirl ratio also in the regions where they undergo rapid changes and b) allowing for clear identification of the maxima and minima of the rotordynamic force spectra.

More importantly, the results of the present research clearly indicate that the complex resonant interaction between the inlet flow prerotation and the impeller whirl motion, which the author and his collaborators recently recognized to be responsible for drastically modifying the behavior of rotordynamic fluid forces on axial inducers in the positive subsynchronous region of the whirl spectrum, is not equally capable of inducing effects of comparable importance also on centrifugal pump impellers. The reasons for this discrepancy are believed to be the relatively weaker intensity of the above interaction in centrifugal machines because of the smaller size of their inlet flow with respect to axial inducers, together with the effect of the nondimensionalization of rotordynamic forces inversely with the cube of the relevant impeller tip radii in the two cases.

Finally, the acquired experimental evidence indicates that, over most of the spectral region covered by present tests, the magnitude of rotordynamic fluid forces acting on both axial and radial impellers tends to decrease with the flow rate, and more weakly with the intensity of cavitation and the occurrence of thermal effects. Besides, in most cases the effect of higher levels of cavitation on the rotordynamic fluid forces is stabilizing. These results are consistent with earlier findings of the author and his research group, as well as with those of previous investigators.

Nomenclature
Symbols
- \( c_a \) full-blade axial length
- \( D \) diffusion factor
- \( F \) dimensional force
- \( F^* \) nondimensional force
- \( h \) mean blade height
- \( h^* \) axial length
- \( N \) number of blades
- \( p \) static pressure
- \( Q \) volumetric flow rate
- \( r_H \) inducer hub radius
- \( r_T \) inducer tip radius
- \( T \) temperature
- \( \alpha \) blade tip incidence angle at design
- \( \beta \) blade tip inlet angle
- \( \gamma \) blade angle
- \( \gamma_{te} \) trailing edge tip blade angle
\( \varepsilon \)  
radius of the whirl orbit (eccentricity)

\( \rho \)  
liquid density

\( \sigma \)  
cavitation number (\( \sigma = \left( \rho_1 - \rho_v \right) / 0.5 \rho \Omega^2 r_i^2 \))

\( \sigma_r \)  
inducer tip solidity

\( \tau \)  
torque

\( \phi \)  
flow coefficient (\( \phi = Q / \pi \Omega r_i^3 \))

\( \Omega \)  
inducer rotational speed

\( \omega \)  
whirl rotational speed

Subscripts

\( D \)  
design conditions

\( H \)  
hub radius

\( le \)  
blade leading edge

\( N \)  
normal to the whirl orbit/nominal

\( R \)  
rotordynamic force modulus

\( T \)  
tangent to the whirl orbit

\( te \)  
blade trailing edge

\( v \)  
vapor pressure

\( x, y, z \)  
rotating reference frame

\( X, Y, Z \)  
absolute reference frame

\( 0 \)  
initial condition/steady forces

\( 1 \)  
inlet station

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