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GEOMETRY RECOVERY OF A FRANCIS RUNNER PROTOTYPE AT SITE

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ABSTRACT

Geometry recovery of a turbine runner can be of prime importance in at least two cases: upgrading of an old power plant and field repair of a runner. Considering the importance of the field geometry recovery, we have decided to compare three methods of measurement, on a Francis runner with a 4.4 m outlet outer diameter.
The first method of geometry measurements is the classical template technique, consisting in drafting both horizontal and slanted sections of the runner blade-to-blade passage. The instrument used for the second method is a 3D Laser interferometer. The last method is based on a portable coordinates measurement arm with 6 degrees of freedom.
The aim of the paper is to describe the procedure and the use of each method, and to compare them from the point of view of their accuracy and their flexibility in the field. As a conclusion, it will be explained why the recovery method with the portable arm seems to be the most advantageous for us.

RESUME

La reconstitution de la géométrie d'une roue de turbine peut être nécessaire au moins dans deux cas: la rénovation d'une ancienne centrale et la réparation de la roue sur place. Considérant l'importance de la reconstitution de la géométrie d'un prototype, nous avons décidé de comparer trois méthodes de mesure, sur une roue Francis de 4,4 m de diamètre extérieur de sortie.
La première méthode de mesure de la géométrie est la technique classique des gabarits, qui consiste à tracer des sections horizontales ou inclinées du canal interaubes de la roue. L'instrument utilisé pour la deuxième méthode est un interféromètre Laser 3D. La dernière méthode est basée sur un bras de mesure de coordonnées portable avec 6 degrés de liberté.
L'article entend décrire la procédure d'application et l'utilisation de chaque méthode, afin de les comparer du point de vue de leur précision et de leur flexibilité sur le site. En conclusion, nous présentons les raisons qui font que la méthode de relevé à l'aide du bras mécanique nous semble être la plus avantageuse.

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1. INTRODUCTION

When owners of old power plants plan to upgrade their turbines [1], the first step towards increasing performance and power consist in replacing the old runner by a new one. However, the shape of the actual runner, usually unknown, is required for analyzing the potential improvement in designing a new runner or to proceed with comparison model tests between the old and the new design [2]. Moreover, for field repair of a damaged runner by cavitation or sand erosion, shape restoration can be improved if the original runner geometry is known.

Owing to the importance of field geometry recovery [3], we decided to compare three methods of field geometry measurement. Depending on the availability of the Hydro-Québec power plants, a $n_q = 57$ ($\nu = .36$) Francis runner of 4.4 m outlet diameter was measured within a 5 days period.

The first method of geometry measurements is the classical template technique, consisting in drafting both horizontal and slanted sections of the flow passage in the runner. Digitalization of the resulting contours leads to a set of data ready for the shape recovery.

A 3D Laser interferometer, the Smart 310 model from Kern Inc., is the instrument used for the second method. The instrument is a laser interferometer associated with a free moving mirror rotating on 2 axes. The laser beam is then tracking a spherical catadioptric reflector which is swept on the blade surface. The angular positions of the mirror and the distance between the laser head and the reflector are continuously sampled by a microcomputer, providing the 3 spatial coordinates of the spherical reflector center. Thus, an offset of the surface corresponding to the radius of the sphere allows a determination of the surface shape.

The last method is based on a portable 3-D digitizer from Faro Inc. that has a measurement arm with 6 degrees of freedom. Combination of precision bearings and optical encoders at each of the 6 joints provides the complete point position of the point probe at the end of the arm. Two switches on the probe handle allow the user to perform the measurement and to send the coordinate data to the microcomputer.

All the results obtained by the three methods are processed and gathered in the data base of a Computer Aided Drafting system, GMS from Unisys, Inc. The surfacing capability of the system allows the recovery of surfaces obtained through the three methods and the comparison of the results.

The aim of the paper is to describe the procedure and the use of each method, and to compare them from the point of view of their accuracy and their flexibility in the field.

2. MEASUREMENT PROCEDURES

2.1. Template technique

The classical template technique consists in tracing the intersections of the flow passage in the runner with both horizontal and slanted planes. The contours are plotted on polyester drawing films with a pen, fixed in the middle of a disc with a known diameter, which is rolled along the faces of the flow passage. The films are fixed on plywood boards having the shape of the theoretical contours. The plywood boards are assembled in desired positions with brackets welded on the faces of the flow passage. Figure 1 shows the different elements of this description. The resulting contours are then digitized with a digitizing table .

The accuracy of the method is approximately 2 mm.

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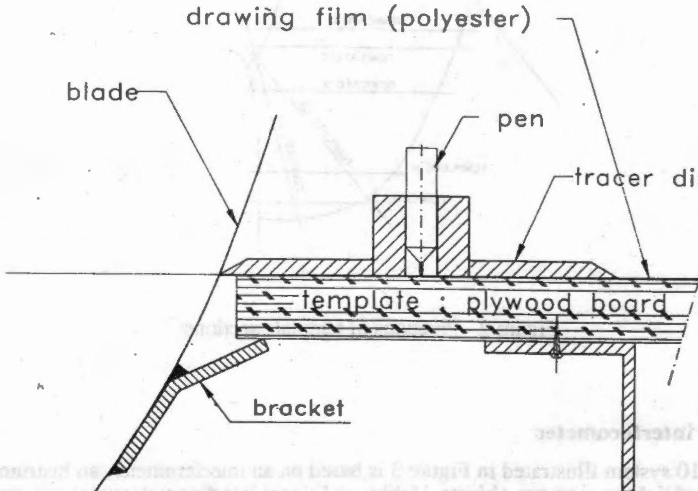

Figure 1 - Classical template technique

This technique has been applied on the flow passage between blades #3 and #4, for six horizontals and two slanted planes as shown on Figure 2, according to the following steps:

- **Cutting of the 8 plywood boards with an offset of about 1"**
- **Positioning brackets on the faces of the flow passage**
- **Positioning plywood boards on brackets**
- **Fixing the drawing films on the plywood boards**
- **Tracing contours on drawing films by rolling the tracer disc along the faces**
- **Definition of reference points on the crown**
- **Reference points projection on drawing films with a plumb line**
- **Digitizing of contours**

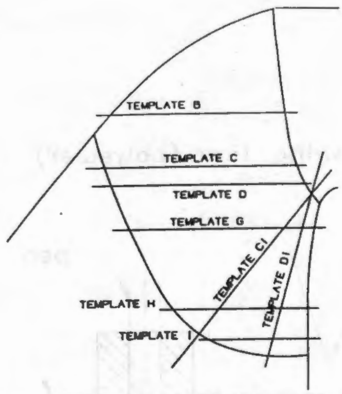

Figure 2 - Positions of template sections

2.2. Laser interferometer

The Smart 310 system illustrated in Figure 3 is based on an interferometer, an instrument that uses a beam of light to measure objects. Unlike traditional interferometers that rely on a fixed beam to measure in two dimensions, the Smart 310 employs a laser beam that moves freely in space. This allows the Smart 310 to take real-time measurements in three dimensions. Servo-controls in the tracking head of the Smart 310 system allows the laser beam to track targets continuously, measuring their changing positions in 3D space.

The tracking head at the top of the Smart 310 sensor unit contains all the electromechanical equipment needed to direct the laser beam. Servo-motors in the tracking head turn the head to direct the interferometer beam. The beam itself is directed onto a target retro-reflector. Tracking of the retro-reflector is controlled with the aid of the reflected interferometer beam. The retro-reflector returns the beam to the Smart 310 unit along a line parallel to the path the beam takes when it leaves the tracking head. Part of the returning beam is directed to a position-sensitive diode or deflector. Any offset on the diode automatically corrects the angle of the measuring head to keep the beam on target.

Only a simple calibration is necessary to convert the path difference measured by the laser interferometer into an absolute distance measurement. As the tracking head moves to track a target, the two angle encoders in the head provide measurements of a horizontal and a vertical angle. At the same time, the laser interferometer beam provides a distance measurement to the target. These measured values define a local spherical coordinate system.

A personal computer transforms the measured spherical coordinates to any user-defined cartesian or cylindrical coordinate system and stores them directly on the computer's hard disk. The accuracy of the system is said to be approximately 0.07 mm.

The measurement technique consists in moving the target retro-reflector along curves traced on the faces of runner blades. The instrument's frame of reference to the runner is set by measuring points on the circle at the outlet between the band and the draft tube. This method has been applied for the pressure side of runner blade #2, the pressure and suction sides of runner blade #3 and the pressure side of runner blade #4. Each face has been measured along 13 curves from leading edge to trailing edge, with aproximately 1500 points per curve.

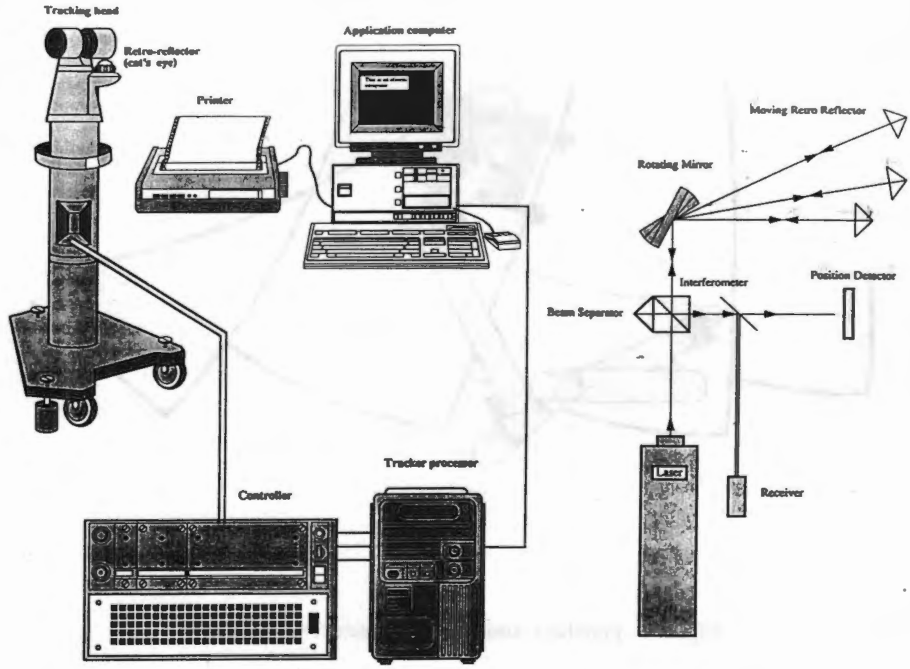

Figure 3 - Laser interferometer

2.3. Portable coordinate measurement machine arm

The Metrocom is a 3D measurement arm illustrated in Figure 4. This portable coordinate measurement machine (CMM) arm has six degrees of freedom that can instantly scan and measure complex 3D surfaces. The measurement envelope of the arm goes to nine feet in diameter and offers one-touch capture of small and large parts directly on the surface.

Each of the six joints of the arm has an encoder which transmits to the control box angular position of that specific joint.

By knowing the position of each joint and the physical dimensions of the arm, the control box automatically determines the 3D position of the probe tip installed on the arm. The probe can be a point or a sphere. The raw data from the control box is sent to a computer through the RS 232 serial port. As the arm is moved, the position of the arm tip can be viewed continuously in X, Y, Z coordinates on the screen of the computer.

The object to be measured can be captured point by point or as a stream of points. The measured coordinates are automatically saved on a hard drive computer disk. The software controlling the arm can also be interfaced with different kinds of CAD software. The accuracy of this CMM arm is said to be approximately 0.07 mm.

The measuring technique consists in moving the probe along curves traced on the faces of runner blades. The instrument's frame of reference to the runner is set by measuring points on the circle at the outlet between the band and the draft tube. This method has been applied for the pressure and suction sides of runner blade #2. Each face has been measured along 15 curves from leading edge to trailing edge, with aproximately 600 points per curve.

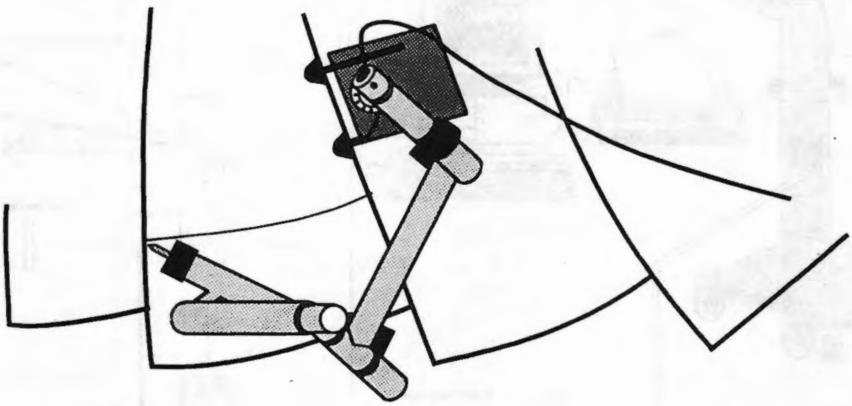

Figure 4 - Portable coordinate measurement machine arm

3. CAD SHAPE RECOVERY

3.1. Geometric modeler

The Geometric Modeling Software GMS from Unisys, Inc. is a powerful surface modeling tool and has its own interface programing language which can integrate Fortran or C routines. From the various types of surfaces offered, the NURC (Non Uniform Rational Cubic) interpolating surfaces are the ones chosen for the runner shape recovery [4].

3.2. Template technique

Each contour of the flow passage and its reference points were digitized and put in the GMS database.

The 6 horizontal contours B, C, D, G, H, I are positioned on the basis of the reference points. The position of the runner axis is found by computing the center of the intersection circles of the planes G, H, I with the runner band, in terms of least squared distances. The 2 slanted contours C1 and D1 are positioned on the basis of the reference points by computing the equation of their planes in terms of least squared distances.

3.3. Laser interferometer

The files containing the 3D coordinates of the retro-reflector target center are put in the GMS database.

For each face, the points are sorted and classified in order to build a mesh of control points to define the NURC intermediate surface modeling the measured points, as shown in Figure 5. An offset of this intermediate surface at a distance corresponding to the radius of the retro-reflector target (37.5 mm) gives the final surface. Figure 6 illustrates the offset operation. The number of points defining each surface is equal to 13 x 35.

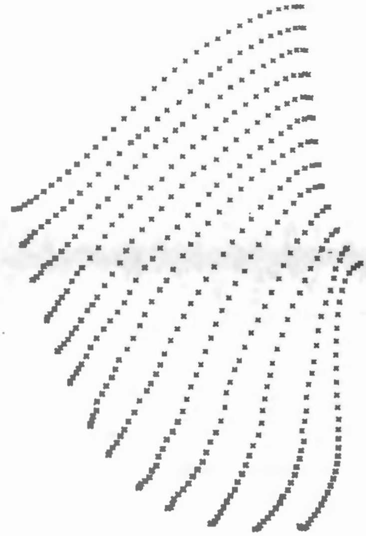

Figure 5 - Point mesh for NURC surface

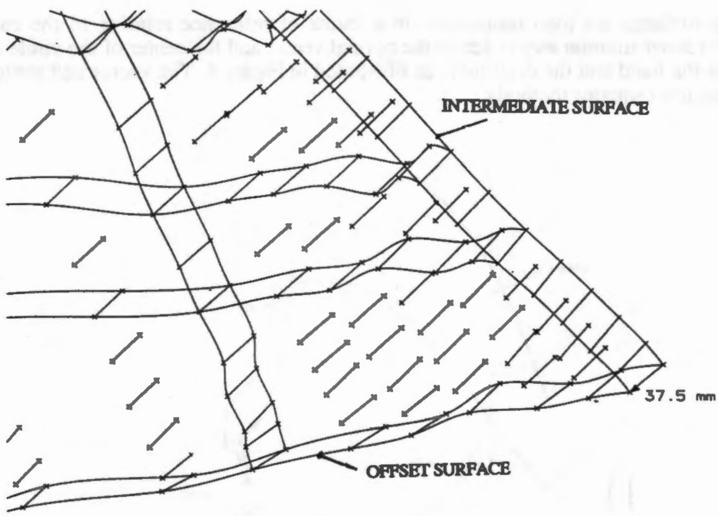

Figure 6 - Offset operation

A validation of the intermediate surfaces, such as computing the distance between the surfaces and the measured points, allows to ensure that each measured point is less than 3 mm distant from the surface, the average distance being aproximately 0.05 mm around the retro-reflector target's diameter, which is 37,5 mm. The same validation of the surfaces modeling the runner blade faces gives similar results. According to the instrument's accuracy, the surface accuracy is set to 0.1 mm. Figure 7 shows the distance between the surface modeling the suction side of blade #3 and the measured points, versus a normalized curvilinear abscissa along a curve going from leading to trailing edge and passing through the considered point.

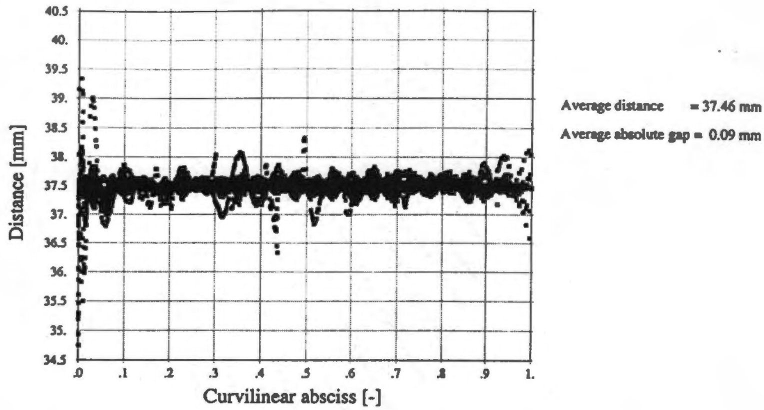

Figure 7 - Distance between the suction side surface and measured points

The resulting surfaces are then transposed in a frame of reference relative to the runner. Therefore, the runner rotation axis is set by the normal vector and the center of the circle at the outlet between the band and the draft tube, as illustrated in Figure 8. The vector and center are estimated using least squares methods.

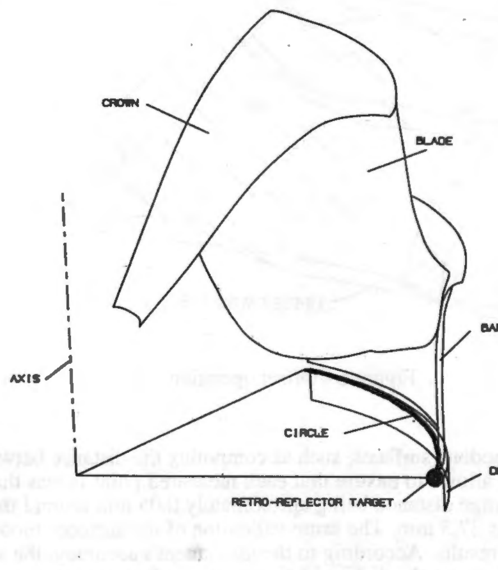

Figure 8 - Frame of reference definition

3.4. Portable coordinate measurement machine arm

The files containing the 3D coordinates of the measured points on the runner blade faces are also put in the GMS database.

The NURC surfaces modeling the measured faces are built following a procedure similar to the one presented for the Laser interferometry intermediate surfaces.

The same kind of validation gives similar results. This ensures that each measured point is less than 3 mm distant from the surfaces, with an average distance of 0.05 mm. According to the instrument's accuracy, the surface accuracy is set to 0.1 mm.

The resulting surfaces are transposed in a frame of reference relative to the runner, using the circle at the outlet between the band and the draft tube.

4. COMPARISONS

4.1. Resulting surfaces comparison

4.1.1. Laser interferometer - Template technique

The template contours are compared to the corresponding sections of the surfaces obtained by laser interferometery. The comparison consists in computing the distance between two corresponding curves. Figure 9 shows this distance as an average of all 8 sections, versus a curvilinear abscissa along the considered curves.

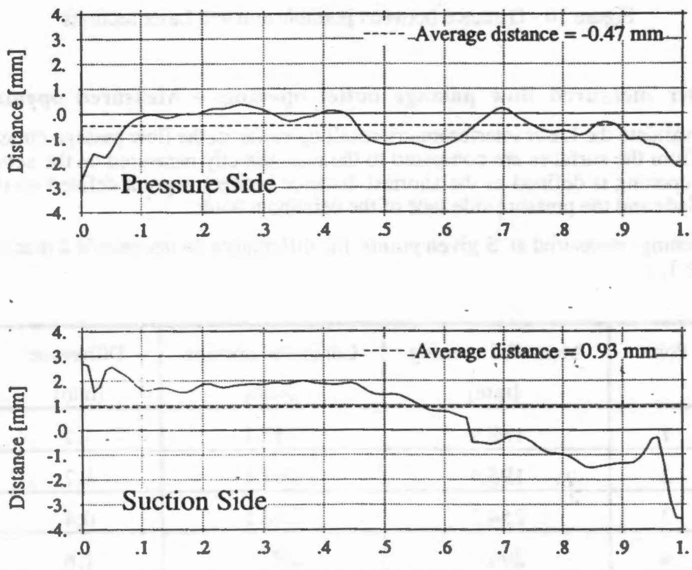

Figure 9 - Distance between templates and Laser sections

The average distance for the 6 horizontal and the 2 slanted sections is about 1 mm, but deviations reach 3 mm. These quite important differences are due to the lack of care in defining the different frames of reference.

4.1.2. Laser interferometer - Portable arm

The comparison of surfaces resulting from laser interferometry and portable arm measurements consists in computing the distance between corresponding sections, as done above. Figure 10 shows this distance as an average of the eight sections defined by the templates. The average distance is 0,2 mm, but deviations reach 2 mm for the same reason as above.

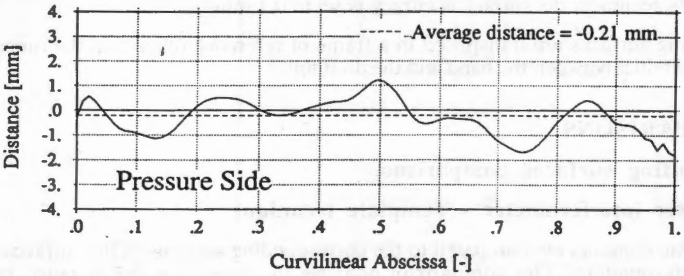

Figure 10 - Distance between portable arm and Laser sections

4.1.3. Laser measured flow passage outlet openings - Measured openings

In order to validate the Laser interferometry resulting surfaces, the flow passage outlet openings computed from the surfaces are compared to the ones directly measured on the actual runner. The outlet opening is defined as the shortest distance between a point defined on the trailing edge of a blade and the pressure side face of the neighbour blade.

For five openings measured at 5 given points, the differences do not exceed 2 mm, as one can see in Table 1.

Point	Measured opening [mm]	Computed opening [mm]	Difference [mm]
1	188.9	187.7	1.2
2	195.4	197.1	1.7
3	254.5	254.1	0.4
4	296.0	297.6	1.6
5	327.1	327.6	0.5

Table 1 - Comparison of measured and computed openings

4.2. Procedures comparison

4.2.1. Template technique

The classical template method is rather complicated in use, because of the templates fixation in the flow passage. The time needed to position and trace the 8 flow passage sections is 130 hours for one working man. Time needed for CAD shape recovery is 80 hours.

A complete flow passage recovery would require aproximately 10 horizontal and 3 slanted sections to get precise results. The resulting accuracy would however hardly be better than 2 mm.

The cost of the total operation is approximately 8'700 USD.

4.2.2. Laser interferometer

One advantage of Laser interferometery is that it requires no more preparation than marking the curves to be measured on the runner blades. The drawback of this method is the fact that an offset of the resulting surfaces is needed, which means more CAD processing and a lack of accuracy. Another drawback is that the instrument's operator must be careful not to lose the Laser beam, while he is moving the retro-reflector target along the face. This may often occur because of the reduced optical operture of the reflector.

The time needed to mark the pressure and suction sides of one blade is aproximately 4 hours. The time needed to measure one runner blade face is 8 hours, and 120 hours of CAD shape recovery.

Taking care of the instrument's frame of reference definition, the method's accuracy could be brought to less than 0.1 mm.

The cost of one face recovery is approximately 3'500 USD.

4.2.3. Portable arm

The portable arm has the same advantage as the Laser interferometer over the template technique, which is little preparation. Another advantage is that the points are directly measured on the face. The drawback is the fact that the arm reaches only to about 3 m. This means that the arm attachment must be moved several times for one runner blade face measurement and leads to additional difficulties for the instrument's frame of reference definition.

The time needed to mark the pressure and suction sides of one blade is 4 hours, 5 hours to measure it, and 80 hours for CAD shape recovery.

The method's accuracy could be about 0.1 mm, taking care of the instrument's frame of reference definition.

The cost of one face recovery is approximately 2'500 USD.

5. CONCLUSIONS

The field recovery of the geometry of a 4.4 m diameter prototype Francis turbine runner was done using three different methods: the classical template technique, 3D Laser interferometry and coordinates measurement with a portable arm.

The measurement procedure for each method was described. The results of geometry recovery consist in CAD surfaces. Comparison of the surfaces obtained by the different methods shows the prime importance of the instrument's frame of reference definition. The comparison between the three methods is summarized in Table 2, for one runner blade recovery (two faces).

Method	Preparation	Measurement	CAD Processing	Accuracy	Cost
Template technique		130 hours	80 hours	2 mm	8'700 USD
Laser interferometry	4 hours	8 hours	120 hours	0.1 mm	3'500 USD
Portable arm	4 hours	5 hours	80 hours	0.1 mm	2'500 USD

Table 2 - Comparison of the three methods

In comparison with the classical template method, the two modern methods, which are the Laser interferometry and the portable arm measurement, seem to be the most advantageous ones from the point of view of their accuracy and their flexibility in the site. Our preference is for the portable arm, which measures points directly on the blade face, is faster, cheaper and requires less CAD proceeding.

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