Photogrammetric evaluation of geometrical tolerance standards: a DARPA suboff model case study

Evaluación fotogramétrica de los estándares de tolerancia geométrica: un estudio de caso de modelo de DARPA suboff

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Abstract

A DARPA Suboff scale model was used for the development of an analysis methodology for geometric deviations of the hull, aiming the quality control of model manufacturing process. The surface three-dimensional coordinates were obtained through a photogrammetric survey and analyzed based on statistical tools.

The results were classified according to the ITTC and DIN ISO geometric tolerance standards, allowing the investigation of the compliance of the model to such criteria and the study of local geometric deviations.

Key words: Photogrammetry, DARPA Suboff, Geometric Tolerance.

Resumen

Se utilizó un modelo a escala DARPA Suboff para el desarrollo de una metodología de análisis para las desviaciones geométricas del casco, con el objetivo de controlar la calidad del modelo del proceso de fabricación. Las coordenadas tridimensionales de la superficie se obtuvieron a través de un estudio fotogramétrico y se analizaron en base a herramientas estadísticas.

Los resultados se clasificaron de acuerdo con los estándares de tolerancia geométrica del ITTC y DIN ISO, lo que permitió investigar el cumplimiento del modelo con dichos criterios y estudiar las desviaciones geométricas locales.

Palabras claves: Fotogrametría, DARPA Suboff, Tolerancia geométrica.

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Introduction

The adoption of more rigorous methods for the evaluation of small scale model's geometry is an important issue in the field of experimental methods applied to marine hydrodynamics. The experimental facilities have been improved the quality control in model's manufacturing process, in order to ensure geometrical similarity with consequent improvement in reliability and reduction of uncertainties of experimental results.

The procedure recommended by the ITTC (International Towing Tank Conference) consists of a succinct set of rules for surveying the main dimensions of the hull, which can be applied for any type of model. Length tolerance of ±0.05% Lpp or ±1.0 mm, whichever is greater; ±1.0 mm in beam dimension and ±1.0 mm in depth express a convention between model basins, stablishing minimum requirements for the accuracy of the model and for quality of test results. Each institution is independent to carry out even more restrictive procedures in order to achieve better results. A recognized standard is *(DIN ISO, 1989)*, for example, that establishes geometric tolerance classes based on a nominal size, described as "Fine", "Medium", "Coarse" and "Very Coarse" adjustments.

Based on results obtained through the use of an optical metrology technique, this work presents a procedure to evaluate the geometric deviations of the hull surface of a DARPA Suboff model, using both ITTC and DIN ISO standards.

The data used in this evaluation come from a photogrammetric survey of the hull, which, by numerical triangulations between reference targets and points located on the hull surface, is able to provide the three-dimensional coordinates of them. The algorithm used in the photogrammetry software performs a biunivocal transformation between two-dimensional and three-dimensional planes. Photogrammetry point cloud and DARPA Suboff reference mesh were aligned by means of an ICP (Iterative Closest Points) algorithm and an in-house software was used to calculate the hull deviations.

Once verified the feasibility of adopting this dimensional control technique during the manufacturing process of small-scale models, the proposed procedure can be used in experimental hydrodynamics research institutions. However, there is the need of control and standardize the measurement process itself in order to reduce its uncertainties.

Data Acquisition

This work aimed to verify the viability of the quality control of reduced model of ships according to *(ITTC, 2011)* and *(DIN ISO, 1989)*.

(Andrade et al., 2018) made the photogrammetric acquisition of a 1.5879 scale model of a DARPA Suboff submarine hull *(Groves, 1989)*. This geometry was chosen because it is defined by a set of polynomial equations, which allows the obtaining of coordinates all over the hull's surface, as shown in Fig. 1.

The photogrammetry is a metrology technique based on numerical analysis of digital images captured from targets applied to the object's surface. The images where obtained using a general purpose professional photographic camera. The procedure is relatively low cost in comparison to other optical techniques, with a 10^{-3} *mm* uncertainty for the measured coordinates. Fig.2 presents the equipment employed in this work.

Fig. 1. DARPA Suboff main lines.

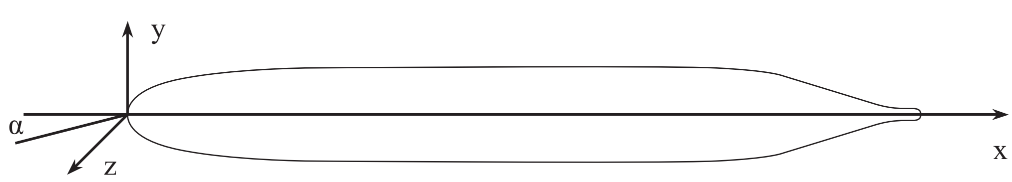
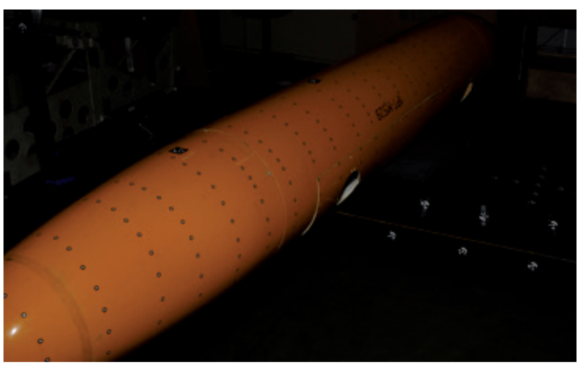


Fig. 2. Photogrammetry equipment.

At first, the model was prepared for the image acquisition by being placed in a position with adequate illumination. Adhesive targets are applied in the regions of interest, according to the model's geometry. For instance, DARPA Suboff model was filled with targets all over the circumference, as presented in Fig. 3.

Fig. 3. Applied adhesive targets in the DARPA model for the photogrammetry procedure.



The images where analyzed by commercial software *(GOM, 2009)* which consists of a library of algorithms for estimating target distances to a reference object adopted as the origin, also registered by the photos.

The algorithms are capable of identifying the same target in different images, taken in different angles, and evaluate the point position. The quantitative output of the procedure is a point cloud represented by its 3D coordinates with the origin located in the object of reference. These points are represented in the Fig. 4, contained in an uncertainty margin.

Fig. 4. Example of point cloud (white) obtained after digital image processing.

The obtained coordinates were compared to the model's expected geometry by *(Andrade et al., 2018)*. For each obtained point, the longitudinal coordinate x was used to calculate the target radius, R_{Target}, employing the DARPA Suboff polynomials. Due to the axial symmetry, the radius measured by photogrammetry, R_{real}, is obtained as follows:

$$R_{real} = \sqrt{y^2 + z^2} \tag{1}$$

The possible definitions from R_{real} and R_{Target} comparison are: when $R_{real} < R_{Target}$ the point is an inside or interior point. On the opposite, if $R_{real} > R_{Target}$ the point is considered an outside point.

This analysis allows the verification of the geometric bias for each station, taken perpendicular from the axis of revolution of the model. The method can be thought as an analogy for the use of templates shaped with the geometry of the hull on the position of each station. Other available software for geometry comparison, CloudCompare for example, usually results in the normal distance from point to surface.

Statistics

The obtained deviations were treated in a statistical way to provide useful information regarding the model's geometry, evaluating its quality and making it possible to improve the manufacturing process.

Were evaluated 309 points on the surface of the hull, identified in the adhesive targets applied to the model. The targets were organized in transversal sections equivalent to the ship's stations, with distribution approximately uniform. Since the adhesive application is manual and there is no need, or even feasibility, for a more precise spacing control, these points do not represent stations. This organization has the objective of facilitating the image processing, especially when operator intervention is needed.

A useful way to evaluate the deviations of this model is its arrangement as a function of the longitudinal coordinate of the hull. Figs. 5 and 6 show distinct ways to visualize deviations: The first one plots the radii measured by photogrammetry over the DARPA Suboff hull reference curve. The Figure 6, in turn, shows only the deviations as a function of the longitudinal coordinate. It is possible to observe, qualitatively, greater deviations in the two extremities. In the bow, near the zero coordinate, there is greater concentration of negative amplitude big deviations. This means that the surface of the bow has a slightly smaller radius than the reference. The red markers highlight positive deviations (outside points), while the blue markers highlight the negative ones (inside points).

The region of the parallel middle body fits reasonably to the reference geometry, in the longitudinal coordinate close to 1000 millimeters. Starting

Fig. 5. Bias comparison of measured points over the reference polynomial curve.

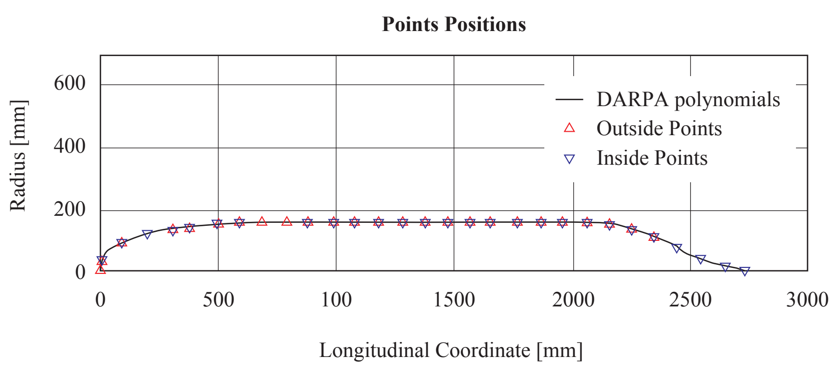


Fig. 6. Radii deviations, as function of the longitudinal coordinate of the hull.

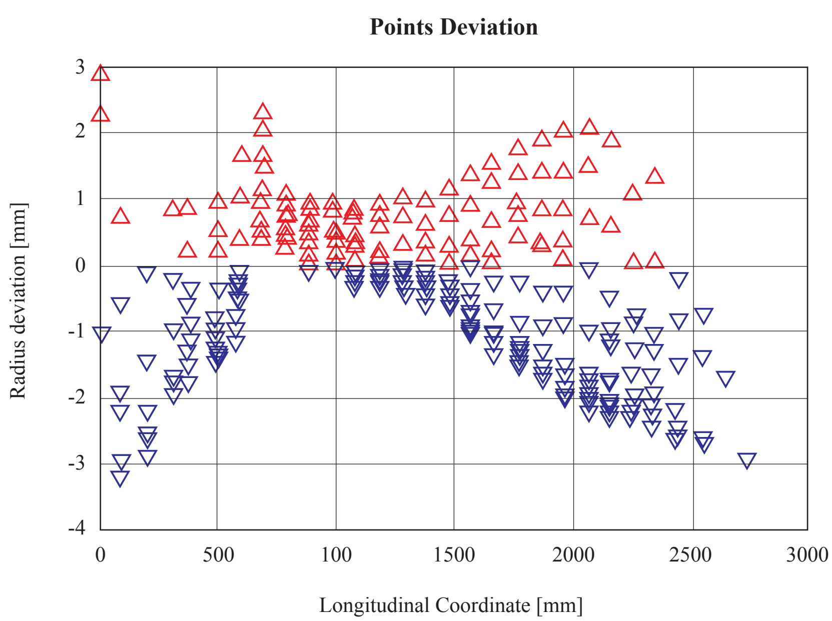
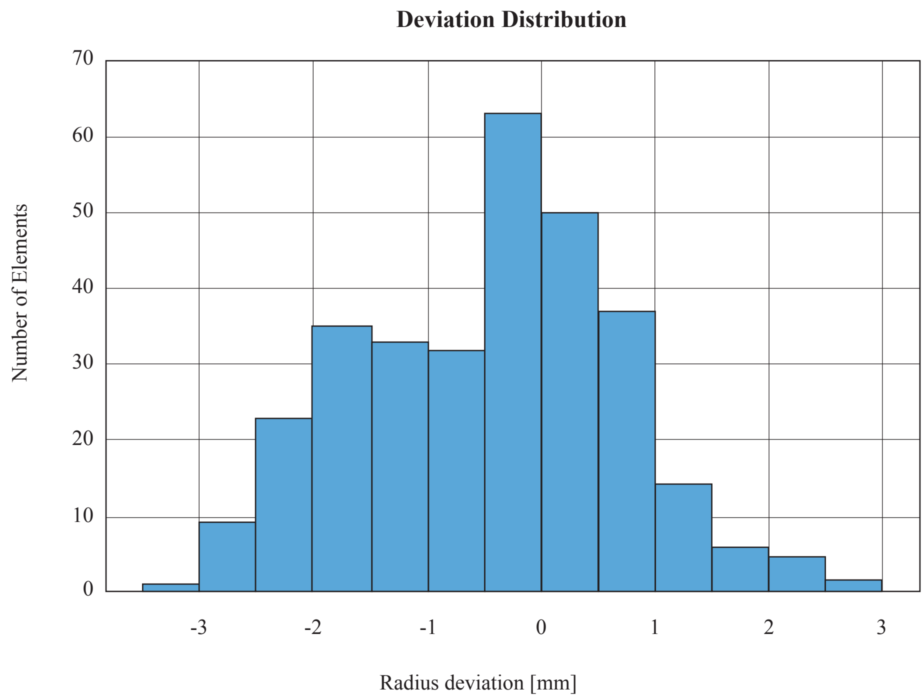


Fig. 7. Distribution of deviations.



from 1500 millimeters, there is a deviation increase to both positive (external) and negative (internal) values. The average value for the whole sample is -0.438 mm, showing a slight tendency for smaller radii than the design. In absolute values, the mean deviation is 0.968 mm.

The distribution of deviations is shown in Fig. 7. This distribution makes it clear that there is a greater density of points in the negative part of the graph, illustrating the value expressed by the simple mean. The variance for this distribution is 1.314 mm.

The International Towing Tank Conference Recommended Procedure (ITTC, 2011) does not establish a local surface tolerance, as presented in this paper. The geometric verification of the models is made by taking measurements of their main dimensions: length, depth and beam.

The recommendation for depth and beam, dimensions relevant to this work, once the radius is being checked at each point (Fig. 8), is that the principal dimensions deviations should be less than 1 millimeter. In a conservative approach, the points whose radius deviation exceeds this value were highlighted. In practice, it is verifiable that, at least due to radial symmetry, it is not possible to comply the standard with local deviation values close to 1 millimeter, since the great majority of the point's sections present values in the positive and negative half-planes of the graph. A total of 127 points (41.1%) with absolute deviation greater than 1 mm were observed and 182 (58.9%) presented deviations less than 1 mm. The first group had an absolute mean of 1.734 mm and a variance of 0.255 mm, while the second one had an absolute mean of 0.434 mm and a variance of 0.087.

The standard *(DIN ISO, 1989)* classifies the geometric tolerances in "Fine", "Medium", "Coarse" and "Very Coarse" groups. Each of these groups is related to a tolerance interval that also depends on a nominal size. Initially, were analyzed the deviations of each point, relative to the nominal value of the radius, as function of its longitudinal coordinate. In this way, it was possible to classify them according to the tolerance classes and to identify points in non-compliance with the standard.

Fig. 8. ITTC Recommended Procedures compliance to ship models manufacturing.

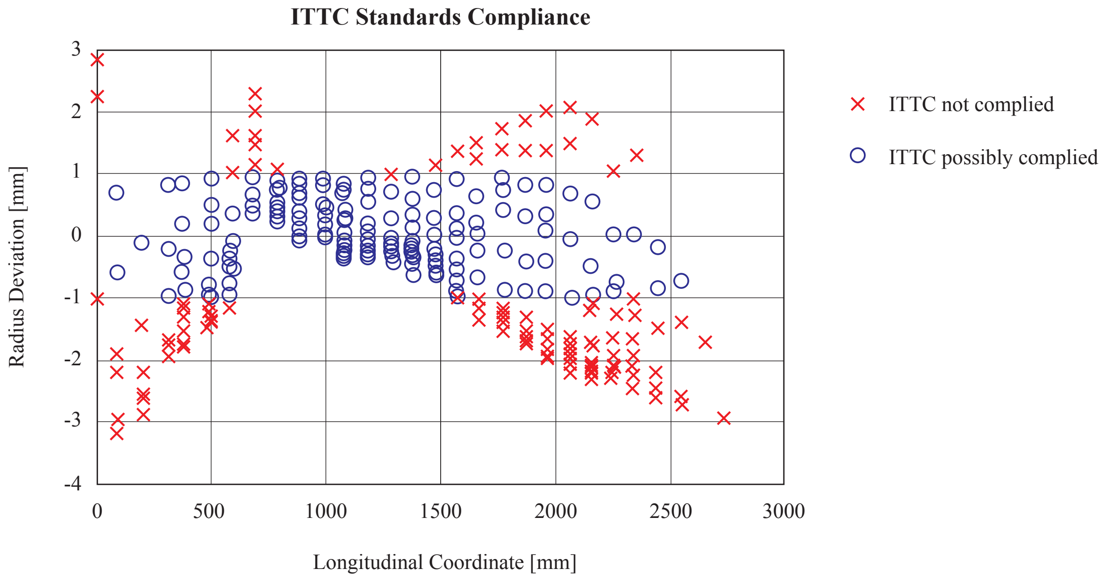
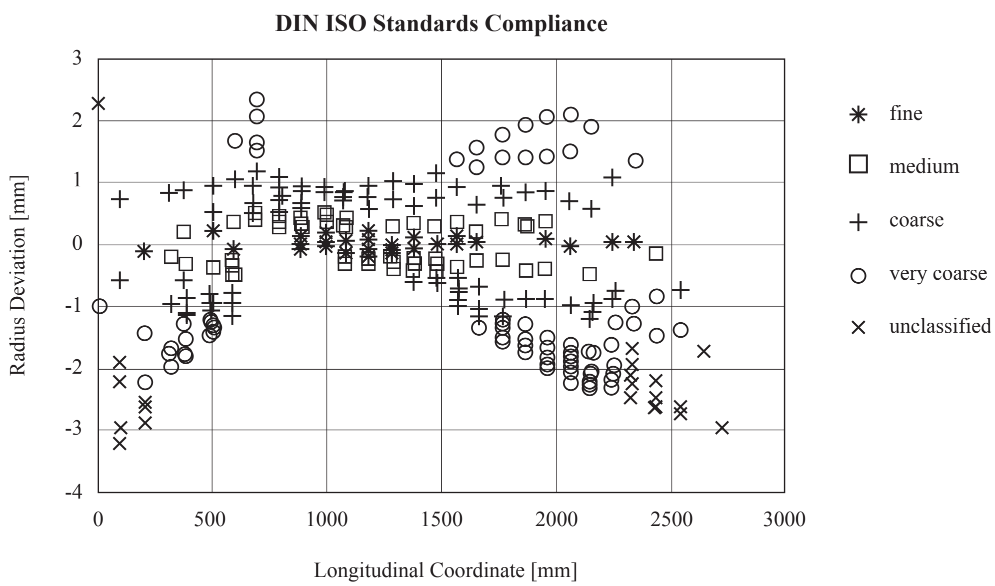


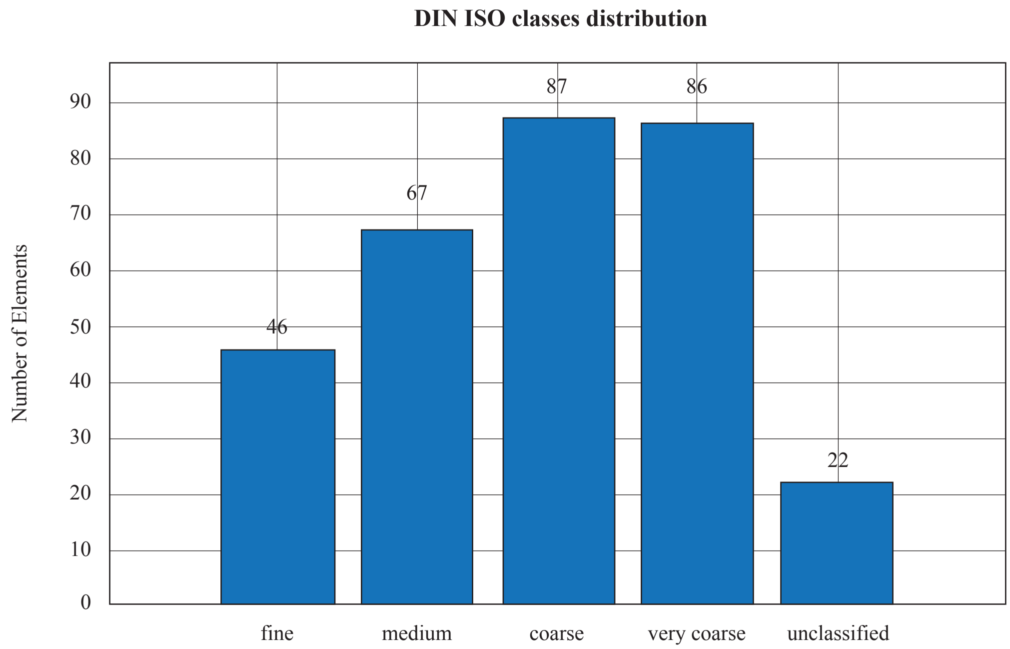
Fig. 9. DIN ISO Compliance.



The Fig. 9 shows the same distribution of deviations as a function of the longitudinal coordinate, but the points were grouped according to the class in which they fit the norm *(DIN ISO, 1989)*: “Fine” adjustment, “Medium” adjustment, “Coarse” adjustment, “Very Coarse” and points that do not fit the rules in any range of values, i.e., no class. It is possible to observe that in some cases, there may be up to three classes of deviation in the same arbitrary section at most.

The distribution among the classes can be better studied in the Fig. 10 which shows 46 points in "Fine" adjustment, 67 points in "Medium" setting, 87 "Coarse", 86 "Very Coarse" and 22 out of standard ranges.

Fig. 10. DIN ISO classes distribution.



The same procedure can be verified in the Fig.11 and Fig. 12, this time with the loosening of the rule, in order not to penalize too much the bow and stern end points, where the reference becomes smaller and smaller. In this case, it was decided to adopt the maximum radius R_{max} as nominal size for all analyzes. With this hypothesis, several points have undergone class improvement, resulting in 47 "Fine" adjustment points, 66 "Medium" adjustment, 90 "Coarse", 95 "Very Coarse" points and only 11 unclassified points, according to table presented by the standard.

Fig. 11. DIN ISO Compliance using R_{max}.

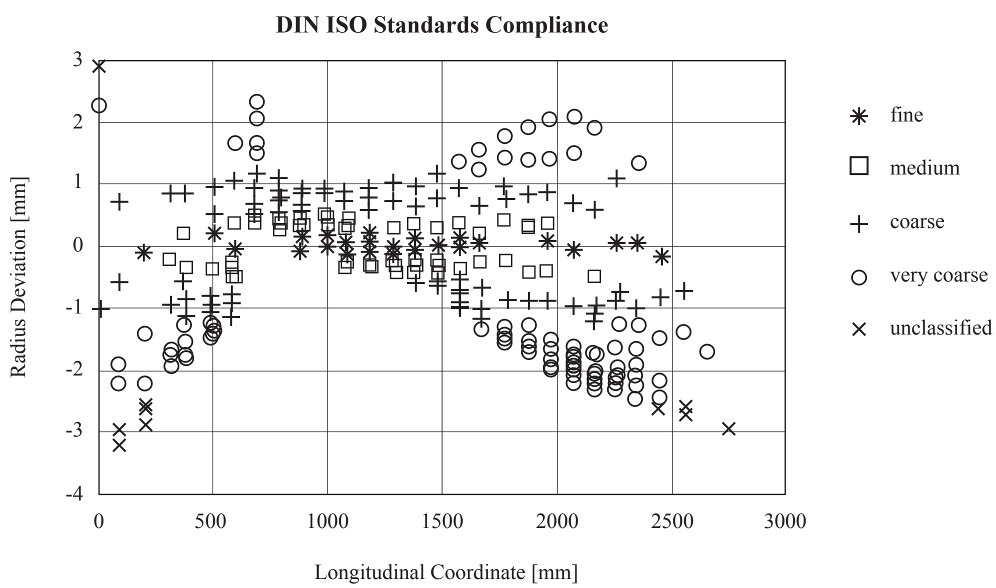
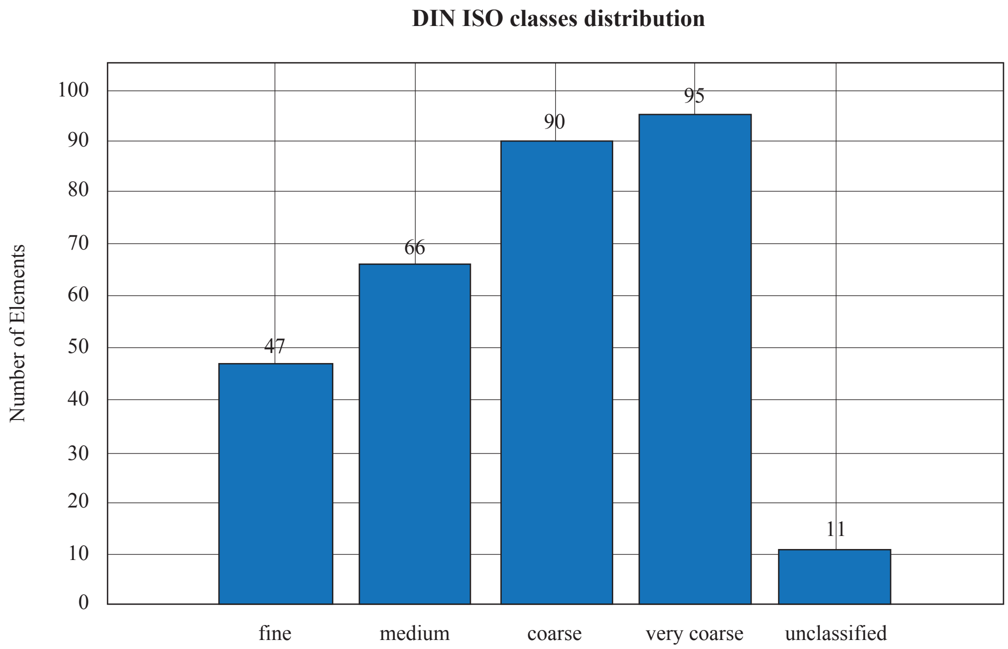


Fig. 12. DIN ISO classes distribution using R_{max}.



In addition, it was explored a way of representing deviations in dimensionless numbers. Two alternatives were studied, in both adopting a value of radius as denominator. The first one consisted in adopting the local value of radius, *i.e.*, the nominal radius for the longitudinal coordinate corresponding to the point. Again, a larger penalization was observed for smaller radius in the bow and stern regions. Also in the distribution of deviations it was possible to observe values very distant from the average.

The second alternative considered the value of the maximum radius R_{max} as denominator when making the deviation dimensionless. This option presents more significant dispersion and distribution, allowing a faster and more efficient evaluation of the results. In this way, the nominal radius was adopted equal to the maximum radius for the purposes of this work.

In this sense, the Fig. 13 shows the dispersion of the deviations as a function of the longitudinal coordinate, showing the classification of each point, according to the criterion *(DIN ISO, 1989)*, in the same color scale previously used. It is possible to observe very clear levels between the different classes, which is the advantage of having a single nominal size. In absolute values, it is possible to verify the mean of this dimensionless equal to 0.006, median equal to 0.005, maximum value 0.020 and minimum value equal to zero. The maximum value of the dimensionless, which still complies the rule, is 0.015.

In relation to the real values, were obtained the mean equal to -0.003, median equal to -0.002, maximum value 0.018 and minimum value -0.020. The maximum value of the dimensionless, which still complies the standard, is 0.014 and the minimum that obey the same rule is -0.015.

Fig. 14 shows the distribution of the dimensionless deviations in absolute values. Due to the use of the maximum radius, the shape of this distribution was preserved as in Fig. 7.

Conclusions

This work presented a statistical analysis of geometric deviation data obtained by means of a photogrammetric survey in a DARPA Suboff scale model. The results were compared to two reference

Fig. 13. Deviation / Maximum Radius dimensionless, as function of longitudinal coordinate.

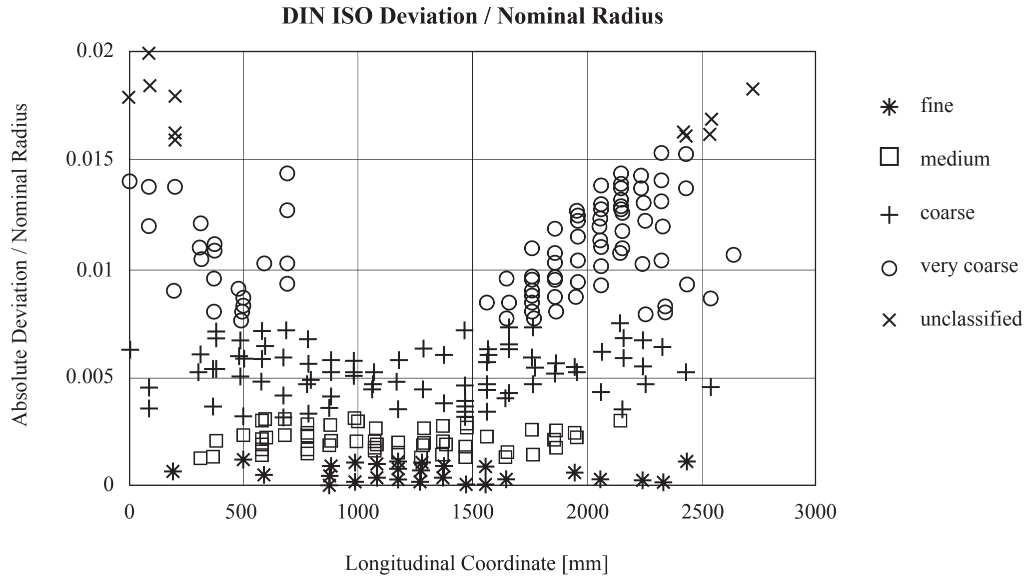
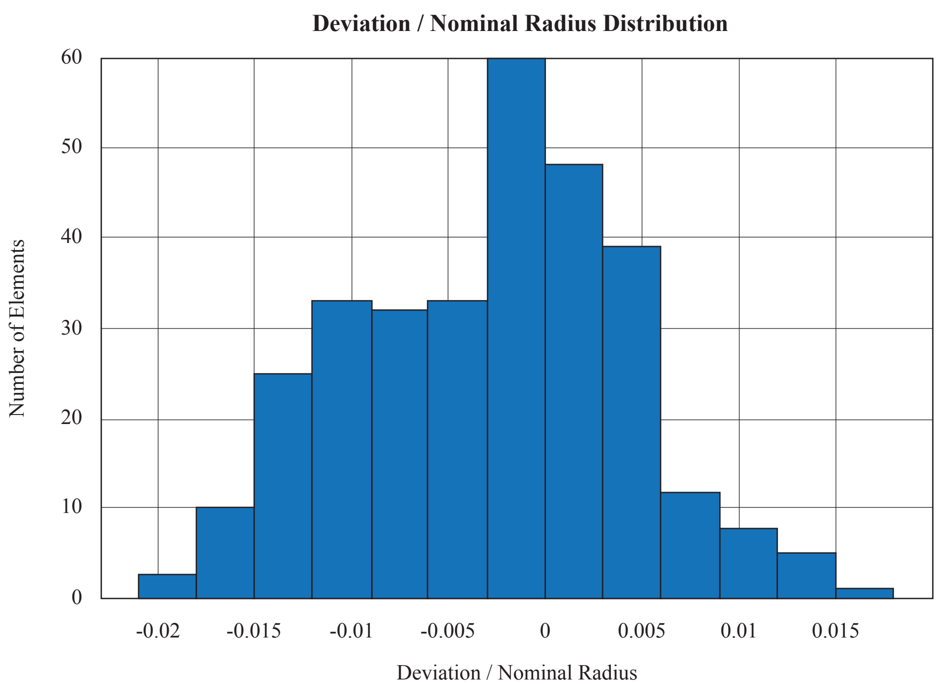


Fig. 14. Deviation / Maximum Radius dimensionless distribution.



standards for dimensional control. The first one *(ITTC, 2011)* is focused specifically on the control of the ship model manufacturing process, but does not show a very clear equivalence with the exposed method, since only the main dimensions of the hull are regulated. The *(DIN ISO, 1989)* presents geometric tolerance standards for parts in general, and its method proved to be more suitable for evaluating the points obtained by photogrammetry, organizing them according to the standardized classes of "Fine", "Medium", "Coarse" and "Very Coarse" adjustment or rejecting values that do not fit the norm.

Dimensionless values of the deviations were also obtained, using the maximum radius of the hull as denominator. It was verified that, in this study case, points that meet the norm showed absolute values of $Deviation / R_{max}$ less than 0.015.

The presented method can still be adapted for surface hulls with the implementation of a module that calculates the beam deviation, given the longitudinal and vertical positions of the point. Multihulls should be evaluated separately and thrusters require further refinement of data collection techniques so that they can provide adequate assessment.

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