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An accurate double-faced optical-interferometric strategy for estimation of gauge block Fo/Fu dimensional variations

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ABSTRACT
A new and fast calculation method proposed for length variations or Fo/Fu, as form estimations for gauge block measurement surfaces, uses a double-face-wringing interferometric approach, through length scanning of their five center and corner points, as defined through their optical inspection in both opposite gauge measurement surfaces. This method achieves realistic dimensional/bidirectional length definitions for such dimensional standard parameters as obtained by optical measurements. Two sets of real gauge block double one-sided interferometric measurement results are taken as examples, combined and inserted within the proposed algorithm, in order to achieve more accurate center and corner deviation lengths for each of such reliable metrological standards.

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Keywords: Interferometry; Fo/Fu; geometrical parameters; mechanical comparators

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1. INTRODUCTION

According to a definition from a fundamental gauge block pair standard [1] used for characterization of electromechanical length comparators, a thin block must be chosen, from a specific pair gauges set mentioned in that standard, in order to calibrate all gauge block mechanical length variation measurements performed by these devices. The so-called Fo/Fu parameters are defined there as the maximum and minimum length variations of gauge corner points with respect to its central point and, as such, must be defined only from their five-axis passing through its central and four corner points.

Actual mechanical comparators measure lengths through pair of probe sensor displacements, by bringing them toward close contact in both opposite gauge faces, along a measurement axis. Dimensional gauge lengths are defined from its main axis connecting both their centralized face points, and as such is "bidirectional" by definition. Common optical-interferometric measurements, as those from GBI/Mitutoyo operating in Interferometric Laboratory in Inmetro [2], otherwise, are one-directional by construction. Their measurements result from optical path differences between one-sided beam reflection from an upper gauge block surface and parallel beams reflected from high-flatness wringing support plates (for researches at other type of "plateless" interferometric measurements, see [3]). This lower reflection surface corresponds to an abstract reference plane, coplanar to the lower gauge block face, and their measuring reference points are laterally displaced from the gauge central axis.

2. FIVE-POINT HEIGHTS AND FO/FU MODELLING

The main drawback of this one-sided optical approach lies in the bold assumption that both lower gauge and wringing plate surfaces are "ideally planes" or without any height variations that can affect any inspected local variations seen at upper gauge faces. Figure 1 shows an example of global upper height mapping for a gauge block, and without any height variation contributions due to irregularities in supported face or wringing plate, its flatness excluded.

2.1. Mechanical-Optical geometric modelling

A proposed solution for achieving a better agreement of both gauge length measurands (i.e., those produced by optical-interferometric and electromechanical methods), is to inspect all height variations through both gauge surfaces. For accurate Fo/Fu estimations we need to execute double interferometric measurements, by wringing both opposite faces over the same wringing plate, Afterwards, their surface curvatures and parallelism deviations from both interferometric measurements

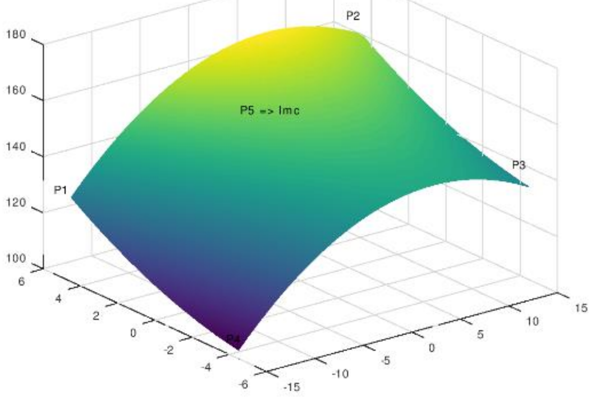

Figure 1. Hypothetical definition of five-height points taken from one-sided optical-interferometric measurement of a gauge block upper surface. Any variations due only to the lower face wringing and faces coupling are not taken in account.

can be numerically extracted directly from its 2 × 5-point lengths.

For the proposed strategy, non-plane surfaces attached to the wringing plate were described as based on 3-4 points support triangles, as we get them directly from all five-centre-and-corner-points height information got from both previous interferometric measurements. If the centre point is included in such triangle, that condition defines a lower convex face. Otherwise, the gauge lower face must be considered as a concave one, only if its centre point is excluded from the gauge support triangle, as shown in Figure 2. A special case can be included when the support stands over all four corner points (still a concave one).

Therefore, we can classify global gauge block double-face profiles within six generalized type forms: Bi-Plane (B-P), Plane-Convex (P-V), Plane-Concave (P-C), Bi-Convex (B-V), Bi-Concave (B-C) and Convex-Concave (V-C), with respect to both surface curvatures, as seen in Figure 3. Each form must offer distinct contributions to evaluate its final five-point mechanical lengths.

2.2. Surface classification

If one of surfaces is classified as "Plane" (i.e., for B-P, P-V or P-C), within some predefined tolerance, and a gauge was wrung over this face on a flat plate, any accurate phase-shifter interferometric system can indicate the five-point mechanical heights, as taken directly from its opposite upper face. For all other types, some discount for centre and corner lengths must be included, due to any support and curvature effects from both gauge surfaces. A fast algorithm was developed, in order to use this basic information to discount and correct their measured heights, giving accurate Fo/Fu parameters as their final results.

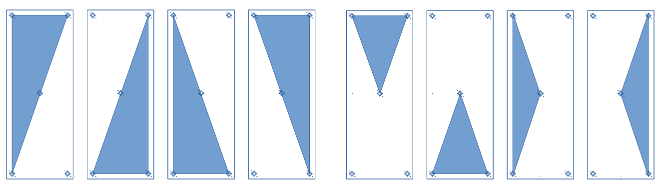

Figure 2. Eight hypothetical support triangles from gauge block support surface, chosen in function of strict non-planarity at its five points. The last four triangles include the centre point (fulfilling convexity conditions) but the first four exclude it (associating themselves to concavity conditions).

Table 1. Five-point heights and their Fo/Fu measured and calculated values (in nm) obtained by an estimation algorithm that is based on form models and previous two-opposite-wring-surfaces ("e" and "d") interferometric measurements, from two steel gauge blocks wrung over a fused silica platen.

Surface	l_1	l_2	l_3	l_4	l_c	*Fo*	*Fu*
1,01 (e)	9	2	50	44	28	23	26
1,01 (d)	55	53	5	-15	43	11	58
Calculated	19.75	28.25	10.75	2.25	**35.50**	**0.00**	**33.25**
1,005 (e)	71	100	66	93	68	32	2
1,005 (d)	114	82	111	82	55	59	0
Calculated	91.84	91.00	88.50	87.50	**16.00**	**75.84**	**0.00**

3. MEASURED AND ALGORITHMIC RESULTS

3.1. Recalculation from 2-sided interferometric results

A double set of five height points, taken from two automated interferometric measurements of opposite wrings, are fed within an algorithm that embed the above-mentioned form and support type modelling, in order to obtain more accurate Fo/Fu parameters than those obtained by previous one-sided interferometric measurements. Table 1 depicts the measured and obtained ("Calculated") height corrections for five-point lengths (l_1 to l_c columns) as produced at once by GBI/Mitutoyo interferometric measurement, as also the Fo/Fu adequate measurands for two steel gauge blocks (those with nominal lengths 1.01 mm and 1.005 mm).

Note: Due to a bidirectional Fu = 0, got from second gauge, it can be seemingly classified as a 'biconcave", shown that its realistic "l_c" (centre gauge length) must be presented as strictly smaller than both their individual as also unidirectional measurements. A "hidden" length that could reduce the centre value cannot be extracted from any one-sided measurements.

3.2. Rough view from coding and calculation routines

As the main strategy was to use only the numerical information gave by interferometer for each block and its wrung side, those two sets of five-point lengths obtained from measurement at opposite gauge faces were used to feed our least-square routines. Those were the best methods to deduce any tilt for both faces, and their respective first-order x-y-curvature equations, considering such little amount of previous data. Based on those calculated length variations, and on a threshold criteria limited by estimated measurement uncertainties over each of five-points, a further classifying step use such tilt/curvature information to choose the most probable from the six previously quoted generalized forms, and the most probable support triangles at both wringings.

At last, any estimated "hidden" lengths at any support face hanging points above the plate are subtracted from their respective upper five-point heights, previously obtained from direct interferometric measurements for each wring. This proposed method fit for single-sided interferometers can produce closer length values towards those from double-sided methods, with 2 σ-uncertainties at least of ±10 nm, as should be by using double-ended interferometric systems described in [3]. By this approach, we achieve a better compliance and closeness of both optical and mechanical measurand versions for same results. Both final Fo and Fu values obtained afterwards follow similar criteria of calculating differential lengths, as used in mechanical comparator checking.

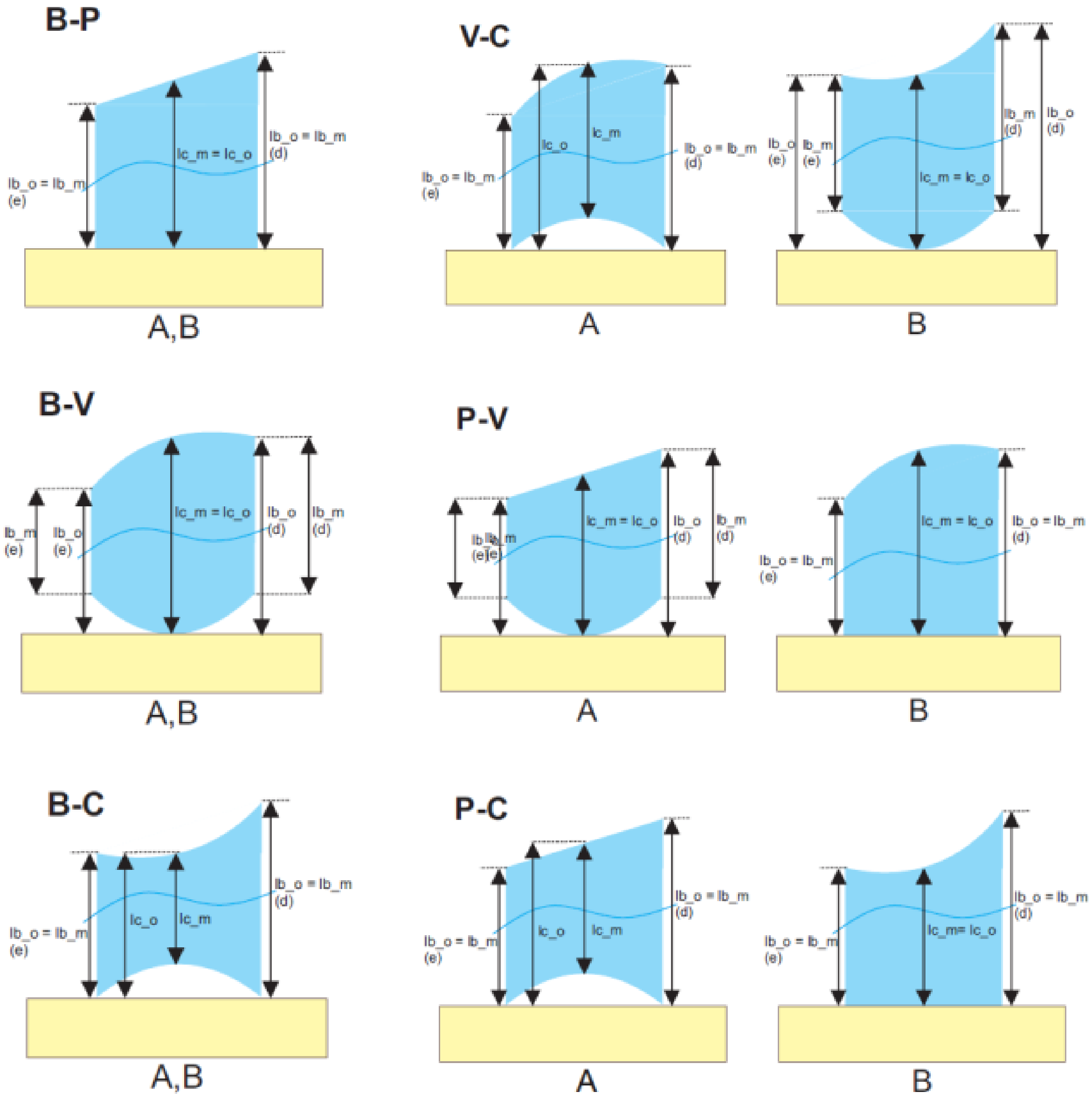

Figure 3. Six suggested “generalized form” gauge profiles wrung over ideal flat plates.

3.3. Method limitations

Correct values can only be achieved by this method if some external conditions are fulfilled. These are mainly due to material stability at objects and measurement conditions. Firstly, the support and wringing of gauges over platen should not deform both the attached and measured surfaces. It is known that thin gauge blocks made of softer materials (for instance, steel is pliable than ceramics and carbides) are prone to adapt their wringing surfaces to any relief variations on the plate surface in contact [4]. Previous analysis of such height changes could be performed to estimate this effect for any further calculations, as can be seen in [5].

Other limitation is due to GBI interferometer wavefront errors in regions far from image and gauge block centres. Their corner point measurements are sharply sensitive to such uncompensated variations. Therefore, it is advisable to take its built-in compensation step with a high-quality reference flat, designed to remove interferometer main wavefront deviations.

4. DISCUSSIONS AND CONCLUSIONS

A well-defined model and almost-realistic algorithm was proposed to calculate realistic extreme variation height lengths (Fo/Fu) at gauge block surfaces through double interferometric five-point automated measurements.

Further optical-mechanical intercomparisons must still be performed, with these measurands as its main issue, in order to validate any results obtained from this approach for national dimensional metrology laboratories. It can be seen that any isolated real-world one-sided interferometric results could not able to find more accurate corner (and centre) lengths, due to form variations on their wrung and not seen surfaces. The Table 1 results for actual gauge block interferometric measurements obtained by opposite wringings show that there can be huge length variations, caused by their form variations. For the second 1.005 mm gauge block it is presented the greater centre length variation, mainly due to its strong bi-concave form.

The measurement uncertainties for these strategies should be strongly dependent from the classified gauge form type, and from each tilt and x-y-curvature fit. For that we must take in account not only the partial uncertainties from double one-sided classic interferometric measurements, as also those components due to the calculation/estimation of curvature parameters. Nevertheless, such deductions were out the scope of this study.

It must be considered that the best 1 σ uncertainty values declared for one-sided automated length interferometric measurements at these gauge sizes, excluding the common components caused by wringing effects and phase change on reflection, amount to circa ±3.5 nm, but the shown differences between each one-sided measurements depicted at Table 1 are far greater than that. The main cause for that anomaly are their no-ideal surface forms, affecting the wringings themselves, their experimental uncertainty components been circa ±7 nm. By combining both figures we could barely cover such differences.

Therefore, we can see that the suggested approach can provide us much more reliable measured lengths and uncertainties, by design, than those obtained by any previous formless approximate methods. As a collateral result, we still potentially can achieve better measurement accuracies for centre gauge lengths, for example in severe cases of combined bi-concave and non-parallel surfaces, than those obtained from our both two-sided mechanical and ordinary one-sided interferometric methods.

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