

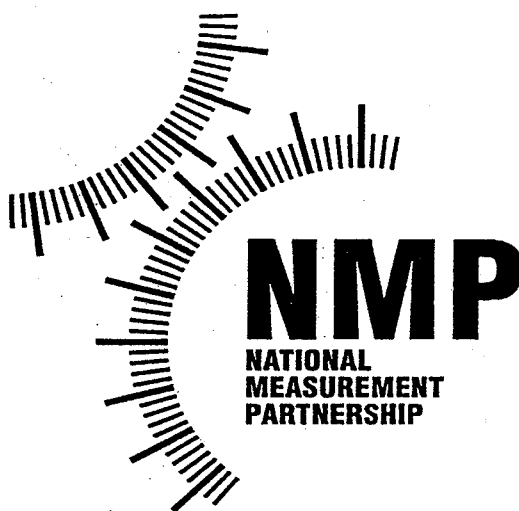
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Summary

Roundness measurement to ultra-high accuracy using mathematical-modelling techniques

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Abstract

This paper is concerned with roundness measurement using an instrument incorporating a precision, automatic rotary stage. The use of this stage permits the component being measured to be rotated through arbitrary specified angles. Measurement traces taken for each position of the rotary stage are combined to estimate both the component form errors and the instrument spindle errors. In particular, the Fourier harmonics of these errors are determined. The measurement uncertainties associated with these harmonics and with the estimated component form error and instrument spindle error are evaluated.

1. INTRODUCTION

The Talyrond 73HPR roundness-measuring instrument (Figure 1) has been developed by the National Physical Laboratory and Taylor Hobson Limited as part of the UK's National Measurement System (NMS) Programme for Length Metrology, 1996-9. The instrument is used to establish the form of a nominally circular section of an artefact.

Typical measurements comprise a trace of suppressed-radius values (radius with respect to a nominal centre) of the profile of the section. A total of m equiangularly-spaced values is recorded, where m is arbitrary, but currently equal to a maximum of 2000 and in the future likely to equal 3600.

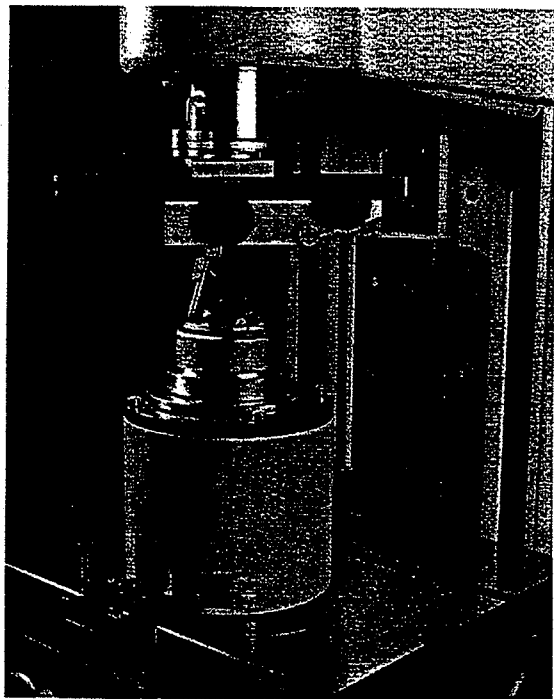


Figure 1. The Talyrond 73HPR roundness-measuring instrument.

Although the spindle of the instrument does not rotate perfectly, its rotational behaviour is highly repeatable. Accordingly, there is a systematic instrument spindle error which depends on angular position. Thus, the recorded values are not those of the component alone, but a superimposition of component form errors and instrument spindle errors. The measurements $Y(\theta)$, say, can be regarded as those of $C(\theta) + S(\theta)$, where $C(\theta)$ denotes the component form error and $S(\theta)$ the instrument spindle error, and θ is the angular position of the gauge head.

The instrument contains an indexing table which permits the component to be rotated relative to the spindle by an arbitrary angle, ϕ , say. Measurements taken in the rotated position correspond to those of $C(\theta - \phi) + S(\theta)$.

In practice, measurements are taken at several, q , say, of positions of the indexing table. The complete set of such measurements can be expressed as those of

$$Y^{(1)}(\theta) = C(\theta - \phi_1) + S(\theta),$$

$$Y^{(2)}(\theta) = C(\theta - \phi_2) + S(\theta),$$

...

$$Y^{(q)}(\theta) = C(\theta - \phi_q) + S(\theta),$$

where the indexing angles $\phi_1, \phi_2, \dots, \phi_q$ are known.

It is required to determine the component form error and the instrument spindle error.

This paper presents an approach which is based on a general theory which models the suppressed radius measurements for a set of indexing positions. The model applies to an arbitrary set of index positions. Other approaches to roundness measurement have been reviewed by Flack and Cox (1998).

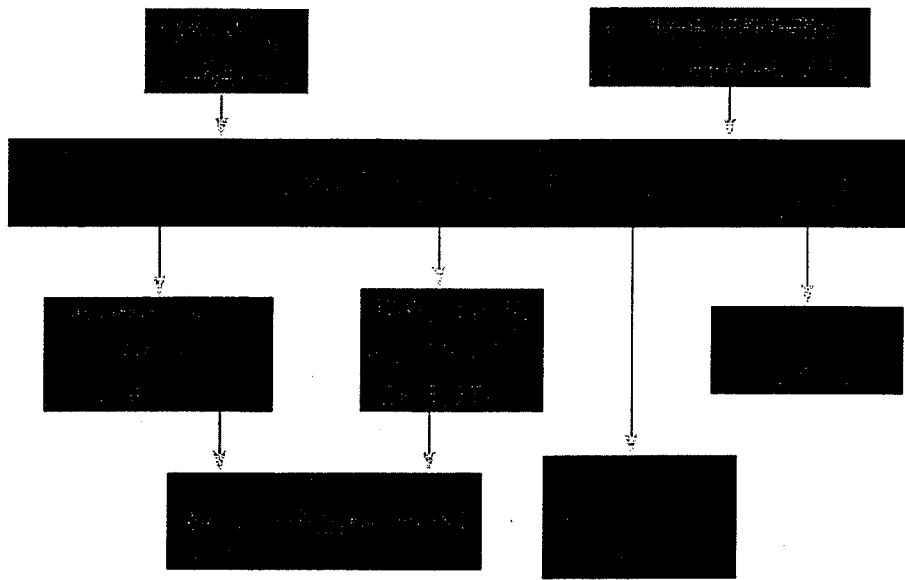


Figure 2. The main inputs and stages in the error-separation approach.

2. APPROACH

The approach, which is implemented in the computational algorithm "ROUNDALG", is based on the following steps:

1. The instrument spindle error $S(\theta)$ and component form error $C(\theta)$ are expressed algebraically in terms of Fourier series with (as yet) undetermined coefficients.
2. The numerical form of the Fourier representation is computed for each signal, i.e., the trace corresponding to each indexing position.
3. A mathematical model is constructed in the frequency domain which relates the various Fourier representations.
4. This model is solved for the Fourier representations of the component form error and instrument spindle error. The coefficients for each Fourier harmonic are calculable independently, and their "quality" and whether harmonic suppression exists are also determined.

5. The measurement errors in the raw traces are propagated through a statistical model and the uncertainties in the computed Fourier representations determined.

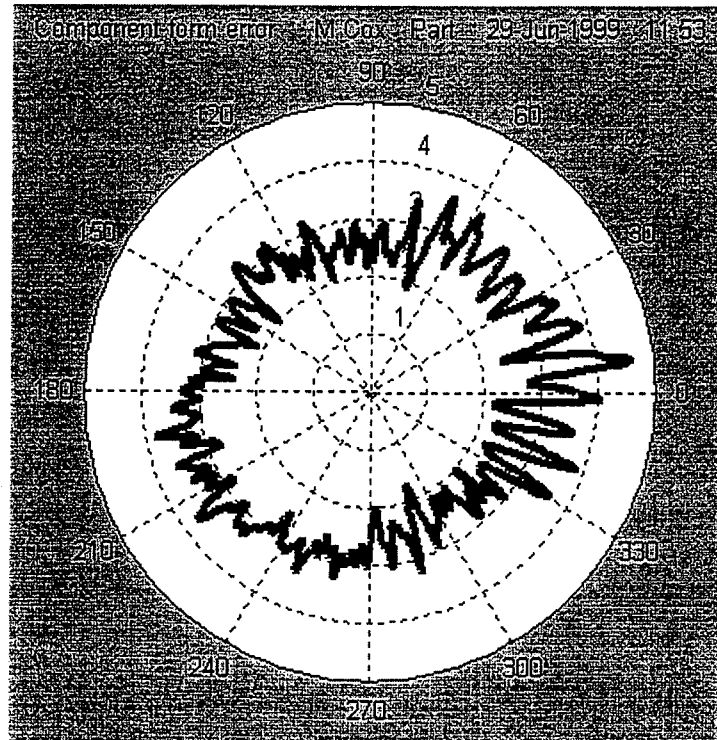


Figure 3. The component form error of a typical part determined using the indicated approach.

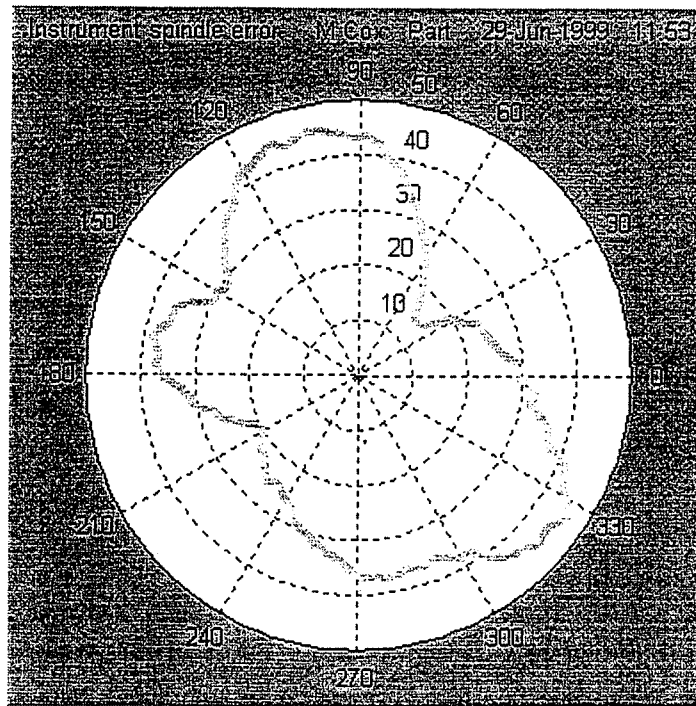


Figure 4. The instrument spindle error determined using the indicated approach.

3. FEATURES

The main features of the approach (also see Figure 2) are

1. It is model-based.
2. It is applicable to any set of indexing angles.
3. Harmonic-suppression diagnostics are provided, as is a measure of the “quality” of each harmonic.
4. An explicit formula is available for the measurement uncertainties in terms of the indexing angles.
5. The computation is carried out rapidly, taking advantage of the FFT and harmonic separation.
6. The results are validated by “reconstructing” the measurement traces from the model.

4. RESULTS

Figure 3 shows the computed component form error based on measuring a section of a nominally-spherical artefact at 22 non-uniformly-spaced indexing positions and the use of 150 Fourier harmonics in the model. Figure 4 shows the corresponding instrument spindle error; results for differing artefacts show that this error is very reproducible. Figure 5 shows one of the raw traces (in green) and its reconstruction (in red).

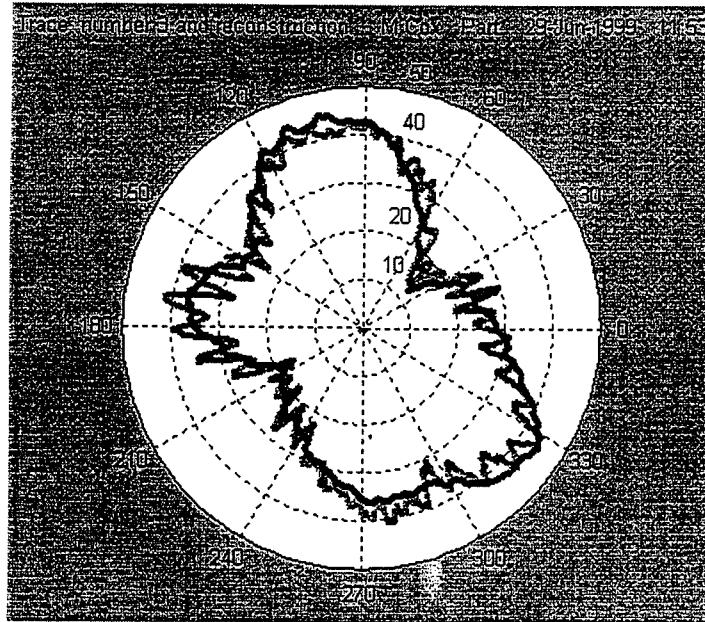


Figure 5. One of the measurement traces and its reconstruction from the model.

5. CONCLUSIONS

An approach is outlined which is based on mathematical modelling used to analyse measurements taken with the Talyrond 73HPR roundness instrument in order to determine component form error and the instrument spindle error. It is general, being applicable to any number of traces, any number of measurement points per trace and any set of indexing angles. Uncertainties are explicitly calculable.

6. REFERENCES

Flack, D. R. and Cox, M. G. Review of the literature: roundness separation techniques. Internal un-numbered NPL report, 1998.