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Identifying and Minimising Uncertainty for Experimental Journal Bearing Studies

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Over the last few decades, different experimental methods, with varying forms of data analysis, have been employed on a wide range of journal bearing types. Under these circumstances, it is not surprising that the results presented, and their accuracy, are subject to varying scatter. Many of the assessments have been rather imprecise, often using unquantified statements such as "generally good agreement with predictions." Most authors seem to have accepted that the appreciable scatter of results, especially in the dynamic oil film coefficients, was inevitable. Uncertainty is defined as the estimate of the errors. Note that the estimate may often be too optimistic because some sources of error have not been identified. This paper highlights sources of error for experimental journal studies, including some associated with the measurement system and physical misalignment. It is intended that this paper presents a coherent source of information on best practice in the field of experimental bearing research, offering a clearly prescribed methodology to estimate uncertainty and reduce error. The results of calculations of the sensitivity of the dynamic bearing coefficients to experimental errors in some commonly used rig configurations are presented. It is shown that one of the excitation schemes gives significantly lower sensitivity, but even this scheme has quite high sensitivity to measurement errors, especially phase. In conclusion, some of the critical precautions in the search for good quality results for experimental journal bearing studies are described.

Keywords and phrases: journal bearings, experimental studies, uncertainty, errors, accuracy.

1. INTRODUCTION

When the results of an experimental study are presented, theauthors need to indicate how reliable they consider the results to be. Ideally, the methodology,results and the assessment of their accuracy should be presented ina way that can be audited and reproduced. In certain circumstances, for example, in an acceptance test for a high value machine of an established design, it is common for there to be a fairly small number of results, but, as there is usually a high financial value placed on the results of the tests, it is very important that the results are accurate and auditable. The way in which the measurements are made and the way the results are calculated from the test measurements may be closely regulated [1]. Whilst this specific standard [1] focuses on a particular application area, the methods are general and are well described.

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Over the years, there have been numerous experimental journal bearing studies with measurements made by different workers on different types of bearings in different ways, with results calculated by different methods. In the circumstances, it is not surprising that the results and their accuracy have been assessed in many different ways. Many of the assessments have been rather imprecise, often using unquantified statements such as "generally good agreement with predictions." Most authors have seemed to accept that appreciable scatter of results, especially in the dynamic oil film coefficients, was something inevitable. This was noted in a survey of over 100 experimental cases [2], where the authors stated in "some general comments" that "*these (dynamic) coefficients generally exhibit a great deal of scatter—both within a particular work and from work to work*." However, a few authors [3, 4] have described their work on the identification and reduction of uncertainty, but much more remains to be done.

Typically, the problem is that few authors have given enough information for later investigators to benefit from their experiences in attempting to obtain high quality results.

This aspect was commented on in [2], where it was stated in "Conclusions" that "*There are many sources of experimental data available in the literature. Much of this data is of some use to both analyst and experimentalist. Some of the weaknesses which should be addressed by future experimental works include:*

(1) *Complete information on parameter uncertainty*
(2) *Providing data on the thermal boundary conditions*
(3) *Tabular presentation of results, and/or equation coefficients for curve fits to plots*
(4) *Precise, accurate measurements of dynamic coefficients under well documented operating conditions.*"

Many commercial organisations have adopted formal quality procedures, for example, ISO 9001. The basic aim of these procedures is to provide proper scrutiny, control, and documentation of what is to be done and, when completed, documentation and archiving of what has been done. The preparation of a quality document involves serious thought about what is important and ensures that it is recorded. Swanson and Kirk [2] noted that published records were oftenlacking in the details needed for others to benefit from the work described, and there was sometimes doubt about the quality of the results. The adoption of suitable quality systems by organisations working in this area would go far in overcoming these difficulties.

The object of this paper is to present some ideas on how the quality of results, especially for dynamic oil film coefficients, might be improved in future work, and meet some of the requirements identified above. It is hoped that this paper may promote discussion on best practice, as most authors have clearly thought carefully about various aspects of the task, but there seems to be no single document that summarises current best practice. We use the following notation:

(i) B_{xx}, B_{xy}, B_{yx}, B_{yy}: nondimensionalised linear velocity coefficients,
(ii) c: bearing clearance (m),
(iii) E_{xx}, E_{xy}, E_{yx}, E_{yy}: nondimensionalised linear stiffness coefficients,
(iv) F_x, F_y, F_{x1}, F_{y1}, F_{x2}, F_{y2}: oil film forces (N),
(v) i: $\sqrt{(-1)}$,
(vi) n_1, n_2: ω_1/Ω, ω_2/Ω,
(vii) R_{xx}, R_{xy}, R_{yx}, R_{yy}: nondimensionalised complex oil film receptance,
(viii) W: bearing load (N),
(ix) x, y, x_1, y_1, x_2, y_2: oil film perturbations (m),
(x) $(xR+ixI)\ldots$: complex representation of x and so forth,
(xi) Z_{xx}, Z_{xy}, Z_{yx}, Z_{yy}: nondimensionalised complex oil film impedance,
(xii) ω: excitation frequency (rad/s),
(xiii) Ω: journal rotational speed (rad/s).

2. ERROR AND UNCERTAINTY

Every measurementhas error, which is thedifference between the measured value and the true value. As the true value is unknown in a practical situation, so is the error, but it is useful to make an estimate of the error. This paper uses the usual definition of "uncertainty" to mean the estimate of the error. In most cases, the results of several measurements are used together to obtain a calculated final result, and the same definition is suitable for the uncertainty in the result. The uncertainty in each measurement will contribute in some way to the uncertainty in the final result, and the contribution from each measurement will generally be different. It is most important to note that uncertainties as defined above are only estimates of the errors, and may bear little relation to the true errors. It is very easy to overlook contributions to the error and obtain a grossly optimistic estimate of the uncertainty.

There are essentially three types of error. The first of these occurs when some item is only measured once, and the real value under the current working conditions may be different, either due to incorrect original measurement or due to subsequent change. This type of error is sometimes called "bias." It causes incorrect results, but does not cause scatter in repeated measurements under the same conditions. The second type is due to lack of precision in making a measurement, and can be identified by the variance of repeated measurements (ideally by different methods/instruments) under the same conditions (scatter). Kline and McClintock [5] consider this in more detail and define two types of experiment, the first where a single measurement is made, and the second where many independent measurements are made. When many independent measurements are made, it is possible to use statistical techniques to both estimate and reduce the uncertainty. This is not as easy as it sounds, and the best that can be done in most circumstances is to make repeated measurements with the same setup, though this does not reduce any error due to the setup itself. For example, many tests could be made on a particular bearing, but any uncertainty due to the geometry of test bearing itself is not reduced, this is covered later. Equally, multiple tests made with the same instruments are not totally independent, as some of the errors will be associated with the instruments themselves. However, wherever possible, multiple tests should be made, as at least some of the uncertainty can then be reduced by statistical methods. The more independent the tests, the more the uncertainty can be reduced. An example of independent measurements could be the journal position, where one measurement could be made from the fixed bush-shaft probes, the other from the rotating shaft-bush probes.

Additionally, independent tests allow more than one estimate of both the value and the uncertainty of the measured quantity. If the uncertainty bands from two or more independent tests do not overlap, it shows that some contribution to the uncertainty has been omitted and that further investigations should follow. Where truly independent tests are not possible, the usual method of reducing uncertainty in the fixed (single measurement) items is to perform calibrations against external standards. In this case, the uncertainty on the fixed items is the combination of the uncertainty in the standard and the uncertainty in the calibration process.

The third type could reasonably be called mistakes. Examples include the use of the wrong settings, wrong calibrations, inappropriate calculation methods, and so forth, the only way of avoiding such errors is care. Proper prior consideration and documentation of theexperimental procedure are very helpful and are required in most quality systems.

3. UNCERTAINTIES AND ERRORS IN MEASUREMENTS

Some sources of uncertainty are well recognised and discussed, such as those arising from the inevitable and usually small differencebetween an instrument reading and the true value, or in the achievement of a particular physical dimension or running condition. However, it is most important that all the possible sources of error are identified, or the results may be grossly incorrect, even though the estimated uncertainty is acceptable. There are many similarities here with risk assessment, unless a risk is identified, its possible effects will be ignored, with potentially disastrous results.

Errors due to changes in supposedly fixed parameters are particularly difficult to detect, especially if they arise as a result of the running conditions, and return to their original values at the end of the tests. An example could be a change in the bearing clearance as a result of differential expansion between the journal and the bearing bush/housing due to dissimilar temperatures or materials. Other examples include a change in shape of the bearing as a result of the test loads [6] or under the thermal gradients that arise in the bearing and its housing during running [7, 8]. It is now known [9, 10] that these fairly small changes in shape have a profound effect on the dynamic characteristics of the bearing.

Other sources of error arise because the understanding (model) of the test object is inadequate, or that the test regime violates some (possibly unidentified) requirement. A now well-recognised difficulty arising from the test regime is the effect of nonlinearity in the determination of the linearised dynamic oil film coefficients. It is well known that linearity needs small perturbations about the mean running position, but few experimentalists have declared how small the perturbations should be, or to have tested the results in some manner to establish whether linear conditions had been obtained. Some, of course, have recognised this and even declared the linear and nonlinear components [11, 12]. It is to be hoped that the experimentalist has thought carefully (with appropriate calculations) about the physical arrangements for the tests and has recorded the justification for any design decisions.

The measurement process has many possible sources of error. The first item in the measurement chain is the transducer converting the physical variable into an electrical signal. In order to reduce errors, these are usually calibrated before building into the rig, and often in situ as well. However, such calibrations usually only relate to static properties, and it will be shown later that phase errors are normally responsible for most of the dynamic measurement errors. For proper identification of errors, such calibrations should be dynamic, covering the working frequency range. This may involve the use of specialist knowledge and equipment. If possible, in situ calibrations should extend from the primary quantity under consideration to the displayed value in the working setup. Despite advances, the rest of the instrumentation/measurement process also has its problems, but these are not often discussed.

An ideal measurement system would allow perfect identification of the signals of interest and would take no account of any other signal. Any real system has to rely on measurements of signals that may have been distorted during acquisition or processing, and that may have had spurious signals added. It is most important that the experimentalist understands the issues raised and takes measures to mitigate their effects. Some of these effects are mentioned later. It is sufficient to note here that many of them are considered to be in the field of electrical and electronic engineering and are not taught in most mechanical engineering courses. The best an inexperienced experimentalist can usually do is to confer with knowledgeable colleagues or seek information in the literature. There is vast literature on instrumentation and measurements, ranging from quite general introductions on the subject to manufacturer's information on specific products. The problem is that the information needed in the assessment and subsequent use of a suitable system will be scattered over a range of publications, and many of these will assume prior knowledge of some aspects of electrical/electronic engineering. It is usually necessary to consult a range of references in order to build up a picture of what needs to be done.

Generally, the accuracy of instrumentation has improved over the years, but it is still very easy to obtain erroneous results due to a lack of a proper understanding of the underlying issues.

4. UNCERTAINTY IN RESULTS

In calculations of the propagation of uncertainty from the measurements to the final result, there are published procedures to assist the investigator, for example, in [1]. The contribution of uncertainty from each measurement is usually taken as the product of the uncertainty and the sensitivity of the result to that uncertainty. There are essentially two ways in which it is possible to estimate this sensitivity. The first is analytical, where it is possible to partially differentiate the equation relating the result and the measurements. In this direct method, the relationship between the uncertainty in the result and the uncertainty in the measurements is fairly obvious. The second method is numerical and indirect, in which the established procedure for calculating the results from the measurements is used as it stands, the values entered for the various measurements being perturbed in turn. In the extraction of the linear dynamic oil film coefficients, this process normally includes the inversion of a matrix, and the effect of altering the value of a measurement on the results may be far from obvious.

In the assessment of a new procedure, there may be no experimental measurements available, in which case, it is necessary to start from some assumed results and work backwards to the measurements that would have produced the results.

5. UNCERTAINTIES IN LINEAR DYNAMIC OIL FILM COEFFICIENTS: AN EXAMPLE

The ideas above have been applied to give guidance on the choice of configuration and test method for a bearing rig. The object was to choose the method giving the lowest sensitivity to errors, and hence the highest potential accuracy. The numerical values presented later arose during this part of the design process and also showed what features need particular attention in the quest for high accuracy. The numerical results are to be regarded as indicators rather than values that will necessarily be achieved.

The dynamic oil film coefficients describe the relationship between oil film force and displacement (E terms) and velocity (B terms) of the perturbation. There are two main approaches indetermining the dynamic oil film coefficients. Thefirst involves examining a rotor dynamic system containing the test bearing and extracting the effect of the rotor, and so forth, from the combined response to obtain the properties of the test bearing. The second, which is covered in this paper, uses an arrangement in which the test bearing dynamic properties dominate. For the latter system, the test method involves excitation by known forces and observing the resultant perturbation.

In this study, four of the many excitation methodologies reported in the literature have been assessed. All use successive application of a different forcing regime, employing two different sinusoidal dynamic excitations to give two different orbits, with measurements and subsequent representation of the values in the frequency domain. The choice of the frequency domain representation of the dynamic quantities is slightly subjective, but it is plausible to believe that a frequency domain measurement, which is essentially a special sort of average of many cycles of the variable, is likely to be the best practical indicator of the variable.

The choice of measurement direction is subjective, most workers seem to have used the oil film thickness displacement transducers set horizontally "x" and vertically "y." This has been adopted without further analysis as it seems plausible that the best directions for the measurements should be the same as those implied by the definition of the dynamic coefficients. It was therefore assumed that the oil film displacements were measured in the "x" and "y" directions irrespective of the direction of the excitation.

In selecting the test methods for assessment, there are two widely used arrangements for a bearing rig, the first with the shaft floating and the test bearing grounded. The second, and more common arrangement, uses a fixed axis shaft with a floating test bearing. In the floating shaft arrangement, the most convenient way of applying the dynamic excitation is from a second shaft rotating within the test shaft and carrying unbalance weights. The excitation shaft has its own drive and can rotate in either direction at a speed set by the experimentalist. The speed need not be the same as the test shaft. It is not necessary that the two tests are conducted at the same frequency, but, for the assessment, it was assumed that the same excitation frequency was used. This way of applying the dynamic excitation has been called the unbalance method.

In the floating bearing arrangement, actuators acting on the bearing bush supply the dynamic excitation forces. Three variants were chosen for analysis as follows.

(i) Method 1: excitation in the "x" and "y" direction, $(0^\circ, 90^\circ)$, using the same excitation frequency. It would seem plausible that this should be a good method, as both the forces and displacements are measured in the directions implied by the definition of the coefficients. In principle, this arrangement can also supply any reasonable forcing regime (including simulation of the unbalance method) by the use of both actuators at once. For the purposes of these calculations, it was assumed that only one exciter was used at a time at the same excitation frequency, though it is also possible to use different frequencies.

(ii) Method 2: excitation at $\pm 45^\circ$, the same frequency. The actuators are set at $\pm 45^\circ$ to horizontal, which leads to a more compact and convenient placing of the actuators than in Method 1. In principle, this arrangement can also provide any reasonable forcing regime by the use of both actuators at once. For the purposes of these calculations, it was assumed that only one exciter was used at a time at the same excitation frequency, though it is also possible to use different frequencies.

(iii) Method 3: excitation at 45°, using a single actuator set at 45° to horizontal and using two different excitation frequencies. It has the advantage of having only one actuator, so reducing size and cost.

The frequency of excitation chosen for any experiment is also subjective. If the dynamic coefficients are frequency-sensitive, it would be useful to conduct tests at a number of different frequencies. It is known that the lower the frequency of excitation is, the more accurate the phase measurements need to be, and the value chosen for the assessment (0.3 of the shaft rotation frequency for single frequency excitation, and, 0.2 and 0.4 for the single-actuator example) could be regarded as typical rather than end-of-range. Worst-case sensitivities could therefore be substantially greater than those presented.

The coefficients chosen for this example were for single-arc bearings, though it is known that multiarc bearings might show higher sensitivity to errors. Values for an eccentricity ratio of 0.4 and 0.8 were adopted as these are typical values of a likely test range. It is considered reasonable to assume that some bearings under some test regimes may have considerably higher sensitivities than the values reported here. The values adopted were as in Table 1.

Next, a calculation procedure was established to give the displacements arising from the specified excitation regimes. The relationship between the linear dynamic coefficients, the forces, and the displacements is shown below in the usual

Table 1: Selection of coefficients. Note that in this representation x is horizontal and y is vertical.

ε	E_{xx}	B_{xx}	E_{xy}	B_{xy}	E_{yx}	B_{yx}	E_{yy}	B_{yy}
0.4	1.8	2.5	1.0	−1.7	−3.9	−1.7	2.5	7.3
0.8	1.5	0.9	−0.5	−1.5	−4.0	−1.1	7.9	7.3

manner:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{W}{c}\left\{\begin{bmatrix} E_{xx} & E_{xy} \\ E_{yx} & E_{yy} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} + \frac{1}{\Omega}\begin{bmatrix} B_{xx} & B_{xy} \\ B_{yx} & B_{yy} \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}\right\}. \tag{1}$$

For a particular sinusoidal excitation of frequency ω, the relationship may be rewritten in complex number notation as in

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{W}{c}\begin{bmatrix} E_{xx} + \left(\frac{i\omega}{\Omega}\right)B_{xx} & E_{xy} + \left(\frac{i\omega}{\Omega}\right)B_{xy} \\ E_{yx} + \left(\frac{i\omega}{\Omega}\right)B_{yx} & E_{yy} + \left(\frac{i\omega}{\Omega}\right)B_{yy} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}. \tag{2}$$

This may be rewritten yet again in terms of complex stiffness (impedance) as in

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{W}{c}\begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}, \tag{3}$$

where $Z_{xx} = E_{xx} + (i\omega/\Omega)B_{xx}$, and so forth.

As it is intended to calculate the displacement arising from a chosen dynamic forcing regime, (3) is now rearranged in terms of complex receptance in

$$\begin{bmatrix} x \\ y \end{bmatrix} = \frac{c}{W}\begin{bmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{bmatrix}\begin{bmatrix} F_x \\ F_y \end{bmatrix}, \tag{4}$$

where $\left[\begin{smallmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{smallmatrix}\right] = \left[\begin{smallmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{smallmatrix}\right]^{-1}$.

It should be noted that all the forces above are oil film forces, whilst the applied forces are the combination of the inertia forces and the oil film forces. This distinction is very important in the single-actuator method. Except in calculations on the single-actuator method, where it is essential to include inertia terms, these were omitted from the calculations as having a small effect in a small bearing.

At the end of these calculations, values of the responses (x, etc.) corresponding with the specified forcing (F_x, etc.) were declared. These would correspond exactly with the results that would have been obtained in a physical test and include

(i) $F_{x1}, F_{y1}, x_1, y_1, \omega_{1/\Omega}$ from calculation 1,
(ii) $F_{x2}, F_{y2}, x_2, y_2, \omega_{2/\Omega}$ from calculation 2.

The first step in the derivation of the coefficients is to write the equations relating the coefficients and the test results, and the second is to perform the calculations. As the tests will have been made under specified force conditions, whereas the coefficients refer to specified displacement conditions, the use of an inversion of a matrix is required. It would be possible to write the equations in the form of an 8*8 matrix, or as two separate 4*4 matrices. The latter would seem to lead to simpler calculations and has been adopted in this analysis. The resulting relationships are shown in

$$\begin{bmatrix} F_{x1}R \\ F_{x2}R \\ F_{x1}I \\ F_{x2}I \end{bmatrix} = \frac{W}{c}\left[M\right]\begin{bmatrix} E_{xx} \\ E_{xy} \\ B_{xx} \\ B_{xy} \end{bmatrix}, \qquad \begin{bmatrix} F_{y1}R \\ F_{y2}R \\ F_{y1}I \\ F_{y2}I \end{bmatrix} = \frac{W}{c}\left[M\right]\begin{bmatrix} E_{yx} \\ E_{yy} \\ B_{yx} \\ B_{yy} \end{bmatrix}, \tag{5}$$

where $x = xR + ixI$, and so forth; and

$$\left[M\right] = \begin{bmatrix} x1R & y1R & -n1^*x1I & -n1^*y1I \\ x2R & y2R & -n2^*x2I & -n2^*y2I \\ x1I & y1I & n1^*x1R & n1^*y1R \\ x2I & y2I & n2^*x2R & n2^*y2R \end{bmatrix}, \tag{6}$$

$n1 = \omega 1/\Omega$, $n2 = \omega 2/\Omega$.

It should be noted that there is the same relationship between the "y"coefficients and the "y" forces as between the "x" coefficients and the "x" forces. The solution of the equations therefore requires that the "x" oil film force set and the "y" oil film force set are different.

In the single-actuator method, the applied forces in the "x" and "y" directions are identical, so that any difference between the oil film forces is due solely to different bearing inertia forces in the "x" and "y" directions. In a bearing of about 125 mm diameter, as in a proposed bearing rig, the inertia forces for a practical size of bearing/housing are 2% or less of the applied force for normal excitation frequencies. This means that the oil film forces in the "x" and "y" directions are very nearly equal in both tests. This leads to a very ill-conditioned matrix and very high sensitivity to errors in the measurements, therefore this method is unsuitable for a small bearing rig and the results are not presented. There is a size effect, and in a large bearing rig (shaft diameter of the order of 500 mm), the inertia terms could give an acceptable difference between the oil film forces.

The next step is the perturbation of each of the "results" in turn. The perturbation chosen was 1% of the value of the

Table 2: Results of error analysis. $\omega/\Omega = 0.3$ (dynamic excitation at 15 Hz (single actuator 10/20 Hz) for a bearing running at 3000 rpm). Individual "measurement" errors are 1%/0.57°.

Excitation method	Mean errors in E terms (%)	Mean errors in B terms (%)
$(0^\circ, 90^\circ)$, $\varepsilon = 0.4$	1.9	6.0
$(0^\circ, 90^\circ)$, $\varepsilon = 0.8$	2.3	12.1
$\pm 45^\circ$, $\varepsilon = 0.8$	7.1	22.5
Unbalance, $\varepsilon = 0.8$	7.4	26.0
Single 45° actuator	Unacceptably high in a small bearing rig	Unacceptably high in a small bearing rig

variable, represented as a vector in the Argand plane, acting either in line with the vector (value$*$1.01) or at right angles to the vector (value$*(1+0.01i)$). The perturbations represent amplitude error (1%) and phase error (0.57°), respectively. The choice of perturbation is arbitrary, but was adopted as being representative of what could be achieved with care in a real experiment, and so gives a direct indication of the errors to be expected. The sensitivity is the ratio of the changes in the coefficients divided by the changes in the "measurements," so the coefficient errors can be scaled accordingly when the detail of the error in the measurement system is known. The next step is the recalculation of the coefficients arising from each of the perturbed inputs and analysis of the errors.

The results are summarised in Table 2. The calculation method, which is described in more detail in the appendix, takes the total error in a particular coefficient as the square root of the sum of squares of the error arising as a result of each individual perturbation. This was converted to the "%" of the initial value and the mean of the "%" values presented. It was found that the velocity (B) terms were more sensitive to errors (especially phase errors) than the stiffness (E) terms, so the results are shown separately.

It is seen from the first two examples that the higher eccentricity ratio leads to higher errors, notably in the velocity terms. The $(0^\circ, 90^\circ)$ method leads to the lowest sensitivity to errors of any of the methods considered and so is to be preferred. Similar analyses with other example coefficient sets showed considerable variations in sensitivity, with some having higher sensitivity than reported in this paper, but the ranking of the methods in terms of sensitivity to errors remained unchanged.

Even using this method, in order to measure the velocity terms to an acceptable accuracy at higher eccentricity ratios and with possibly more sensitive coefficients, or with a lower excitation frequency, the accuracy of the individual measurements (especially of phase) needs to be considerably better than that assumed for the sensitivity assessment. Amplitude errors would probably need to be 0.2% or better, while phase errors would probably need to be 0.1° or better. Such accuracy is difficult to achieve in the face of the generally low signal-to-noise ratio. However, modern instrumentation with a good quality digital analyser as the final module (or the PC equivalent) should give acceptable results as long as it is carefully chosen, and the problems in the rest of the setup are well identified and controlled.

On the assumption that "Method 1" was the best choice, the effects of certain build errors in this arrangement were explored in the same manner. The errors considered were angular misalignments of 0.01 radians in the "XY" plane of each of the actuators, and each of the oil film thickness displacement probes. It was found that the pattern of sensitivities was very different from the "measurement error" set and the detail of both sets of results is shown in the appendix and summarised below.

In principle, any random component of measurement error can be reduced by repeated measurements and subsequent statistical analysis. However, it would be better to improve the general quality of the measurements by other means in order to include the bias component also. On the other hand, the misalignment error cannot be reduced by statistical means, and the only way to reduce the effect is to reduce the build error.

For the $(0^\circ, 90^\circ)$ method and for the errors (1%/0.57°) specified above, a coefficient-by-coefficient numerical summary is shown in Table 3. The error values shown are scaled values of the sum of squares of the individual errors. The corresponding combined error is also shown. The errors arising from build errors are shown in the same way in order to allow comparisons. Of particular note is the dominant effect of "Y" actuator misalignment on the E_{xy} term. The significance of the error in each coefficient will depend on the use made of the coefficient set. A descriptive summary, coefficient by coefficient, is given in Table 4.

6. THE REDUCTION OF UNCERTAINTY

In the example above, an obvious way to reduce the uncertainty in the velocity terms would have been to use a higher dynamic excitation frequency. Many workers have used synchronous excitation, but all choices have their problems. Synchronous forcing has the specific problem that it can result in a significant temperature gradient across the diameter of the test shaft, resulting in a thermal bend in the test shaft [13]. The effect on the results depends on the experimental setup.

It is generally accepted that the dynamic oil film coefficients in tilting pad bearings are frequency sensitive, and some workers believe that this is also true in fixed geometry bearings. This suggests that it is necessary to conduct tests over a reasonable frequency range, and thetechniques used should be sufficiently robust to allow this. Multiple tests also

TABLE 3: Summary of error results. Note that individual measurement errors are 1%/0.01 radian, individual misalignments 0.01 radians in the XY plane. Error fig is (change in coefficient°100)ˆ2 to 1 decimal place.

	E_{xx}	B_{xx}	E_{xy}	B_{xy}	E_{yx}	B_{yx}	E_{yy}	B_{yy}
Amplitude measurements	5.8	5.7	1.2	15.1	88.7	30.7	159.3	270.9
Phase measurements	0.5	66.1	1.4	13.7	2.6	998.3	23.9	1806.6
All measurements	6.3	71.7	2.6	28.8	91.3	1028.9	183.2	2077.5
X-actuator misalignment	0.0	0.0	0.0	0.0	2.3	0.8	0.3	2.3
Y-actuator misalignment	16.0	1.2	62.4	53.3	0.0	0.0	0.0	0.0
X-displacement probes misalignment	0.0	0.0	2.3	0.8	0.0	0.0	16.0	1.2
Y-displacement probes misalignment	0.2	2.3	0.0	0.0	62.4	53.3	0.0	0.0
All misalignments	16.3	3.5	64.7	54.1	64.7	54.1	16.3	3.5
All errors	22.6	75.2	67.2	82.9	156.0	1083.0	199.5	2081.0

TABLE 4: Descriptive summary of coefficients.

Coefficient	Observation
E_{xx}	The biggest single contribution to the error arises from misalignment of the Y actuator
B_{xx}	The biggest single contribution to the error arises from the measurement errors, especially of phase
E_{xy}	The dominant error arises from misalignment of the Y actuator This term is often regarded as particularly important in stability assessments
B_{xy}	The biggest single contribution to the error arises from misalignment of the Y actuator
E_{yx}	The biggest single contribution to the error arises from the measurement errors, especially of amplitude, but the error due to misalignment of the Y displacement probes is not far behind
B_{yx}	The dominant contribution to the error arises from the measurement errors, especially of phase
E_{yy}	The dominant contribution to the error arises from the measurement errors, especially of amplitude, though there is a small contribution from misalignment of the X displacement probes
B_{yy}	The dominant contribution to the error arises from the measurement errors, especially of phase

allow the possibility of the use of statistical methods to reduce uncertainty.

7. THE REDUCTION OF ERRORS

A parallel and potentially more powerful way to reduce errors is to achieve better understanding of the factors affecting the errors in the experimental setup and the measurements. The following comments refer specifically to the instrumentation setup and some of its problems. As an example, many transducer systems use a high-frequency carrier signal and subsequent lowpass filtering (inductive probes, LVDTs and some strain gauge systems) and have their upper cutoff frequency specified in terms of the -3 dB point. At this frequency, the response is 30% down, and there is normally a phase shift of 45°. This is far too much error for such purposes of dynamic oil film coefficient determination, and the useable frequency range is far less. For even moderate accuracy with a phase error of 0.57°, the upper useable frequency is only about 1% of the cut-off frequency. For higher accuracy, the frequency range is reduced in proportion. A similar effect occurs at low frequencies in piezo-electric accelerometers, and in any system using a highpass filter to remove standing DC. The useable frequency is therefore much less than the published -3 dB range, so it is very important to interpret the frequency range restrictions correctly. If necessary, the errors can be calibrated and corrected. It seems that this is seldom done.

A very common difficulty is noise on the signals. This can arise at the measurement interface itself, for example, at proximity probes due to the rotation of the shaft, this will be repetitive at shaft speed and can, in principle, be compensated. Spurious signals at mains frequency are commonplace and can arise in three different ways. The first way is capacitive, but is usually easily cured by the use of screened signal leads. The second is electromagnetic, and is the result of the electromagnetic field surrounding adjacent electrical motors, heavy current leads, and so forth, coupling with the signal circuits. Electromagnetic screening at mains frequency is difficult and rarely very effective. The best plan is usually to arrange sufficient spatial segregation of the power and signal components. The third route is through the signal common. Although it is not the only way that noise currents can infect the signal common, the signal common is often internally linked to the safety earths in individual items of equipment, and the safety earths may well be at different potentials. These potentials are usually at mains frequency, and the problem is often referred to as an earth loop problem. The method used to overcome the problem will depend on the detail of the arrangement. It is not acceptable to run with a completely floating system for safety reasons.

Whatever the source of spurious signals might be, it is important that their presence can be detected and dealt with. Even when the more easily controlled noise sources are eliminated, it is usually necessary to use some form of signal averaging/windowing/filtering to obtain acceptable results. Digital measurement systems have the additional problem of aliasing unless appropriate prefiltering is used, but this is often omitted in low-cost PC-based systems. Additionally, systems using sequential sampling introduce time skew into the results, with exactly the same effect as phase errors. In the context of the extraction of the dynamic bearing coefficients, a time skew of more than about 10 μs between the most separated dynamic signals is unacceptable. When all the sources of error have been identified and controlled as well as possible, there will be a residual uncertainty in each measurement, which cannot be reduced. This is true uncertainty and is the starting point for calculations of the uncertainty in the final result.

8. DISCUSSION

It has been noted that few authors give sufficient information for later workers to benefit from their experiences, whether this is under the constraints of publication space or for some other reason is not clear. However, it would clearly be valuable if some way of disseminating best practice can be found. It is hoped that the comments in this paper on some sources of errors will be useful.

Many workers have noted the presence of significant scatter in their results; this type of random error can be reduced by statistical means, and typically arises from noise in the measurements. Some results show different trends for the theoretical and experimental results, and results from different workers are often at variance. These differences will be due to systematic errors, which may be in either the theoretical or experimental results. It may not be easy to identify which results may be the more reliable: this is evidence of how difficult it is to obtain accurate results.

Measurement techniques have evolved over the years, and have influenced the ways in which investigations have been conducted. The quality of the results has always largely depended on the availability of suitable measurement tools. Good experimental results can only be obtained if the experimental apparatus, instrumentation, and procedures have been properly researched and well chosen. Some of the material presented in this paper has arisen from a design study for a new bearing rig, which is intended to be of the highest accuracy. In particular, it has been found that significantly lower uncertainty in the dynamic coefficients can be obtained by excitation at (0°, 90°), rather than in some other reported methods. Even so, the accuracy required, especially in phase, is only achievable with considerable care. It has also been found that the time skew and accompanying phase error arising from sequential sampling of the various signals arising during the extraction of the dynamic coefficients are sufficient to give rise to unacceptable errors. In consequence, the rig will use parallel sampling, which eliminates this problem, despite its higher cost. The effect of phase shift in the filters associated with many of the items in the instrumentation chain has been shown to be much more serious than the casual observer might imagine, this effect is not widely reported. The single-actuator, two-frequency method, although potentially very attractive in reducing the cost of the rig, has been found unsuitable.

9. CONCLUSIONS

It has been shown that it is very important to distinguish between uncertainty, which is the estimate of the error, and the true error, which includes unidentified sources of error. A parallel with risk assessment has been drawn, indicating the problems of unidentified risks/errors. It has been noted that the estimate may often be too optimistic because some sources of error may not have been identified, and it is believed that hidden errors may well account for the widely reported scatter and variance of results in experimental bearing studies.

Certain sources of error associated with the measurement system have been described, mostly to do with phase error, and do not appear to have been described in experimental journal bearing study literature. This may be because they are generally considered to be in the domain of electrical/electronic engineering, and may indicate the need for a greater breadth of knowledge than has traditionally been considered sufficient for workers in the field of experimental bearing studies. It is suggested that one way of overcoming this problem could be the better dissemination of information on best practice, and more widespread adoption of quality systems.

A worked example arising from a design study for a proposed bearing rig has shown that some methods give lower sensitivity to errors than others. Even the preferred method requires high build accuracy and high accuracy in the measurements, especially in phase.

APPENDIX

This appendix explains the method and presents the results for one of theassessments, the other assessments were identical in procedure, though with different parameters. The error-analysis method is straightforward, and is outlined in

Table 5: Worked example.

Rows									
5	$\varepsilon = 0.8$, $n = 0.3$	E_{xx}	B_{xx}	E_{xy}	B_{xy}	E_{yx}	B_{yx}	E_{yy}	B_{yy}
6	Initial values	1.5000	0.9000	−0.5000	−1.5000	−4.0000	−1.1000	7.9000	7.3000
7									
8	Recalculated coefficients for amplitude perturbations								
9	$x1*1.01$	1.4819	0.8831	−0.4944	−1.4797	−3.9513	−1.0709	7.8838	7.2514
10	$x2*1.01$	1.5033	0.9082	−0.5057	−1.5207	−4.0093	−1.1188	7.9164	7.3495
11	$y1*1.01$	1.5033	0.9082	−0.5007	−1.5056	−4.0494	−1.1300	7.9164	7.3495
12	$y2*1.01$	1.4967	0.8919	−0.4944	−1.4797	−3.9513	−1.0709	7.8057	7.1796
13	$F_{x1}^{*}1.01$	1.5150	0.9090	−0.5050	−1.5150	−4.0000	−1.1000	7.9000	7.3000
14	$F_{y2}^{*}1.01$	1.5000	0.9000	−0.5000	−1.5000	−4.0400	−1.1110	7.9790	7.3730
15	(Change in coefficient*100)^2								
16	$x1*1.01$	3.2761	2.8561	0.3136	4.1209	23.7169	8.4681	2.6244	23.6196
17	$x2*1.01$	0.1089	0.6724	0.3249	4.2849	0.8649	3.5344	2.6896	24.5025
18	$y1*1.01$	0.1089	0.6724	0.0049	0.3136	24.4036	9.0000	2.6896	24.5025
19	$y2*1.01$	0.1089	0.6561	0.3136	4.1209	23.7169	8.4681	88.9249	144.9616
20	$F_{x1}^{*}1.01$	2.2500	0.8100	0.2500	2.2500	0.0000	0.0000	0.0000	0.0000
21	$F_{y2}^{*}1.01$	0.0000	0.0000	0.0000	0.0000	16.0000	1.2100	62.4100	53.2900
22	Sum of rows (15:20)	5.8528	5.6670	1.2070	15.0903	88.7023	30.6806	159.3385	270.8762
23	1/100*Sqrt(sum)	0.0242	0.0238	0.0110	0.0388	0.0942	0.0554	0.1262	0.1646
24	Initial value (abs) (%)	1.6128	2.6451	2.1973	2.5897	2.3545	5.0355	1.5978	2.2546
25	1/100*Sqrt(sum of E terms in row 21) = 0.1597								
26	1/100*Sqrt(sum of B terms in row 21) = 0.1795								
27									
28	Recalculated coefficients for phase perturbations								
29	$x1*(1+0.01i)$	1.5049	0.8388	−0.5061	−1.4808	−4.0083	−0.9353	7.9146	7.2447
30	$x2*(1+0.01i)$	1.4975	0.9109	−0.4938	−1.5188	−3.9944	−1.1307	7.8852	7.3545
31	$y1*(1+0.01i)$	1.4975	0.9109	−0.4983	−1.5022	−3.9910	−1.2639	7.8852	7.3545
32	$y2*(1+0.01i)$	1.5024	0.8889	−0.5061	−1.4808	−4.0083	−0.9353	7.9355	6.9801
33	$F_{x1}^{*}(1+0.01i)$	1.4973	0.9500	−0.4955	−1.5167	−4.0000	−1.1000	7.9000	7.3000
34	$F_{y2}^{*}(1+0.01i)$	1.5000	0.9000	−0.5000	−1.5000	−3.9967	−1.2333	7.8781	7.5633
35	(Change in coefficient*100)^2								
36	$x1*(1+0.01i)$	0.2401	37.4544	0.3721	3.6864	0.6889	271.2609	2.1316	30.5809
37	$x2*(1+0.01i)$	0.0625	1.1881	0.3844	3.5344	0.3136	9.4249	2.1904	29.7025
38	$y1*(1+0.01i)$	0.0625	1.1881	0.0289	0.0484	0.8100	268.6321	2.1904	29.7025
39	$y2*(1+0.01i)$	0.0576	1.2321	0.3721	3.6864	0.6889	271.2609	12.6025	1023.3601
40	$F_{x1}^{*}(1+0.01i)$	0.0729	25.0000	0.2025	2.7889	0.0000	0.0000	0.0000	0.0000
41	$F_{y2}^{*}(1+0.01i)$	0.0000	0.0000	0.0000	0.0000	0.1089	177.6889	4.7961	693.2689
42	Sum of rows (35:40)	0.4956	66.0627	1.3600	13.7445	2.6103	998.2677	23.9110	1806.6149
43	1/100*Sqrt(sum)	0.0070	0.0813	0.0117	0.0371	0.0162	0.3160	0.0489	0.4250
44	Initial value (abs) (%)	0.4693	9.0310	2.3324	2.4716	0.4039	28.7231	0.6190	5.8225
45	1/100*Sqrt(sum of E terms in row 20) = 0.0533								
46	1/100*Sqrt(sum of B terms in row 20) = 0.5371								
47									

Table 5: Continued.

48	Total changes (amplitude and phase perturbations combined)								
49	Sum of rows 21 & 41	6.3484	71.7297	2.567	28.8348	91.3126	1028.9483	183.2495	2077.4911
50	1/100* Sqrt(sum)	0.0252	0.0847	0.016	0.0537	0.0956	0.3208	0.1354	0.4558
51	Initial value (abs) (%)	1.6797	9.4104	3.2044	3.5799	2.3889	29.1611	1.7135	6.2438
52	Mean of E terms in row 50 = 2.3%								
53	Mean of B terms in row 50 = 12.1%								
54									
55	Selected build errors								
56	X actuator at 0.01 rad	1.4999	0.9	−0.5	−1.4999	−3.985	−1.091	7.895	7.285
57	Y actuator at 0.01 rad	1.54	0.911	−0.579	−1.573	−3.9998	−1.0999	7.8996	7.2996
58	X probes at 0.01 rad	1.5001	0.9	−0.515	−1.509	−4.0002	−1.1001	7.94	7.311
59	Y probes at 0.01 rad	1.495	0.885	−0.5	−1.5001	−3.921	−1.027	7.9004	7.3004
60	(Change in coefficient* 100)ˆ2, for comparison with row 48 for the measurement errors								
61	X actuator at 0.01 rad	0.0001	0	0	0.0001	2.25	0.81	0.25	2.25
62	Y actuator at 0.01 rad	16	1.21	62.41	53.29	0.0004	0.0001	0.0016	0.0016
63	X probes at 0.01 rad	0.0001	0	2.25	0.81	0.0004	0.0001	16	1.21
64	Y probes at 0.01 rad	0.25	2.25	0	0.0001	62.41	53.29	0.0016	0.0016
65	Total error	16.3	3.5	64.7	54.1	64.7	54.1	16.3	3.5

Table 6: Excitation forces ($\omega 1/\Omega = \omega 2/\Omega = 0.3$, $W/c = 1$).

	F_x	F_y	X	Y
Excitation1	1.0	0.0	$0.81538 - 0.06649i$	$0.38607 - 0.10663i$
Excitation2	0.0	1.0	$0.06231 + 0.02496i$	$0.14980 - 0.02629i$

Section 5 of the main text, and reference is made below to certain information in that Section. The first step is the choice of the test method and the dynamic coefficients. The results presented here relate to the (0°, 90°) method, with $\varepsilon = 0.8$. The values of the dynamic coefficients are shown in row 5 of the spreadsheet presented in this appendix, Table 5. The displacements arising for the specified excitation are now calculated according to (1)–(4) of Section 5, and the normalised default force and displacement set for this example is shown in Table 6.

These represent ideal values (apart from rounding errors) from which coefficients calculated would be exactly the same as assumed (this has been checked). With the exception of ω, all the values would normally be complex. In a real physical test, it would be difficult to arrange F_y to be exactly zero under exactly real F_x excitation and vice versa, due to residual stiffness in the actuators and cross coupling in the bearing. This is of no practical consequence, as the observed (complex) values would be used in the coefficient extraction and the result would be correct.

The next part is the perturbation of one of the variables in turn, all other variables being set to the default value, and the coefficients recalculated according to (5) of Section 5. The perturbations are shown in Table 5 as two sets; one of amplitude, one of phase. A slightly cryptic list of the perturbations for the chosen examples is shown in cells A8–A13 and A28–A33. Cell A8 notes that the value of $x1$ has been taken as 1% larger than the default value, while cell A28 notes that the phase of $x1$ has been advanced by 0.01 radians. The "errors" (difference between the current value and the initial value) were combined in the usual way as the square root of the sum of the squares. The values shown in rows 15 to 20 and rows 35 to 40 are scaled to make the numbers easier to present, multiplication by 10^4. Rows 21, 22 and 41, 42 of Table 5 represent the total effect of changes in either phase or amplitude on the recalculated coefficients. The errors are shown as a percentage of the initial values in rows 23 and 43. The total effect of the perturbations on the E values and B values are shown in rows 24 and 25 for amplitude perturbations, and in rows 44 and 45 for phase perturbations.

It is seen that the amplitude errors cause similar errors in both the E terms and the B terms, while phase errors cause some errors in the E terms, which may not be expected, though the effect on the B terms is ten times as large. The largest single effect is of phase errors on the B terms. This is a clear indication of the importance of good phase accuracy in a practical experiment. The changes due to measurement errors are consolidated in row 48, 49, and presented as individual % changes in row 50. The mean overall effect is shown in rows 51 and 52. These values also appear in Table 2 in Section 5.

The analysis continues with consideration of the effect of actuator or oil film displacement probe angular misalignment in the direction of shaft rotation. The misalignments and the recalculated coefficients are shown in rows 55–58, and the scaled squares of the errors in rows 60–63. The pattern of effect on the coefficients is very different from measurement errors and it is probably not very useful to present the results in the same way. Instead, the errors from all the sources considered are summarised in Table 3 in the main paper.

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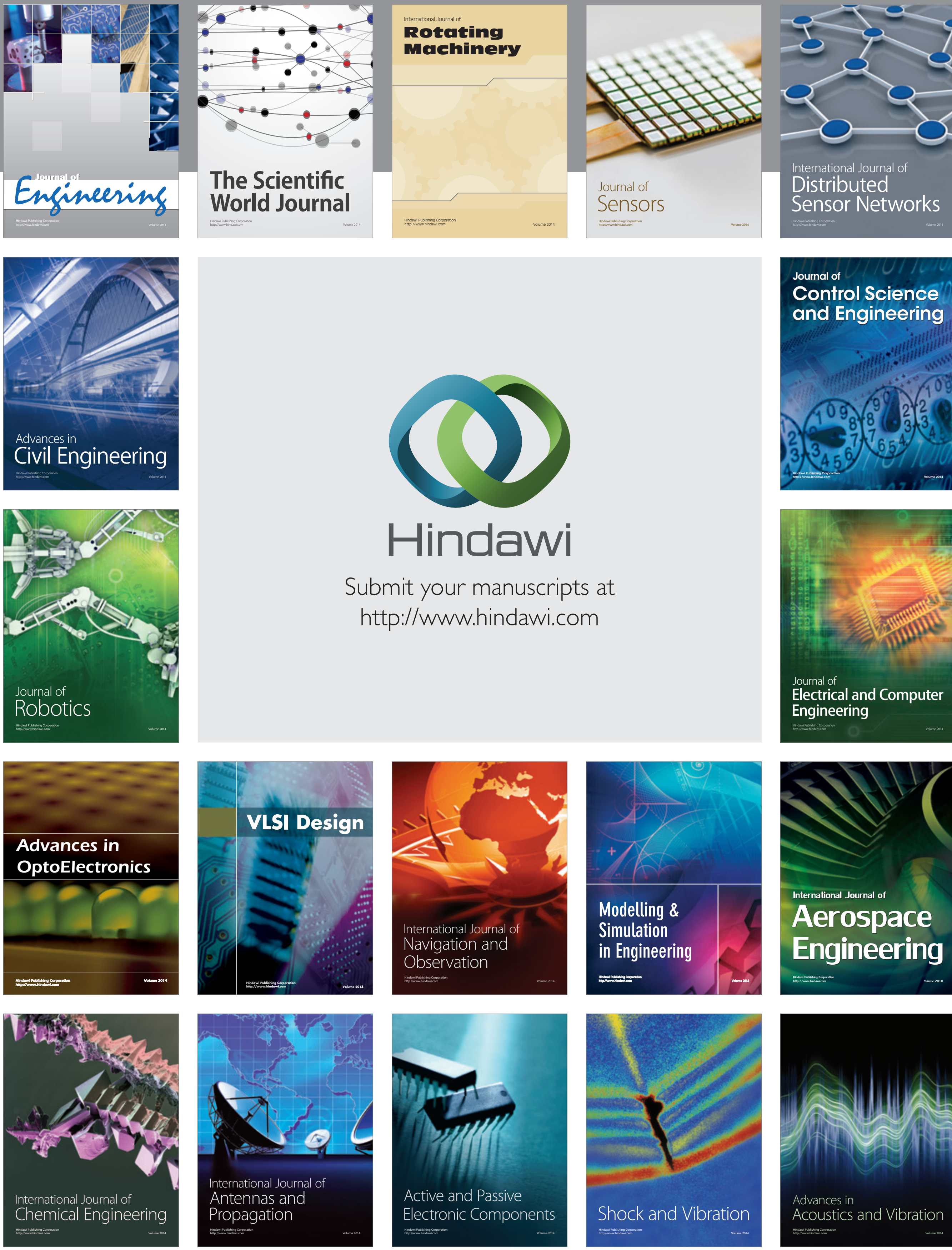
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