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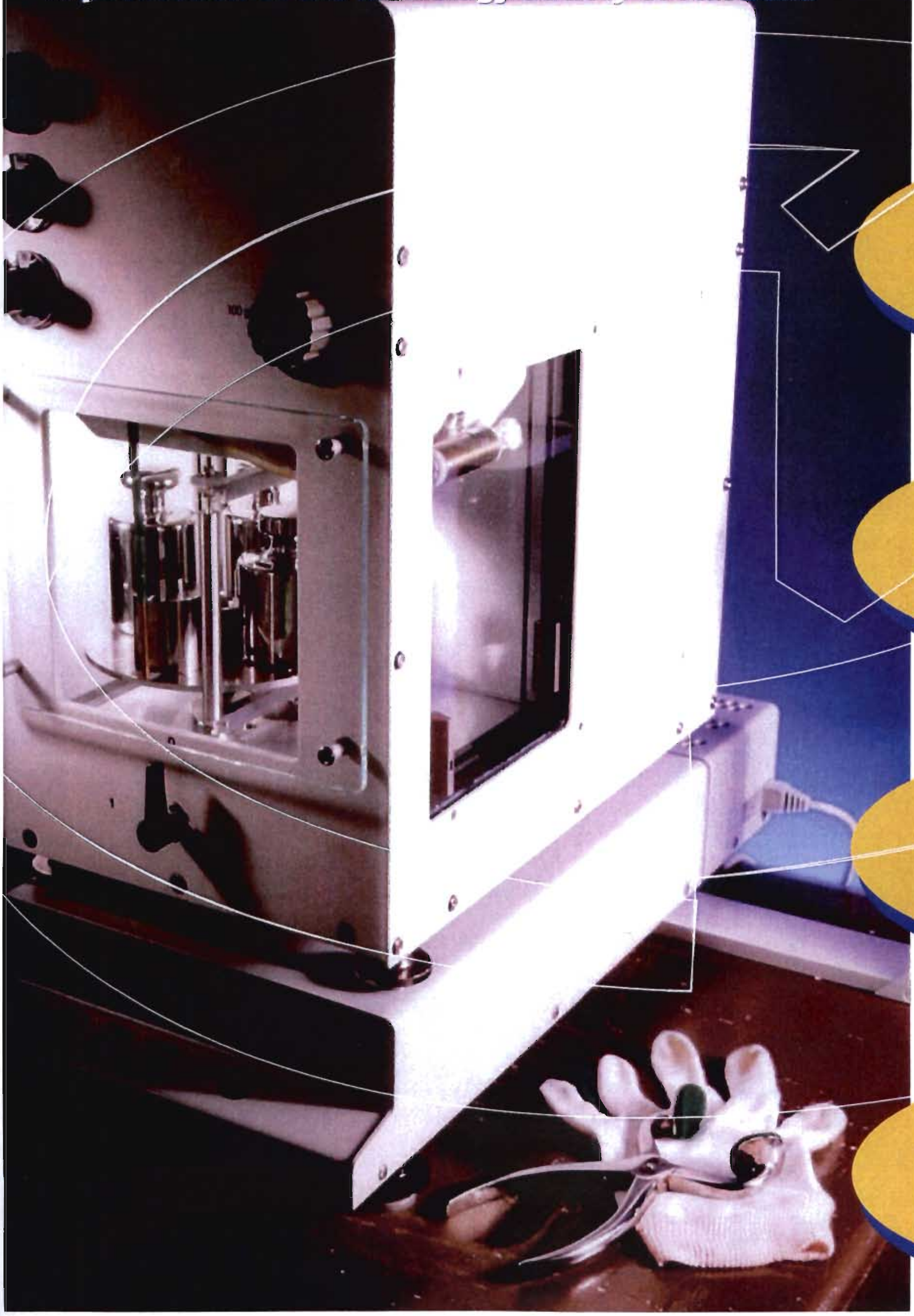

Australian Kilogramme

Training

Timed to Perfection

Mutual Inductance at 50 Hz

From the Editor

This issue focuses on training, with a letter to the editor and the President's report exploring the current situation and possible changes.

As well, you will find the Notice of AGM and forms as required by the constitution.

There is something for everyone in this issue: an article on the Australian kilogram standard, another on that necessary chore - uncertainty estimation, a further delving into units ancient and modern - Quantification by Jeff Tapping, and an article on time standards.

It is usual to present MSA conference articles here from time to time. In this issue I have included a paper on calibration of mutual inductance at power line frequencies.

- *Maurie Hooper*

Cover photo: Comparison of the Australian prototype kilogram No.44 with stainless steel laboratory standards.

The Australian Metrologist

The Australian Metrologist is published four times per year by the Metrology Society of Australia Inc., an Association representing the interests of metrologists of all disciplines throughout Australia. Membership is available to all appropriately qualified and experienced individuals. Associate membership is also available.

Contributions

Articles, news, papers and letters, either via e-mail, disk or hard copy, should be sent to:

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The deadline for the next issue is 16th December 2004.

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Write or e-mail the Editor with your details including years of experience and qualifications. This service is offered free of charge.

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If you have a position vacant, write or e-mail the Editor with the details. A charge of $20 for up to 10 lines applies. (The circulation may be small but it is well targeted.)

The deadline for positions wanted/vacant is as above.

Letters to the Editor

Letters should normally be limited to about 300 words. Writers will be contacted if significant editorial changes are considered necessary.

Editorial Policy

The Editor welcomes all material relevant to the practice of Metrology. Non-original material submitted must identify the source and contact details of the author and publisher. The editor reserves the right to refuse material that may compromise the Metrology Society of Australia. Contributors may be contacted regarding verification of material.

Opinions expressed in *The Australian Metrologist* do not necessarily represent those of the Metrology Society of Australia.

Editor: Maurie Hooper

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Contact the TAM editor for further details.

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MSA Membership Enquiries

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President's Report - September 2004

Training. Where has all the training gone...?

I was recently reminded of one of the reasons the MSA came into being. Nearly eleven years ago some metrologists recognised that metrology was facing a crossroad. Quality Systems had emerged as a significant movement in the manufacturing industry. For all the benefits of quality systems, one of the early negatives was the belief that with quality systems in place there was no need to measure anymore. Naive or not, industry believed that they did not need to check the products of companies that had quality systems. As a result metrology laboratories around the country started to close or shrink. This was one of the driving forces behind the emergence of the MSA.

Since that time, and hopefully with the assistance of the MSA, industry has recognised the fallacy of this way of thinking. However despite a win on this front, in the past few years, there have been other events that have led to fragmentation of the metrology industry. One of the key influences has been the privatisation of government bodies and the utilities. As a result there has been a significant change in the landscape of metrology in Australia.

While many of these privatised laboratories have survived and even thrived. A significant number have closed or gone through downsizing and frequent changes of ownership. Most importantly they have undergone a change of focus. This has had a long term and fundamental effect on the metrology industry.

Traditionally a large fraction of the shop floor and bench metrologists have come out of the government, military and utility laboratories. Now with privatisation the focus for these laboratories has become more commercial. This means the traditional training ground for metrologists is disappearing.

Training is emerging as a critical issue for the industry. There are a wide variety of short courses of a specialised nature from a variety of sources: - NATA, NMI and private providers. There is also the Graduate Diploma in Metrology from Swinburne and TAFE units. The problem is there is little coordination of this training and hands on training grounds have vanished. There is also an issue with respect the dispersed nature of the industry and a patchy demand for training. There are only ever a handful of people across the country looking for training in any one particular field of metrology. This makes the private provision of training expensive and supply of student unreliable.

It is this issue of training that has occupied much of the national committee's thinking since the MSA2004 conference. What is the MSA's role in finding a solution to the problem of training? Should we be a training provider? Can the society act as a focal point for coordination of training? What training is needed by industry? What recognition do individuals get for the training they have?

The national committee believes that at the very least we, the MSA, can act as a focal point for industry, government, educationalists, metrologists and the metrology infrastructure to tackle these issues. It is clear that we need find some way of raising the profile of metrology and the educational issues. Measurement plays too large a role in economic future of this country for us to allow this issues to go unresolved.

- Dr Jane Warne

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Notice of Annual General Meeting

The Annual General Meeting for the MSA 2004 will be held on
Wednesday 24th November, 2004 at 6:00 pm
at a venue to be advised.

The agenda for the meeting will be also advised later.

Nominations for the National Committee of Management are sought and should be with the Secretary Mehrdad Ghaffari no later than close of business on 17th November 2004.

METROLOGY SOCIETY OF AUSTRALIA

APPOINTMENT OF PROXY

To the Secretary
Metrology Society of Australia

I, ____,

Member No ___________

Hereby appoint

____,

being a member of the Metrology Society of Australia, as my proxy to vote for me on my behalf at the 2004 AGM of the Society and at any adjournment of that meeting.

Signed: ____

Date: ________________

Note: This Proxy form must reach the Secretary 24 hours before the AGM.

METROLOGY SOCIETY OF AUSTRALIA

NOMINATION FORM

To the Secretary
Metrology Society of Australia

We,

____, Member No __________

and

____, Member No __________

hereby nominate

____, Member No __________

for election to the position of (circle one)
President
Vice-President
Secretary
Treasurer
Ordinary committee member

of the Society at the MSA's Annual General Meeting of 2004.

Signatures
Nominator ______________________

Seconder ______________________

I affirm that I am willing to stand as a candidate

Nominee ______________________

Date ________________

A Short History of the Australian Kilogramme

Dr Noel Bignell

National Measurement
Institute, Australia
PO Box 264
Lindfield NSW 2070

The astute reader will have noticed the archaic spelling of "kilogram" in the title of this article. This is because we are referring not to the unit of mass, which is spelt "kilogram", but to a particular and special object and the convention is that it be spelt "kilogramme" to give it dignity. Even greater dignity is given to the object of which it is a copy, the International Prototype Kilogramme by calling it by the Gothic letter K. This kilogramme, which is **the** kilogramme, was made by Johnson Matthey & Co in 1878-9 and rose to become Gothic K when it was chosen by the CIPM (International Weights and Measures Committee, but in French) to be the international prototype in 1883. It was accepted internationally as the definition of the unit of mass in 1903.

The Australian prototype (No. 44) is one of a number of copies of Gothic K that have been made over the years. Like the others it is a cylinder of an alloy of 90% platinum and 10% iridium with the minimal surface area, that is with an equal height and diameter of 39 mm. It has a density of 21.5 kg/m^3. It was made in 1938 from the same ingot as prototypes numbers 43 and 47 prepared by La Société Nouvelle du Comptoir Lyon-Alemand in Paris. While it was sent to the antipodes its brothers have gone on to become official copies of Gothic K and thus have stayed in Paris at the BIPM where Gothic K is kept. The Australian Government purchased No. 44 in 1946.

A provisional certificate for it was issued by the BIPM in January 1946 that assigned it the value 1.000 000 270 kg or 0.27 mg higher than Gothic K. This small difference from Gothic K is of no significance; all the international prototypes and the official copies are slightly different, sometimes less but usually more than Gothic K. Our prototype is marked "No. 44" by a slight roughening of the polished surface on the side. Its first journey took it to the National Physical Laboratory in the UK where it was compared with prototype number 18. The value found for this comparison was 0.22 mg heavier than 1 kg, slightly lighter than the BIPM value. It was however noted that there were some dark spots of pinhead size. The weight was not cleaned but was brushed with a camelhair brush before weighing. Of course dirt on the weight would have made it appear heavier so it was returned to the BIPM for a further determination of its mass. It was cleaned in a jet of steam, the usual treatment, and a new value of 0.283 mg heavier than Gothic K obtained. This was within the standard deviation of the results (0.013 mg) and was taken as agreement with the previous value of the BIPM.

Our prototype No 44 was sent back to NPL and compared with the British prototype again to give much the same value. This naturally threw some doubt on the value of prototype No. 18 and it was decided to send it back to the BIPM for a redetermination of its mass. NPL asked to retain our prototype until after this so that they could measure it again on its return from the BIPM and we agreed

The British prototype went to the BIPM in January 1948 where it was not immediately cleaned except by a light brushing with a badger-hair brush (un pinceau à poil de blaireau). Why the British use camels and the French use badgers is not clear. It was weighed and then given the proper cleaning procedure with jets of steam and weighed again. Its mass was found to increase by 0.0693 mg. This made the value of No. 44 as determined at NPL that much heavier or 0.289 mg more than a kilogram. This agrees well with the second BIPM value. When the now clean British prototype returned to the UK further comparisons with the Australian prototype took place at NPL in March 1949. They found that the difference between the British and Australian copies was 0.2026 mg whereas the difference found by the BIPM was 0.1986 mg, the Australian one being heavier. This agreement was considered satisfactory and so the Australian prototype could at last be sent to Australia.

The BIPM had already decided that its original value was correct and on November 30 1948 issued the first certificate for Prototype Number

44 ascribing to it a value of 1.000 000 27 kg. Subsequent values are given in Table 1 with some values before the cleaning process. In the next few years it will be returned to Paris for a further comparison with Gothic K.

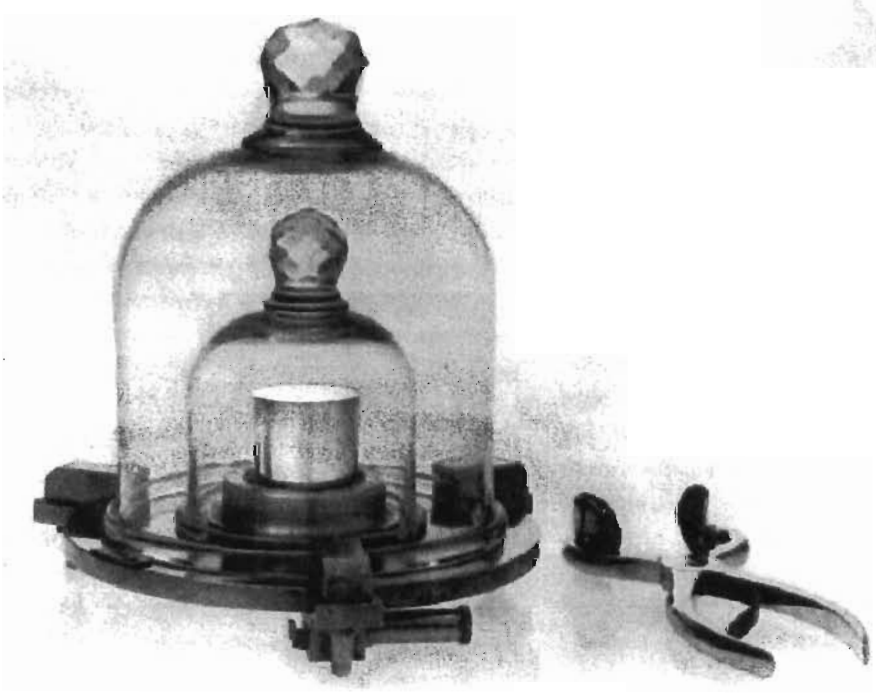
So it is clear that the value of the Australian prototype seems to vary slightly with respect to the international prototype Gothic K. But these are more or less equivalent standards so there is no reason to suppose that this represents a true picture of the change in mass of No. 44. The real danger is that they may both be changing in some way and it is only their ratio that is relatively constant. This brings us to the article in the July TAM on ways to replace these artefacts with a definition that does not rely on material objects.

For day-to-day weighing there will always be a need for actual weights but these may be made from stainless steel. The great advantage in this is that the buoyancy correction is very much less when calibrating other stainless steel weights. The greatest single source of uncertainty in the chain of measurements leading from our platinum-iridium kilogramme to the best weights used in Australia is this correction because the density of the prototype is so high. The BIPM does not have this difficulty when it compares its copies, or Gothic K itself, with national prototypes because they are all very nearly the same density. When the BIPM does calibrate stainless steel weights, as it does for some countries, for example New Zealand, it faces the same problem. This is some of the past of our kilogramme No 44, perhaps it does not have much of a future but it will, I think, be still important for a decade or two - time will tell.

Australia now has two Platinum-Iridium kilograms, a second one being delivered from the BIPM in early October, hand carried by Dr Barry Inglis. Legally the old kilogram will still be the Australian primary standard but it will be compared with the new one and its behaviour during its regular re-calibrations at the BIPM will be monitored. Because of the negligible air buoyancy correction the comparison of Platinum-Iridium standards can be done with better uncertainty than the comparison of a stainless steel standard with a Platinum-Iridium one. It means that when the legal standard, No. 44, is away for calibration, Australia will still have access to a Platinum-Iridium standard.

Table 1

Year	Value w.r.t. washing		Rate of change per year/ µg y^{-1}
	before/kg	after/kg	
1948	1.00000027	1.000000283	
1964		1.000000262	
1968		1.000000297	
1979	1.000000302	1.000000283	1.73
1991	1.000000318	1.000000287	2.6



Australian prototype No. 44 housed in its double bell jar.

Expressing uncertainty over a range of measurand values

Walter Giardini

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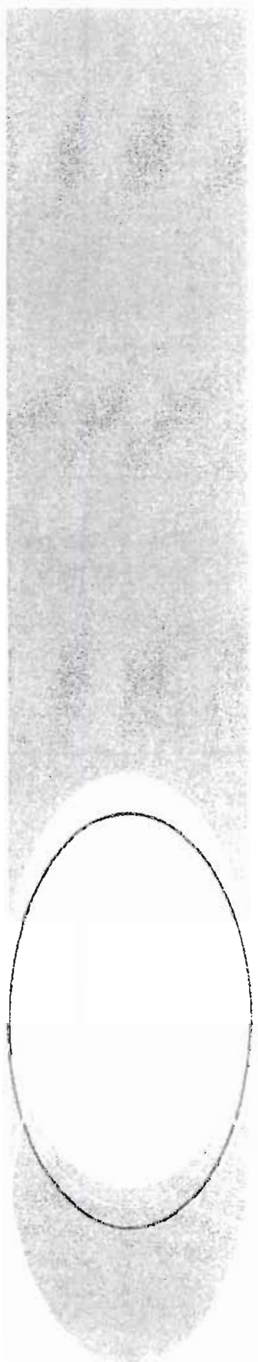
Lindfield NSW 2070



The ISOGUM tells us how to set out and calculate the uncertainty in the value of the measurand, but often the result of a calibration is not a single measurand, but a set of values which relate to a range of nominal measurand values. For example, a pressure gauge is calibrated over a range of values so that a correction is obtained at each nominal scale point, and is associated with an uncertainty which is not in general the same as that at other scale points. A single gauge block has a single value and a single uncertainty, but a set of gauge blocks, a survey tape, a voltmeter, and many other instruments or systems share the same property of having a range of measurand results and range of different uncertainty values. A way of saying this mathematically is to say that uncertainty in this case is a function of the measurand value. There is nothing special about this, and all metrologists know that when operating at very high or very low values of physical quantities, different influence factors come into play, and can result in variable effects, both random and systematic. The question arises however, how to express this uncertainty in a convenient and easily understandable form.

The most basic approach is to simply give a table of uncertainties. There is no ambiguity here and the user knows exactly the uncertainty at each scale value of the instrument. This however is not so convenient to work with, since rigorously, use of the instrument requires a new calculation of the uncertainty at each nominal value. The user could simply use the worst case of the uncertainty at all nominal points, but this will overestimate it over most of the range. If the source of uncertainty is a relatively small component of the total uncertainty budget, this is a simple and effective solution, which may have a negligible overall effect. Using the simple example of a set of gauge blocks below (see Table 1), we could say for example that we will use the same uncertainty of 0.140 µm for all gauge blocks.

Table 1

Gauge blocks	
Size	U95%
10 mm	0.020 um
50 mm	0.024 um
100 mm	0.028 um
150 mm	0.036 um
200 mm	0.048 um
250 mm	0.058 um
300 mm	0.069 um
350 mm	0.082 um
400 mm	0.095 um
450 mm	0.110 um
500 mm	0.140 um

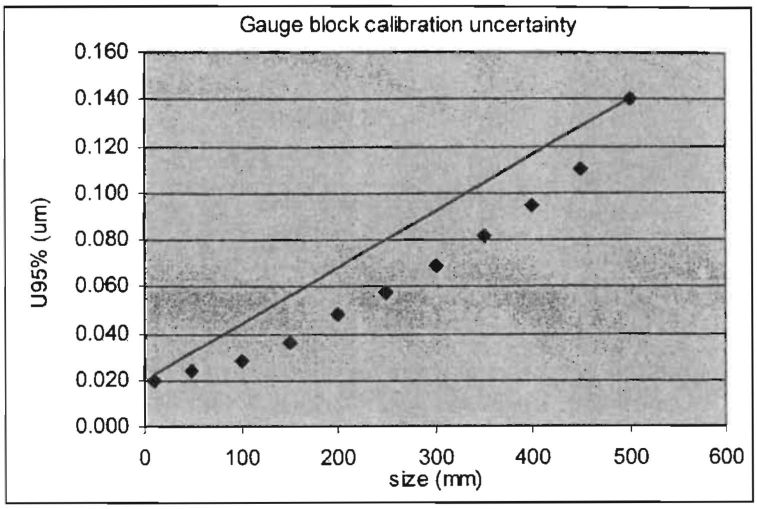
A method (introduced systematically by NATA where required and appropriate) which some laboratories are beginning to use, is to look at a plot of uncertainty versus nominal scale value, and then draw a straight line which covers all the uncertainty points (see figure 1).

The straight line of course is simply an arbitrary line chosen so that it covers all values, in this case whose equation is $0.02 + 0.0024*L$, where L is in mm, and the resulting uncertainty value is in µm.

Note that we ought not to use a FITTED line here, since that would be the "average" linear behaviour of the uncertainty function, and would have some points below the line and some points above the line. We are not trying to describe the uncertainty function here, we are simply trying to make sure that the line captures all the uncertainty results, without "wasting" uncertainty at low values, but ensuring that it is not underestimated at large uncertainties.

Note also that if we wanted to be more exact we could arbitrarily choose to describe the uncertainty function with a higher order equation. In the example given, the graph shows an approximately parabolic behaviour, and it would be tempting to try to fit a parabola to describe it. This would not be recommended in general unless uncertainty is

Figure 1



absolutely critical. In any case, if this were done, then it is again very important to ensure that the parabola so selected is not the FITTED parabola (which again would underestimate some points), but rather the "envelope" parabola which covers all points with least overestimation at any part of the range.

There are some aspects of this approach, which might cause a little confusion, when dealing with certain issues and parameters in uncertainty. Firstly, the somewhat parabolic form of some uncertainty functions, and the fact that the equation is a sum of the form A + B*M, where A and B are the constants, and M is the measurand quantity, can bring to mind the structure of the mathematical equations by which we combine uncertainties. We know for example that when uncertainty components are combined they can be added arithmetically (A + B + C + ...) if they are fully correlated, or they can be added in quadrature ($A^2 + B^2 + C^2 + \ldots$) if they are independent. This is not related to the simple summation form of the uncertainty equation A + B*M developed to describe the uncertainty function for the case of ranged instruments. There is also no logical relationship between the fact that the uncertainty functions sometimes increase non-linearly, and that the combination of uncertainties for the independent case uses the sum of the squares of the components.

Secondly, during the compilation of the uncertainty budget it is convenient with some measurement systems to categorize a complex and large set of uncertainty components as those which are fixed (i.e. the same at all nominal range values) and those which are proportional (i.e. they vary in some well described way with nominal range value). At the end of this process, the variance of the two can be separately combined into a fixed, and a proportional component as in $[(\text{Fixed})^2 + (\text{Prop}*\text{Meas})^2]$.

At the individual component level however, this does not yet include the components which contribute to the scatter which are not in general the same at all scale values (i.e. they are not simply fixed), nor however would they vary in a definite form (i.e., they would not simply be proportional to scale value), so the full expression would be $[(\text{Fixed})^2 + (\text{Prop}*\text{Meas})^2 + (\text{TypeA at Meas})^2]$. In this case, the final combination is a genuine quadrature combination of uncertainty components in the usual ISOGUM format for independent components but the expression, is not in general a parabola.

The generalizing power of mathematics combined with the astounding numerical power of spreadsheets is now making possible the specification of parameters (such as uncertainty) with a high degree of functional complexity. It is important not to confuse elements which look functionally similar, but which arise from quite different sources.

■

Quantification - Number 3

Jeffrey Tapping

First, explanations of the units I listed in the last issue.

Stone is a unit of weight equal to 14 pounds, that was used for the weight of people in Australia and U.K., but it was historically used for other purposes where the weight it represented could vary. For instance my Oxford dictionary tells me that a stone of fish or meat was 8 pounds. Very confusing, but there were plenty of other instances where a unit represented different amounts depending on what it was used for.

It is interesting to consider why this unit was popularly used for body weight. My guess is that when divided into quarters (e.g. 5¼ stone), it gave an interval about equal to the normal variation in a person's weight. And why do I think that? Historically people seemed to prefer to divide units by factors of two, a habit that could be seen in the old school rulers where inches were divided into quarters or sixteenths. And until very recently the U.S. trading markets such as the stock market expressed prices as intervals like 1/32 cents.

Iron is a bit of a mystery. One source says it was an old unit of length used in the boot and shoe trader, equal to 0.53 mm. Another says that it was a printing measure, equal to about 25 ems, used to measure lengths of mixed type characters. It was probably both of these. And what was an em? Would you believe the width of a letter "M", which was the widest letter. And this is not to be confused with the unit en, which was half an em, and equal to the width of the letter "N".

Grade is a unit of angle used in France, equal to one right-angle, and the reason why the old term "centigrade" was not used for the Celsius temperature scale. There would have been confusion between temperature and an angle of one hundredth of a right angle.

Grain was the smallest unit of weight used in olden days. It was originally the weight of a plump grain of wheat, so you can see how inexact it must have been.

Cental was a weight unit, equal to 100 pounds, and was used to measure corn. The name probably derives from the Latin *centum*, for one hundred.

Sthene is a curious-sounding term that attracted my attention. It is actually a non-SI metric unit of force equal to 1000 newtons. The probable origin of the name is from the Greek word for strong, *sthenos*.

Nail is another old unit of length, equal to 2¼ inches, used for textiles in Britain around 1400 to 1600. It is equal to one sixteenth of a yard. And like the term "bolt" also used for textiles, it probably derives from the metal spike on which the cloth was wound. But we have another case of a unit name having multiple uses, because it has also been used as a unit of land area and of weight.

Link also relates to metal, but this time in the form of a chain. It is one hundredth of a chain, the length discussed in the last episode of this series. It is therefore equal to 7.92 inches. The chain was a system for measuring in land surveys invented by Edmund Gunter, and so has also been known as Gunter's Chain. It is surely no coincidence that it was chosen to be one tenth of a furlong, and that an acre is 10 square chains.

Knot is of course a unit of speed still used in marine and aeronautical navigation, and in meteorology. It is equal to one nautical mile per hour, about 12.8 km/h. It's origin is in the method used to measure the speed of sailing ships through the water, in which a float with a knotted rope attached was thrown from the ship and the speed measured from the rate at which the rope had to be reeled out.

Now, did you discover a unit that has been used for two different types of quantity? Actually I have a number. First the **minim**, the last of the units that I asked you to ponder upon in the last issue It is a musical note measure (half a semibreve), but also a fluid measure equal to a sixtieth part of a fluid drachm (about 0.06 millilitres). Both of these seem to have their origin in being considered to be the smallest quantity used.

The second is the **rood**, which was primarily a unit of area, equal to 40 square rods, which equals quarter of an acre. But my Oxford Dictionary says that it was also "a unit of length varying locally from 5½ yards to 8 yards".

Next there is the **ounce**, which was used as a weight, but also as a fluid measure. But to be fair, for fluid measure the context was usually made clear, commonly by using the term "fluid ounce".

The last of my list is the unit **rad** has been used for either a radian of angle, or a measure of atomic radiation. Perhaps this could be viewed as a bit of a fudge, because "rad" for an angle could just be seen as an abbreviation of "radian".

Finally, I asked what quantities were represented by 1 am, 1 pm and 1 dam. No, time is not involved: they are all lengths. The first is one attometre, the second one pico-metre, and the third one deca-metre. The prefix for "deca" is unique in that it is the only SI prefix that is more than one character, and was probably adopted because of historical usage. I could have used some other odd-looking quantities like 1 dan, 1 dalx or 1 dalm instead, but I thought the possibility of 1 deci-morning a bit too amusing to pass up.

Now for another list of units we will discuss in the next issue:

are

scruple

furlong

chaldron

quarter

fathom

clusec

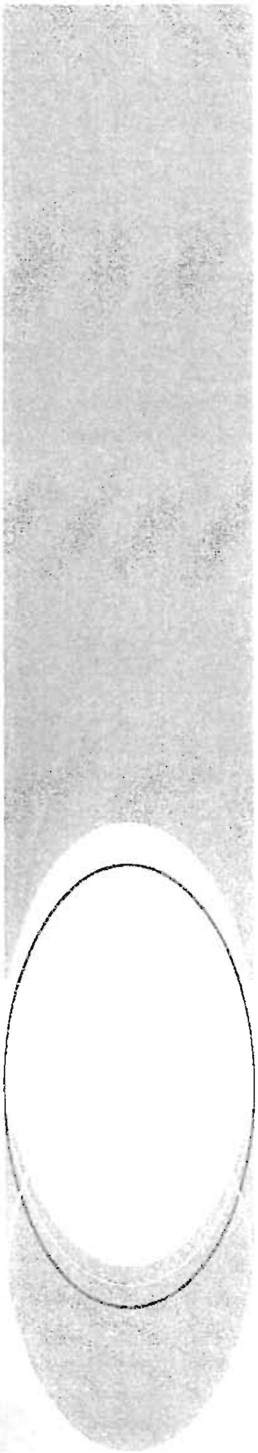
quintal

And can you explain

- the difference between a carat and a karat?
- the difference between a dram and a drachm?
- the relationship between 1 ch, 1 PS and 1 CV?

Letter to the Editor

Ian Bentley



The need for an effective measurement training system is clearly apparent to those involved in NATA assessments. Now that the MSA has taken training on board as a major issue, a few fundamental questions come to mind that I think need to be debated: -

- Is the need for training confined to calibration laboratories, or is it symptomatic of a general lack of understanding of measurement throughout industry?

- Why do we get a significant number of enquiries from industry that indicates that they do not know the accuracy they require (unless it is specified in a standard)?

- Why do some people who have been to training courses still have gaps in their knowledge and lack the ability to adapt to non-standard measurement situations?

I personally have come to the conclusion that people may not be being given a thorough enough grounding in the fundamentals of measurement. Obviously, some people are more suited to think like metrologists but it should be something that can be taught.

This is not a criticism of the training courses currently being offered. Training opportunities are irregular and costly and by necessity they have to cater for a range of participants who have greatly varying levels of prior knowledge, understanding and academic background. Therefore some people are overwhelmed with everything from the principles to advanced techniques and the statistics of uncertainty calculations in too short a time, whilst others gain a great deal from the courses. What is needed is a "fundamentals of measurement" course that will prepare them for these calibration courses.

One of the main difficulties with providing training is the lack of numbers in any one location. This leads to high costs which have to be recovered. Now, if the perception that some people in industry don't have a good understanding of measurement is correct, then a "Fundamentals of Measurement" course could be of benefit to them also. This would give the training providers the necessary economies of scale.

If the MSA were to be involved, then we would have to face the fact that to be sustainable, it can't be done on a part time basis, no matter how enthusiastic and well intentioned the individuals involved are. So the MSA'a role may be to assist as a facilitator and/or content provider to existing training providers and administrators such as the Australian National Training Authority.

I understand that many college and university courses already have a measurement skills component to them. These vary in quality and complexity but as indicated above, what seems to be lacking is a really thorough explanation of measurement principles. The MSA could be involved in providing content for a "Fundamentals of Measurement" course, and lobby, in conjunction with the National Measurement Institute and NATA, the relevant bodies to have it included as a component in university and college courses. This would ensure consistency in measurement training and would certainly lift the profile of the MSA.

If you can get the fundamental thinking right then people will have for more chance to develop themselves through available texts, information and courses on the internet. The MSA could assist by pointing them to the available literature and web sites as collectively we already have a wealth of information; it just becomes a knowledge management exercise.

Is trying to train industry worth all the effort? Well, a lot of effort and cost goes into having an internationally recognised calibration infrastructure in the form of the National Measurement Institute and the NATA calibration laboratories providing traceability of calibrated instruments. The benefits of which may be being negated by those end-users, who because of their lack of measurement knowledge, are introducing significant errors due to poor technique, environmental conditions, uncorrected errors, etc. Consequently, their process control and/or product compliance decisions may be based on unreliable measurement data which will ultimately lead to problems and/or inefficiencies. The standards and conformance regime in part, limits the possible problems, but it doesn't foster the optimisation of their processes.

In conclusion, the formation of the National Measurement Institute presents an ideal opportunity for a nationally coordinated approach to measurement training in Australia. The above are my thoughts based on my experiences; others will have different views based on their experiences. It is essential however that, if the MSA wants to be a key player in measurement training, that we have an open and frank debate about what can be achieved and how best to maximise the benefits from our efforts.

- *Ian Bentley* ■

MSA 2005 - Biennial Conference

The 2005 Biennial Conference of the Metrology Society of Australia will be held in Canberra on 19-21 October 2005, commencing with a cocktail party from 1900 to 2100 on Wednesday 19th October 2005. The Conference will be held over the two days 20th and 21st.

The Conference venue will be Australian National University (ANU). Accommodation will be available at ANU and a block of rooms have been reserved at approximately $110 per room including breakfast. The Conference Dinner will take place on Thursday 20th at the Australian War Memorial. The Dinner will be held in the new section of the War Memorial under "G for George", the famous WW II bomber.

The MSA 2005 Conference Committee looks forward to seeing you again at what promises to be a most exciting conference. With its theme "Smart Measurements: Metrologists Advancing Industry" the Conference will focus on such issues as education as well as showcasing metrology and its relevance to industry to a wide range of stakeholders, including Government, which is one of the reasons Canberra has been chosen as the destination.

Additional information, including the first call for papers, will be posted in due course. In the meantime, please do not hesitate to contact me for any details.

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Timed to Perfection

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In short·-

With the introduction of new ultra-accurate 'optical clocks', the science of horology is undergoing a revolution that may well require that the second is once again redefined .

Optical clocks measure time by locking the oscillation of a laser beam to changes in the energy level of an atom of mercury, ytterbium, strontium, indium or calcium – accurate to within one second every 30 billion years.

Global Positioning Systems based on optical rather than the current atomic clocks promise to improve accuracies from metres to centimetres.

Do we want clocks accurate to one second every 30 billion years? At that precision, gravity weighs down the passage of time – though it might be easier to find your way around the planet.

11 April 1970, Kennedy Space Center, Cape Canaveral, Florida: *Apollo 13* is about to lift off. As the three astronauts lie on their couches in the command module, each wears a mechanical wristwatch strapped to his spacesuit cuff . The fabled Omega Speedmaster is there for good reason; the chronometer, which became the official watch of the US Space Program, has survived every test that Nasa can throw at it and is accurate to within 6 s every 24 hours.

Within days the *Apollo 13* astronauts have good reason to be grateful for the Speedmaster's accuracy. One of the craft's fuel cells explodes and, as part of the emergency regime to conserve power, onboard clocks are turned off. The watch is all that stands between them and infinity.

Astronaut Jack Swigert has been assigned the task of timing the duration of a 'corridor control burn' that will realign the spacecraft into a safe landing trajectory. Too little burn and they will skip off the top of the Earth's atmosphere into space to die a hideous and lonely death of asphyxiation; too much and they will burn up by plunging too deeply and too fast into the Earth's atmosphere.

Swigert's Speedmaster does not let him down. The burn is accurate, and the rest as they say is history. The crew of *Apollo 13* literally owe their lives to 'split-second' timing.

Seconds out

Three years before the launch of *Apollo 13* the science of metrology (not to mention horology) had been revolutionised at the most basic level by the redefinition of the second. The new definition was no longer based on the duration of a single revolution of the Earth, but by 'the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom'.

The era of atomic clocks had arrived and with it the ability to measure time to 14 decimal places. Think of it in this way: a caesium-based atomic clock will lose 1 s in 30 million years, or fractionally more than 2 s in the time that separates us today from the extinction of the dinosaurs.

Today the science of horology is undergoing another revolution that may well require that the second is once again redefined. The latest generation of atomic clocks will not be based on the energy state of the caesium atom. Instead, the so-called 'optical clocks' will measure time by locking the oscillation of a laser beam to changes in the energy level of an atom of mercury, ytterbium, strontium, indium or calcium.

Atomic distortions

Chronometers have three essential ingredients: an oscillator, a reference and a counter. In clocks and watches, such as those used in the US Space Program, the oscillator is a pendulum or balance wheel; the reference is the duration of one rotation of the Earth; and the counter is gears and hands. Periodically, the watch or clock is recalibrated to the reference by re-setting the hands.

In a conventional atomic clock, the oscillator is a group of heated caesium atoms which, when bombarded by microwaves of a specific frequency, 'flip' their electron shells 9,192,631,770 times a second. To achieve this state, caesium atoms are first boiled off and passed into a vacuum tube where a magnetic field separates atoms of the correct energy state. These atoms then enter an intense microwave energy field, the frequency of which is under the precise control of a crystal oscillator. When a caesium atom receives energy of exactly the right frequency (9,192,631,770 Hz) it changes its energy state. A further magnetic field separates these excited caesium atoms and channels them to a detector.

The output of the detector is proportional to the number of atoms arriving, and peaks when the microwave frequency is exactly correct. This in turn is used to correct the crystal oscillator controlling the microwave field, and the resulting 'locked' frequency (the 'counter') is divided by 9,192,631,770 to give a single pulse per second.

This second is the SI (Systeme Internationale) or 'atomic' second first defined in 1967. A crucial point here is that the reference is self-recalibrated by the microwave oscillator; humans have been removed from the calibration loop.

However, caesium clocks have in-built inaccuracies owing to the laws and tolerances of quantum physics. For example, the optimum possible accuracy of measuring the vibration of a single atom of caesium cannot be achieved. According to Heisenberg's uncertainty principle, it is not possible to measure precisely the frequency of the single microwave photon emitted when the caesium atom is stimulated.

Similarly, the hot caesium particles crash through the vacuum chamber in a jumble of angles and speeds. Their susceptibility to the crucial frequency of 9,192,631,770 Hz varies because of the Doppler shift. Particles moving at near quantum velocities experience Einsteinian time-dilation effects (or 'warp drive').

The upshot of all this is that the caesium 'ticks' are no longer identical and the clock's accuracy suffers as a result.

A crucial point about atomic clocks is that their accuracy is proportional to the wavelength of the radiation that the clock uses – microwaves in the case of caesium clocks. Moving further up the electromagnetic spectrum – say into the visible and near-infrared portions – should in theory allow us to improve the accuracy of our clock. At these shorter wavelengths, the higher frequencies provide a more sensitive counter. Such differences in oscillator frequencies are key to the accuracy of all time-keeping devices.

Compare, for example, the sundial with an American railroad grade pocket watch, which lost just 30 seconds a week and represented a breakthrough in precision timekeeping in the late 1800s. The balance wheel (oscillator) of the railroad watch vibrates much more rapidly than the motion of the sun in the former. It is this same principle, therefore, that distinguishes optical clocks from their caesium-based cousins.

Speed of light

Optical clocks differ from conventional atomic clocks in one important respect. The reference at the heart of the clock is not a cloud of hot caesium atoms but rather a single ion (normally mercury although strontium, ytterbium, indium and calcium are also being investigated) captured in a magnetic trap and chilled virtually to absolute zero by a laser. The principle by which the cooling is achieved is simple; as the ion absorbs laser photons its movement is slowed and its temperature drops. This immediately removes the Doppler and 'warp-drive' effects that are the major limitations of caesium clocks.

Once the ion is in its super-chilled state another laser is tuned to the specific frequency needed to shift the ion's outer electron from one energy state to another. When the laser is tuned to this frequency the electron ceases fluorescing – the mercury ion goes dark. As long as the electron stays in this 'dead zone' the laser is at the correct frequency – and the clock is ticking accurately. If the electron blinks 'on' then the laser automatically retunes itself to the dead zone.

The laser's oscillation though is of the order of a quadrillion (10^{15}) cycles a second, much faster than the oscillator in a conventional caesium clock. It is this speed after all (remember the sundial and the pocket watch) that gives the optical clock its superior accuracy.

The problem until recently has been how to measure something that oscillates so fast, way beyond the capabilities of conventional electronics. The answer is a 'frequency comb'. Think of this comb as a gearbox that slows the rapid oscillations of the 'probe' laser down to something that is measurable.

The frequency comb is a device by which the light from the probe laser, now locked to the frequency of the mercury ion electron's oscillation, is transmitted via a special fibre optic cable to another laser pulsing 'only' a billion times a second. This second calibration laser acts as the reducing gear, condensing the probe laser's quadrillion cycles a second to a countable billion times a second. Pulses of light from this laser last for just a few femtoseconds with intervals of darkness between them.

When passed through a prism and split into its constituent frequencies this light has a perfectly regular spectrum – just like the teeth on a cog. By adjusting a mirror in front of the prism it is possible to bring the probe laser pulses into perfect phase with one of the teeth on this cog and *voilà* , you have your reducing gear, or in a plainer language, your clockwork. The 'comb' tag comes from the perfectly regular spacing of the calibration laser's constituent frequencies.

With the principle of the optical clock established it is becoming clear that mercury may not be the ideal element to use. Mercury is sensitive to minor fluctuations in local magnetic fields for example. However, other elements such as indium, strontium, or calcium do not suffer from this disadvantage. But all optical clocks will begin to suffer from the same problems once their ultimate goal of an accuracy of a second every 30 billion years is realised.

At such accuracies even the relativistic effects of rising and walking to the front door become important. And then there is gravity; the stronger its pull the slower the passage of time. A height difference of only 10 cm will change the rate of a conventional clock by one part in 10^{17} so it is clear that the new generation of optical clocks will have to be corrected even for what floor in a building they stand on. And then there are fluctuations in the pull of gravity, caused by tides and even variations in local geology, that will need to be taken into account too. Optical clocks will be a nightmare to set up.

Time and distance

But why should we care about a clock that loses a second in an interval of time that is longer than the age of the Universe? The answer is that time equals distance and in a world where we want to know our position with increasing accuracy we are going to need optical clocks.

The Global Positioning System (GPS) that people increasingly use in cars and other vehicles relies on atomic clocks in a network of satellites and ground stations around the world. The system works by measuring the time taken for signals sent from receivers to travel to and from the orbiting satellites. With the current limitations of atomic clocks, the uncertainty in timing this duration results in an uncertainty on the ground of several metres. With the new generation of optical clocks this uncertainty will shrink to a few centimetres at most. In a world where terrorism is the new menace and satellite surveillance and surgical strikes increasingly likely the advantages of this are obvious.

But distance is important too on the planetary and interstellar scale. As we send spacecraft farther and farther into space we will need to know their position accurately. Once again optical clocks will provide the means to do this.

Finally, there is the problem of the so-called fine structure constant, which is one of the fundamental forces that holds the Universe together. There has recently been speculation that this 'constant' may not be so at all and, since it influences the resonant frequency of ions, comparing two optical clocks based on different ions will allow this theory to be tested.

From plus-or-minus 30 seconds a week to keep railroad passengers safe, through plus-or-minus six seconds a day to save three men in outer space, to plus-or- minus 1 second in 30 billion years to test whether God has a sense of humour after all; time remains of the essence. ■

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CALIBRATION OF MUTUAL INDUCTANCE AT POWER-LINE FREQUENCIES

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Abstract

Because of the difficulties in applying conventional bridge measuring techniques to the calibration of mutual inductance at power-line frequencies, we have investigated an alternative approach that requires only a single resistor of known value and of known phase angle as the standard. This resistor defines the primary current of the mutual inductor in terms of the source voltage. By comparing the secondary voltage of the mutual inductor with a fraction of this same source voltage, the mutual inductance is derived. Measurement uncertainties in both magnitude and phase angle have been estimated. Although directed particularly at the calibration of mutual inductance, the method may also be applied to self-inductance calibrations.

1. Introduction

The calibration of mutual inductance at power-line frequencies presents a standards laboratory with some difficulties. Whether the starting point is capacitance or resistance, the most precise impedance standards are capacitors of values up to 1 nF at frequencies of around 1 kHz. Generally there is no path of traceability for these standards at frequencies as low as 50 Hz. Further, the impedance of a 1 nF capacitor at 50 Hz is 3.18 MΩ, whereas that of a typical mutual inductor of value 10 mH is 3.14 Ω. This large impedance mismatch is both an inconvenience and a disadvantage in sensitivity when the conventional Maxwell-Wien bridge is used for this purpose. Mutual inductors are often required as standards of phase angle, and a further difficulty is to establish the phase angles of standard capacitors and resistors at 50 Hz with demonstrated traceability.

We have investigated an alternative approach that requires only a single resistor of value around 100 Ω with a known phase angle [1] as the standard.

2. Circuit description

The mutual inductance between two magnetically coupled windings is defined as the ratio of the open-circuit voltage across the terminals of the secondary winding to the rate of change of the current, which induces such voltage, flowing in the primary winding. For a sinusoidal excitation of angular frequency ω this definition may be expressed as

$$j\omega M = V_S / I_P \tag{1}$$

where M is the mutual inductance and V_S and I_P are the secondary voltage and primary current respectively. In practice the impedance of a mutual inductor is not purely inductive. Self and mutual winding capacitances give rise to a phase defect. Equation (1) should more correctly be written

$$R_M + j\omega M_M = V_S / I_P \tag{2}$$

where R_M and M_M are the equivalent series resistance and inductance of the non-pure mutual impedance.

The measurement method is to define the primary current I_P in terms of a reference voltage V_{ref} by means of a standard resistor R_{ref} and to compare the secondary voltage V_S with V_{ref}, scaled to be of the same magnitude as V_S by means of a separately excited standard inductive voltage divider (IVD).

The measuring circuit is shown schematically in Figure 1. The high current terminal of resistor R_{ref} is connected to a generator G. The low potential terminal of R_{ref} is connected to the input of a high-gain virtual earth amplifier, A1. The primary winding of the mutual inductor is connected between the output of A1 and the low current terminal of R_{ref}.

The reference voltage V_{ref} is the open-circuit voltage at the high-potential terminal of R_{ref}. This terminal is connected to the defining input of the IVD. The excitation input of the IVD is connected to the generator through a series injection transformer supplied by a voltage source, derived from G and adjustable in all four quadrants [1], by means of which the current taken from V_{ref} may be nulled.

The circuit diagram shows the secondary of the inductor connected to a second high-gain virtual earth amplifier A2. This arrangement allows the secondary voltage to be measured with the low terminal at virtual earth, as it would be in a balanced bridge configuration. Alternatively, if required, the low terminal may be connected directly to ground.

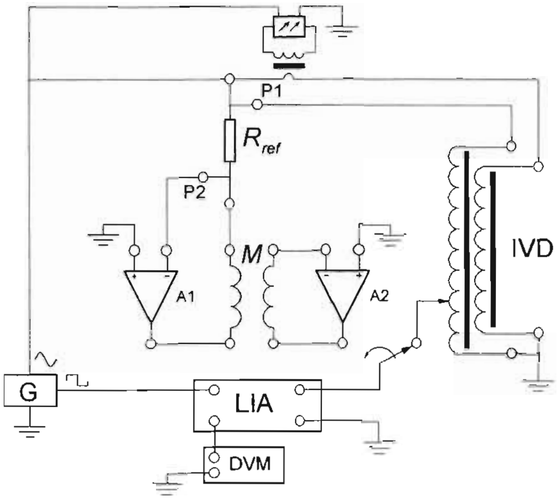

Figure 1. Measuring circuit configuration

The measuring circuit is completed with a lock-in amplifier, LIA, with its external phase reference provided by the generator as a square-wave signal. This square-wave signal is synchronous with the sinusoidal signal, and may be shifted in relative phase in precise steps of $\pi/2$ [2]. The dc output of the lock-in amplifier is connected to a digital voltmeter, DVM. Both DVM and generator are interfaced to a computer via the IEEE-488 bus.

3. Measurement procedure

The secondary voltage V_S of the mutual inductor and the scaled voltage V_D from the IVD are measured alternately with the lock-in amplifier and DVM combination. To minimise linearity requirements, V_D is adjusted to be closely equal in magnitude to V_S. Also, the internal phase control of the lock-in amplifier is adjusted to be close to $\pi/4$ relative to one phase of the reference signal, so that all resolved voltages are closely equal, apart from sign, as the reference signal is stepped through all four quadrature phases. In any complete measurement sequence, the lock-in amplifier and DVM are left strictly undisturbed.

The ac voltages V_S and V_D are resolved into sets of four dc voltages V_{Sn} and V_{Dn} corresponding to reference phase settings of $n\pi/2$ ($n=0,1,2,3$). Components of opposite phase are first combined as mean differences -

$$V_{S02} = (V_{S0} - V_{S2})/2 \quad \text{etc} \tag{3}$$

thereby cancelling any correlated dc offsets. V_S may then be expressed in terms of V_D by

$$V_S = V_D (V_{S02} + jV_{S13})/(V_{D02} + jV_{D13}) \tag{4}$$

$$= V_D(\alpha + j\beta) \tag{5}$$

where

$$\alpha = \frac{V_{S02}V_{D02} + V_{S13}V_{D13}}{V_{D02}^2 + V_{D13}^2} \tag{6}$$

$$\beta = \frac{V_{S13}V_{D02} - V_{S02}V_{D13}}{V_{D02}^2 + V_{D13}^2} \tag{7}$$

At power-line frequencies the separately-excited IVD is without significant error and its output voltage may be expressed simply as

$$V_D = \rho V_{ref} \tag{8}$$

where ρ is the setting of the ratio dials.

The equivalent circuit of the reference resistor may be regarded as a resistance R_{ref} in series with a reactance X_{ref}. The primary current I_P of the mutual inductor is then given by

$$I_P = V_{ref}/(R_{ref} + jX_{ref}) \tag{9}$$

Combining equations (2), (5), (8) and (9) gives

$$R_M + j\omega M_M = \rho(R_{ref} + jX_{ref})(\alpha + j\beta) \tag{10}$$

from which

$$R_M = \rho(\alpha R_{ref} - \beta X_{ref}) \tag{11}$$

$$M_M = \rho(\beta R_{ref} + \alpha X_{ref})/\omega \tag{12}$$

$$\begin{aligned}\phi_M &\equiv \tan^{-1}(R_M/\omega M_M) \\ &= \tan^{-1}(\alpha/\beta) - \tan^{-1}(X_{ref}/R_{ref})\end{aligned} \tag{13}$$

where ϕ_M is the phase defect of the mutual inductance.

The reference resistor used in our measurements has negligible phase angle (0.0 ± 0.1 µrad), and equations (11) - (13) may be simplified accordingly.

The resistance R_{ref} of the reference resistor was determined by comparison with a four-terminal 100 Ω resistor of known dc value and known ac-dc difference. For this purpose the four-terminal resistor was connected in place of the primary of the mutual inductor in the circuit of Figure 1, and the voltages between pairs of potential terminals were measured in a manner similar to that for the mutual inductor.

Because the derived value of mutual inductance is first-order frequency dependent, the generator frequency was monitored with a precision counter.

4. Performance

The circuit was used to measure the mutual inductance of a Tinsley variable mutual inductor Type 1737 that was set at approximately 12 mH. The signal source was set to 1 Vrms approximately and 54.945 Hz. The IVD dials were set so that V_D and V_S were matched in magnitude to within 5 in 10^5. Each measurement of the voltage detected by the lock-in amplifier comprised the set of four averages of twenty successive readings of the DVM, one at each of the four quadrature phase settings of the reference signal. Comparison of V_S and V_D consisted of ten such measurements of the one interleaved with ten of the other.

Table 1 summarises the uncertainties in the measurement of R_{ref}, M_M, R_M and ϕ_M.

Uncertainty component	R_{ref} (μΩ/Ω)	M_M (μH/H)	R_M (%)	ϕ_M (μrad)
Type A of output of lock-in amplifier	15	16	7	10
DVM resolution	3	4	2	2
R_{ref}	-	18	0	-
IVD ratio	-	1	0	-
Frequency	-	0	-	-
R_{SS}	3	-	-	-
Temperature	8	-	-	-
Root-sum-square of uncertainties	18	24	7	10

Table 1. Summary of uncertainties

The relatively large contribution to uncertainty in mutual inductance from the reference resistance is due to variability associated with its large temperature coefficient. A better procedure would be to use the phase-angle standard resistor to calibrate the phase angle of a more stable resistor, as advised by Thompson [1].

The second major source of uncertainty is the Type A uncertainty associated with the lock-in amplifier. Several different lock-in amplifiers were tried; the uncertainties given above were the best obtained.

5. Conclusion

A 12 mH mutual inductor has been calibrated at a frequency of approximately 50 Hz in terms of a resistor of known phase angle, with a standard error of 24 μH/H. This uncertainty could be reduced by substituting a more stable resistor for that used in these measurements. Further improvements might be achieved with a detector system that by design is optimised for the application.

Acknowledgements

The contributions of P.C. Coogan, in assisting with the setting up of the measurement system, and of J.M. Darlow, in constructing the feedback amplifiers, are gratefully acknowledged.

References

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[2] Small, G.W., Synthesizing signal generator for use with lock-in amplifiers in audiofrequency measurements, IEEE Trans. Instrum. Meas., Vol. IM-35, No. 3 (Sep 1986), 249-255.

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