

A METHOD FOR REDUCING SIMULATION PERFORMANCE GAP USING FOURIER FILTERING

Ljubomir Jankovic

Birmingham School of Architecture

Birmingham Institute of Art and Design, Birmingham City University

The Parkside Building, 5 Cardigan Street, Birmingham, B4 7BD, UK

ABSTRACT

The simulation performance gap is a discrepancy between simulated and actual performance of a building, occurring as result of differences between theoretical values in the simulation model and actual properties of and conditions in and around the building. It can be eliminated by a process of calibration of the simulation model if the simulated building exists and is being monitored. As simulations are primarily conducted in the design stage when the building does not yet exist, the calibration is not possible. This paper reports on a method for transferring results of calibration from an existing to a non-existing buildings of a similar type using Fourier filters, thus reducing the performance gap, and discusses advantages and limitations of the approach.

INTRODUCTION

Mainstream simulation models use libraries of building materials, construction types, occupancy patterns, HVAC system specifications, weather data and others, which rarely coincide with the corresponding properties in and conditions around real buildings. Together with the assumptions made by the model creator, this causes discrepancies between the results of simulation and the actual building performance, called the 'performance gap'.

The accuracy of simulation models can increase through the process of calibration, if the building already exists and is being monitored. During the calibration, the simulation model parameters are adjusted in a series of runs until the simulation results and the results of monitoring converge, within a specified error between the two.

Whilst the process of calibration eliminates the performance gap in the case of existing buildings, the calibration results are not transferrable to other models of buildings that are on the drawing board and have not yet been built.

This paper reports on a method that enables the results of calibration to be effectively transferred from an existing building to a building on a drawing board. This is done through the use of simulation, monitoring, calibration of the existing building, and the application of a Fourier filter to transfer the

calibration to a simulation model of the non-existing building. The results of this work can lead to the reduction of the simulation performance gap in non-existing buildings where calibration of a simulation model is not possible.

The existing building used in this research is the Birmingham Zero Carbon House (ZCH), which has been extensively monitored, and the author has extensively reported on the results of its performance elsewhere (Jankovic, 2012; Jankovic and Huws, 2012). In this paper, the ZCH will be used as an experimental test case site for the application of the Fourier method, providing monitoring and simulation results, and containing the simulation performance gap between the two.

Firstly, the monitoring data were used to calibrate the IES simulation model to less than 0.06% of energy error. The relationship between the calibrated and uncalibrated simulation model was subsequently established, expressing temperature time series from each of the two models as Fourier series. A Fourier filter was then created as a ratio between the respective Fourier series. Subsequently, the results of the IES simulation of the ZCH were subjected to a convolution with the Fourier filter, thus numerically regenerating the results of the calibrated model and verifying the method when it is applied on the same building.

Secondly, the Fourier filter obtained from the ZCH was applied to the results of simulation of a similar, non-existing building, thus obtaining the results that are equivalent of those from a calibrated model.

This method enables the simulation results of a non-existing building to be morphed into the results of its future calibrated simulation model, thus reducing the simulation performance gap.

The paper discusses the scope of this approach and its limitations, including the scale of differences between the existing and the non-existing building that still enables the successful application of the method.

This approach potentially opens a new area of research into building performance simulation, and in addition to leading to smaller performance gap, it can also lead to simplified but accurate dynamic models with considerably shorter computational times.

Background to Fourier transform

Fourier series was named in honour of the French mathematician Jean Baptiste Joseph Fourier, who in 1822 published 'The Analytical Theory of Heat'. He demonstrated that every periodic function can be represented with a combination of a series of sine and cosine waves with varying amplitudes and frequencies using a discrete transform:

$$f(x) = \frac{a_0}{2} + \sum_{k=1}^n (a_k \sin(kx) + b_k \cos(kx)) \quad (1)$$

where

$f(x)$ = periodic function of x

$a_{0,1,\dots,k}$ = weighting factors

n = number of harmonics.

This becomes particularly useful where there is a need to investigate the behaviour of a periodic function using different values of input variables, but the representation of the periodic function is not known. The Fourier series can therefore be used to build such function and make it available for experimentation.

As building energy flows are driven by periodic forcing functions, such as diurnal and annual cycles of solar radiation, external air temperature, and by occupancy patterns, the internal air temperatures and other performance parameters are also periodic. This discrete Fourier transform (DFT) is particularly suitable for modelling time series obtained from monitoring external conditions, in the form of:

$$f(x) = c_{av} + \sum_{k=1}^n c_{max,k} \cos\left(\frac{2\pi k}{n}x - \varphi_k\right) \quad (2)$$

where

c_{av} = the average level of periodic fluctuation

$c_{max,k}$ = maximum amplitude of the k -th harmonic

n = number of harmonics

φ = phase angle of the k -th harmonic

This representation of the Fourier transform can then be used for simplified modelling of buildings, where the time lag and decrement factor of the building are known or can be calculated. These two parameters can simply be inserted into the DFT of an external driving function, such as external air temperature, resulting in a simplified simulation model of the building, as follows:

$$f(x) = c_{av} + \sum_{k=1}^n d_{b,k} c_{max,k} \cos\left(\frac{2\pi k}{n}x - \varphi_k - \varphi_{b,k}\right) \quad (3)$$

where

$d_{b,k}$ = building decrement factor for the k -th harmonic

$\varphi_{b,k}$ = building time lag for the k -th harmonic

Limitations of the Discrete Fourier Transform

Jankovic (1988) experimented with Fourier models of buildings, representing data from monitoring with discrete Fourier series, and found encouraging accuracy of the models in comparison with results of dynamic simulations using TRNSYS simulation model, as well as with results of continuous instrumental monitoring. Even though this approach was limited to three harmonics for practical reasons, the building internal temperature was re-built with errors of less than 0.5 °C, in comparison with the measured room temperature, during 99% of the total simulation time. The simulation was carried out for a period of 14 days with hourly time steps. However, the omission of the remainder of the harmonics led to discrepancies between the actual and modelled dynamic behaviour, and this was expected to increase over a longer time period.

Dhar et al. (1999) applied discrete Fourier transform to modelling of hourly energy use in buildings. They modelled weather parameters using the Fourier transform, carried out day-typing to account for week days, weekends and holidays, and worked with a variety of daily and annual cycles. As result of using a few harmonics only, they achieved similar accuracy of predictions.

Luo et al. (2010) modelled wall heat transfer using a complex Fourier analysis method. Although the work showed close correspondence with measured values, the method involved simplifications and resultant errors.

Lu and Viljanen (2011) modelled external air temperature using Fourier series, and developed a simplified building model on that basis. Although a close match between analytical and measured performance was reported, the errors were not specifically quantified and appeared to be of similar magnitude as in other work referred to in this section.

Without simplifications, the number of operations to compute the DFT involves two nested loops of N points of the input signal, and the computational time is therefore proportional to $p \times N^2$, where p is a proportionality constant (Smith, 1997). In the case of dynamic simulation of an annual performance of a building, the total number of discrete data points for each output parameter is 8760, which is equal to the number of hours in the year. Measurements show that there are around 11,700 floating point operations (FLOPs) per each data point, and therefore the total number of FLOPs¹ per data point would be $11,700 \times 8760^2 = 8.98 \times 10^{11}$. Assuming a typical performance of modern microprocessors, such as those found in laptop computers, which was in the region of 10 Giga FLOPs¹ (floating point operations per second) at the time of writing this paper, the computation of a

¹ Note the difference between FLOPs = the plural of FLoating point OPeration and FLOPS = FLoating point OPerations per Second.

discrete Fourier series of 8760 points would take $(8.98 \times 10^{11}) / (10 \times 10^9) = 89.8$ seconds.

The CPU time is only a part of the story. Researchers who use spreadsheets to carry out discrete Fourier transforms would typically experience prolonged setup times of several minutes per harmonic, and computations in the spreadsheet would typically last longer than computations with a dedicated signal processing software. This is why Jankovic (1988) used only three harmonics and Dhar et al. (1999) used day typing in order to reduce the computational intensity of discrete Fourier transforms.

Overcoming limitations of Discrete Fourier Transform with Fast Fourier Transform

Discrete Fourier series can be computed in a much more efficient way using a Fast Fourier Transform (FFT), on the basis of Danielson-Lanczos Lemma (Weisstein, 2012). This approach makes the FFT computation proportional to $p \times N \times \log_2 N$, rather than to $p \times N^2$ (Smith, 1997). Using the same assumptions as above, the total number of FLOPs would be $11,700 \times 8760 \times \log_2 8760 = 1.34 \times 10^9$, which on a 10 Giga FLOPS machine would take $(1.15 \times 10^9) / (10 \times 10^9) = 0.13$ seconds of CPU time.

However, a further adjustment to this calculation needs to be made as the FFT algorithm can only deal with a number of points equal to the power of two ($N = 2^m$, where $m = 1, 2, 3, \dots$). As $2^{13} < 8760 < 2^{14}$, the total number of points in the FFT analysis of annual building time series needs to be extended to the upper end of this range, namely to $2^{14} = 16,384$. Details of how this can be done are discussed later in this paper.

In practice, researchers carrying out Fast Fourier Transform do not need to deal with individual harmonics as the FFT algorithm deals with all harmonics in one go, and therefore the preparation time is considerably shorter. The calculation does not involve simplifications and there is no consequent reduction of accuracy.

However, running an FFT in a spreadsheet, such as Excel, was at the time of writing of this paper limited to 4,096 points only, and it lasted approximately 12.6 seconds on a 10 Giga FLOPS machine. This means that hourly values of an annual time series, such as internal air temperatures in a building, would need to be broken into three parts, and the FFT algorithm would need to be run on each part, adding to the preparation and the execution time. This also means that the spreadsheet adds about 217 FLOPs to the calculation of each point, as $11,700 \times 4096 \times \log_2 4096 = 5.75 \times 10^8$, which on a 10 Giga FLOPS machine would take 0.058 seconds, but it takes 217 times longer, namely 12.6 seconds.

Despite the computational advantages of the FFT explained above, frequent FFT analysis of time series obtained from monitoring or simulation of a building with an hourly time step would therefore be a very time consuming task if using a spreadsheet program.

The alternative to running the FFT in a spreadsheet would be to develop a bespoke FFT program, which takes the required number of points, performs the FFT algorithm and outputs the results. For instance, an FFT program developed by the author in Java programming language takes 272 milliseconds to compute the Fourier transform of 16,384 points on a 10 Giga FLOPS machine, thus containing the entire year worth of hourly data and considerably reducing the computation and preparation time.

The FFT algorithm combined with its implementation as a stand-alone software application therefore opens up research opportunities for modelling of time series obtained from monitoring or simulation of buildings. As no simplifications need to be made that would have an impact on accuracy, the FFT representation of a time series will be almost identical to the original input signal, with practically zero error. The fast execution time of the stand-alone implementation of the algorithm and the minimum preparation time have enabled frequent experimentation with the FFT by the author and the development of the method reported in this paper.

The next section will describe the theoretical basis of this method, and the subsequent section will explain the results of application in building performance analysis.

METHOD

The method reported in this paper will use the FFT to create an accurate response function as a ratio between calibrated and uncalibrated simulation results of an experimental building. The response function will be applied as a Fourier filter to a simulation of another, non-existing building. Assuming that the experimental building and the non-existing building are of similar types, the convolution of the signal, such as room air temperature, and the response function will be equivalent to the results of a calibrated simulation of that non-existing building. The method can therefore be summarised in the following steps:

1. create a simulation model of an existing building and calibrate it using data from monitoring;
2. represent the time series, such as temperature or relative humidity, from the calibrated and uncalibrated simulation, as separate Fourier series;
3. assume that the calibrated time series is a result of a certain response function acting on the uncalibrated time series (in other words that the calibrated time series is the result of convolution between the uncalibrated time series and the response function) and obtain the response function through de-convolution between the calibrated and uncalibrated time series; this response function is named a 'Fourier filter';

4. create a simulation model of a future building and obtain time series of its performance parameters, such as room air temperature, from the simulation;
5. represent the time series obtained in the previous step as Fourier series;
6. create a convolution between the Fourier series from the previous step and the Fourier filter; the result is a representation of a calibrated simulation output for a future building - a building on the drawing board.

How can it be justified that the resultant convolution for the future building is the same as for the existing building? Considering that this method only compares the performance of thermal envelopes in a free floating mode, with heating systems switched off and the buildings driven solely by the same external conditions, the comparison is regarded as appropriate, and it will be subjected to further work as data from monitoring of more buildings become available. Details of geometry will be different, and so will the results of simulations.

When the filter is applied to these simulation results, the convolution will reflect the differences between geometry of the two buildings, but it will also transfer the essence of behaviour from the existing building to the new building.

In order to specify this method using mathematical formalism, the nomenclature defined in the end of this paper will be used.

With that nomenclature in place, the specification of the method becomes considerably simplified. The objective is to obtain

$$m_{i,f} \quad 1 \leq i \leq K \quad (4)$$

This is done firstly by creating the Fourier filter as a de-convolution of the series $M_{i,e}$ and $S_{i,e}$

$$R_j = M_{i,e} / S_{i,e} \quad (5)$$

Having obtained the Fourier filter, the Fourier transform of the simulated time series of the future building $s_{i,f}$ is obtained as $S_{i,f}$. Subsequently, the multiplication of the two Fourier transforms $S_{i,f}$ and R_j gives

$$S_{i,f} R_j = M_{i,f} \quad (6)$$

and the inverse Fourier transform, as explained by Press et al. (2007), represents the convolution of $S_{i,f}$ and R_j in the form of

$$M_{i,f} \Rightarrow m_{i,f} \quad 1 \leq i \leq K \quad (7)$$

Applying the filter to building simulation results

Results of annual simulations carried out with an hourly time step consist of 8760 lines, representing the number of hours in the year. As FFT algorithms can only deal with a number of points equal to the power of two, and as $2^{13} < 8760 < 2^{14}$, the total number of points needs to be extended to 16384. The data set will therefore contain many unused points.

Literature sources (Press, et al. 2007) suggest zero-padding of the extended points. In other words, all points between 8761 and 16384 should be set to zero. However, the use of this approach appears to distort the result by lowering the average level of the filtered signal (Figure 1). Several variations of the application of this method were investigated by the author, applying Equations (6) and (7). The best results were obtained when actual data points from the start of the data set were used for padding, so that 8761st point was equal to the 1st point, 8762nd was equal to 2nd, and so on to the 16384th point (Figure 1).

According to the same authors (Press, et al. 2007), filters shorter than the full data set should be split into half; the first half should be aligned with the start of the signal time series; the second half should be aligned with the end of the signal time series; and the points in between the first half and the second half of the filter should be zero-padded. After the application of the Fourier filter, this approach appeared to result in smoothing out of the resultant time series, thus distorting the dynamic response of the signal (Figure 1). However, the author has obtained a much more dynamically responsive signal with a recursive filter - a filter that is repeated as many times as necessary in order to get the number of filter points equal the number of signal points (Figure 1). The same applies to a full length filter, in cases where it is possible to obtain it. As de-convolution of calibrated and uncalibrated annual simulation results provides a full length filter, this kind of filter will be used in this paper.

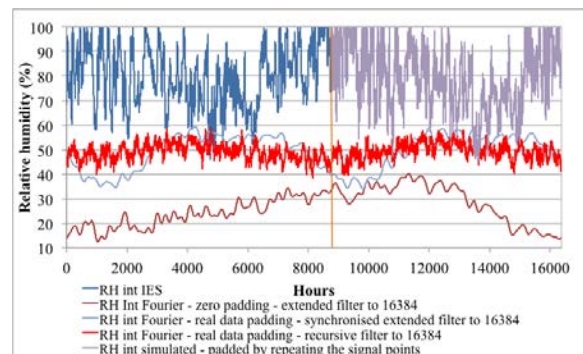


Figure 1 Experiments with signal and filter padding

A question can be raised whether the padding of extra hours from the start of the data set introduces any weighting that would cause errors? As we will see in Figure 3 later in the paper and the related commentary, the rebuilt temperature is not exact, and

one of the reasons for this is the padding method. However, the error is so negligible (0.0005 °C), that the padding method is justified.

SIMULATIONS AND RESULTS

This section will explain the simulation models used; the calibration of the simulation models; the making of the Fourier filter using the performance gap, and the application of the Fourier filter.

Simulation Models

In order to apply the Fourier filtering method, two simulation models were developed: a model of the Zero Carbon House (ZCH), and a model of one other Victorian house (OVH). The latter was similar to the ZCH in terms of the age and construction types.

Whilst the ZCH was retrofitted to carbon negative performance in the real life, the OVH was in its original form. However, the OVH was retrofitted to carbon negative performance in the simulation model, by using exactly the same construction types, thermal insulation, internal heat gains, infiltration heat losses, operation templates, and a PV system.

Simulation model calibration

Calibration of the ZCH simulation model was carried out on the basis of data obtained from instrumental monitoring. The instrumentation system in the ZCH measures and records 20 parameters every minute, including internal air temperatures, heat meters, solar PV generated electricity, total electricity use, as well as external air temperature and solar radiation on the roof plane.

The process included both energy and temperature calibration, and resulted in a model with a mean square root temperature error of less than 0.95°C, and a relative error between simulated and actual energy consumption of 0.06% (Jankovic and Huws, 2012).

The calibration method used was analogous to bracketing in artillery fire, in which the first shell is aimed beyond the target and the second shell is aimed short of the target, so as to establish the initial range (bracket) in which the target is. The process is then repeated, reducing the overshoot and undershoot by adjusting the angle of the weapon, until the target is hit. Taking this analogy back to the simulation, the overshoot and undershoot was achieved by adjusting the heating set temperature and infiltration rate, one at a time, and repeating the process until the error between the simulation result and the target was reduced to a desired magnitude. There were two types of targets, which were used one at a time: monitored annual heating energy consumption; and monitored hourly temperatures. In the case of the former, the relative error was calculated as shown in Equation 8

$$\varepsilon = \frac{(\text{simulated} - \text{actual})}{\text{actual}} \quad (8)$$

and in the case of the latter, the mean square root error was calculated as shown in Equation 9.

$$\varepsilon = \sqrt{\frac{\sum_1^N (\text{simulated} - \text{actual})^2}{N}} \quad (9)$$

Performance gap and making the Fourier filter

Firstly, the Fourier filtering method will be applied to ZCH to obtain a relationship between calibrated and uncalibrated temperature time series. Subsequently, the Fourier filter obtained from the ZCH will be applied to the OVH time series. As the OVH time series is by definition uncalibrated because the OVH is not monitored, the application of the Fourier filter will transfer the results of calibration from the ZCH to the OVH, as explained in the following sections.

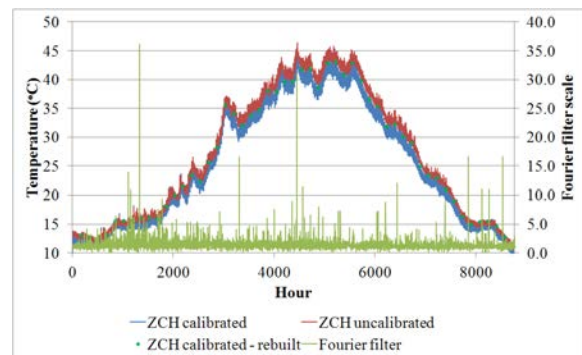


Figure 2 Performance gap, Fourier filter and a rebuilt original signal

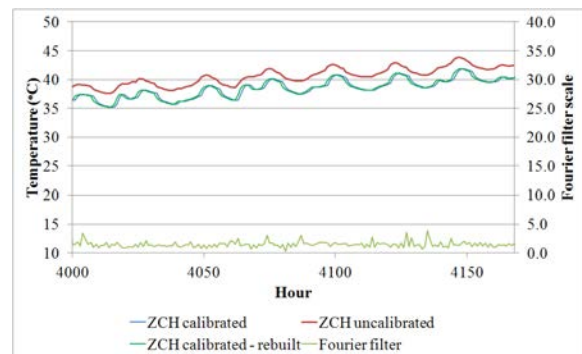


Figure 3 Magnified performance gap, Fourier filter and a rebuilt original signal

A ratio between Fourier transforms of calibrated and uncalibrated time series of the ZCH living room temperatures (Figure 2) was first created. This ratio, shown in the time domain in Figure 2, comprises a Fourier filter that will be used later in this analysis.

Prior to making the Fourier filter, the heating was switched off in all three simulation models (ZCH calibrated, ZCH uncalibrated, and OVH uncalibrated), so that the models were running in a free-floating mode. The calibrated ZCH model was then used as the basis for the application of the Fourier filtering method.

In order to check the accuracy of the Fourier filter itself, the ZCH calibrated time series was subsequently rebuilt in a reverse process, by applying the Fourier filter to the ZCH uncalibrated time series. The overall result is shown in Figure 2, where the rebuilt time series, shown with green markers, appears to be identical to the original ZCH calibrated time series.

As the time scale in Figure 2 does not give a clear indication of how close the rebuilt time series is to the original signal, Figure 3 shows the same data in a magnified time scale. As it can be seen from this figure, the rebuilt and the ZCH calibrated time series are actually not identical, but they are pretty close.

The rebuilt temperature was not exact for two reasons: Fourier series is an approximation of the original series; and padding of extra hours with the start of the data set is also believed to introduce a further error.

A root mean square error between ‘ZCH calibrated’ and ‘ZCH calibrated – rebuilt’ was calculated, and it was found to be 0.0005 °C, indicating very high accuracy of the method and of the Fourier filter. Additionally, as Figure 3 shows, the rebuilt time series follows the dynamic fluctuations of the ZCH calibrated time series quite well.

Application of Fourier filter on the OVH building

The Fourier filter obtained in the previous section was then applied on the time series of living room temperatures obtained from the OVH simulation.

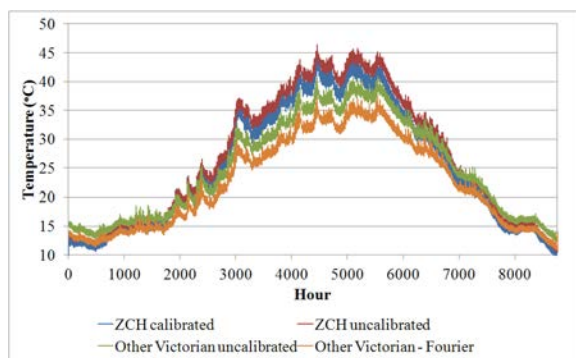


Figure 4 Application of the Fourier filter on simulation results of a Victorian house

The results are shown in Figure 4, alongside the time series from the ZCH. In a similar way as in the ZCH case, the Fourier filtered temperature time series in the OVH is lower than the time series in the corresponding uncalibrated model.

The corresponding pairs of temperature time series: (ZCH calibrated, ZCH uncalibrated), and (Other Victorian – Fourier, Other Victorian uncalibrated), appear to be in a similar, but not in an identical relationship (Figure 4).

This is even more evident from the analysis of the frequency of occurrence of the four temperature time series, shown in Figure 5. As it can be seen from

Figure 5, ‘ZCH calibrated’ and ‘Other Victorian – Fourier’ temperatures are generally above the respective uncalibrated temperatures, but not in exactly the same relationship. The meaning of these results will be discussed in the next section.

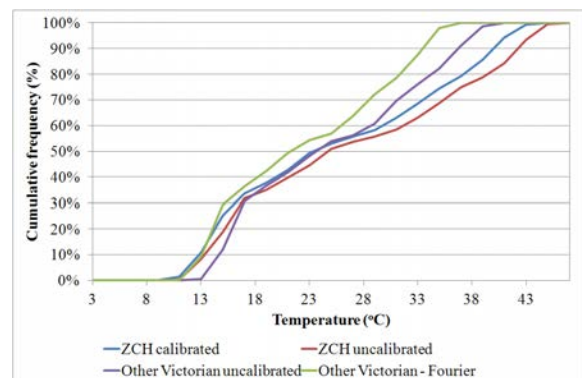


Figure 5 Analysis of frequency of occurrence of temperatures

DISCUSSION

Despite the similarities of the ZCH uncalibrated and OVH uncalibrated models explained above, the geometry of the two buildings is different, as well as orientation and the amount of glazing. This explains why the results of the two uncalibrated models are not identical but different.

As the Fourier filter is created from the ratio between the Fourier transforms of temperature time series obtained from the calibrated and uncalibrated simulation models, it captures the essence of the performance gap between the two. Due to the application of this filter, the differences between ‘ZCH calibrated’ and ‘Other Victorian – Fourier’ temperatures in Figure 4 and in Figure 5 are in a similar relationship to their uncalibrated equivalents.

How would we then use the time series, such as ‘Other Victorian – Fourier’, obtained through Fourier filtering? In other words, how a simulation model of the non-existing building can benefit from an external time series obtained from Fourier filtering?

The answer is simple: the time series obtained from Fourier filtering can be used for the purpose of calibration of the simulation model of the non-existing building, thus transferring the reduction of the performance gap into that model.

Although the designer does not gain any insight from the results of convolution as to which parameter during building operation might cause the simulation performance gap, considerable details of these parameters will become apparent if the convolution is used as a target for the simulation model, and the calibration of the simulation model is carried out so as to reduce the error between it and the target.

If the existing and non-existing building are sufficiently similar, and if the corresponding simulation models were built using the same

principles, construction types, thermal insulation, thermal mass, internal heat gains, infiltration heat losses, etc., then the performance gap in the cases of both models will be similar.

Therefore, even if there are inherent inaccuracies in this method resulting from the differences between the two buildings, the performance gap will certainly be reduced in the case of the non-existing building, as result of the application of the Fourier filter.

It is not possible at this stage to say exactly how similar the performance gap obtained in this way in the two buildings actually is. Although the results of the filtering applied to the building on the drawing board cannot be verified, this will be the subject of further research by the author, as monitoring data from more buildings become available.

The method presented in this paper can therefore be regarded as a transfer of the results of calibration of a simulation model from an existing building that is being monitored, to a simulation model of a building that either does not exist or that it is not being monitored. Effectively, the method can also be regarded as a transfer of the results of monitoring from an existing to a non-existing building. Both buildings need to be of similar properties and construction types, whilst geometry can be different.

There are no critical inputs required for the simulation model in order to perform Fourier analysis, except that the simulated building needs to be based on the same materials, construction types, operating profiles etc. as the source building used for generating the filter. The extent to which the buildings need to be similar is in terms of their envelope construction types and thermal mass. Differences in geometry will be reflected in the simulation results, and the application of the filter will morph these simulation results into the kind of behaviour that would be expected from the non-existing building. Both models of the existing and non existing building need to be run in a free-floating mode, by switching off the heating systems in them, but leaving the sources of internal gains, and infiltration losses.

There is a body of knowledge on the performance gap that recognises the shortcomings of modelling programs in addition to other factors that cause discrepancies between designed and actual performance, such as poor assumptions and lack of monitoring (Menezes et al., 2011). Causes of the performance gap are divided into several categories, such as regulated energy (from fixed building services); unregulated energy (from lifts, security, plug loads etc.); extra occupancy; inefficiencies arising from poor control, commissioning and maintenance); and from special functions, including trading floors, server rooms etc. (Carbon Trust, 2011; RIBA/CIBSE, 2010).

The study presented in this paper deals with shortcomings of the modelling program, as well as

with regulated and unregulated energy use, and inefficiency caused discrepancies, which were all taken into account through calibration. Given sufficient number of monitored buildings, this method has a potential to deal with all other causes of the performance gap.

Menezes et al. (2011) suggest that the way forward in reducing the performance gap is to use post occupancy monitoring data in order to develop realistic benchmarks of building energy performance. This approach would however represent the expected building performance as a single number in terms of energy consumption in kWh/m²/annum, and it would not give insights into dynamics of building performance on an hourly basis throughout the year. The method presented in this paper would open new opportunities for dynamic benchmarks, based on Fourier filters developed for different building types.

CONCLUSIONS

A discrepancy between design simulations and performance of an actual completed building occurs on a regular basis. This is commonly referred to as a 'performance gap' and it is a major reason for building underperformance. The performance gap occurs as result of differences between theoretical values of properties of building materials, and various assumptions in the simulation model on the one hand, and actual properties of building materials, building use, and conditions in and around the building on the other hand.

A method for reducing the performance gap has been developed using principles of digital signal processing based on Fourier series. The method is based on the creation of a digital filter that captures the relationship between Fourier transforms of results of calibrated and uncalibrated simulation models for an existing building. The filter is then applied to simulation results of a non-existing building, morphing these results into values that are equivalent to results of a calibrated simulation model of the non-existing building. Effectively, the results of monitoring of an existing building can be transferred in this way to a non-existing building.

Whilst the Fourier filter obtained in this way captures the essence of the performance gap in the existing building, it is not exactly known at this stage how accurate will be the outcome of the application of the Fourier filter on the simulation results of a non-existing building.

Although this method needs further testing and verification using data from monitoring of other buildings, it is reasonable to conclude that the Fourier filter will move the results of simulation of the non-existing building closer to what they would be in reality when the building is completed.

This work therefore goes already now some way towards the reduction of the performance gap, bearing in mind the limitations discussed.

This work can be also viewed as a method to produce target time series of performance data for tuning simulation models, and subsequent investigation of different patterns of building use that informs the design team about the robustness of their concept.

A successful verification of this method would open new opportunities for reduction of the performance gap, which would go further than evidence based benchmarks proposed by other authors. Whilst a conventional benchmark would be a single number that gives annual energy consumption per square metre without any insights into the dynamics of building energy performance, the Fourier filter based response functions for different building types would comprise a dynamic, high granularity equivalent. This method also opens opportunities for the creation of simplified but accurate simulation models.

The future work will involve a wider scale investigation of transferability of monitoring and calibration results between similar building types, in which both the source and the destination buildings are monitored, thus verifying the quality of transfer.

NOMENCLATURE

ZCH= Zero Carbon House

DFT= Discrete Fourier Transform

FFT= Fast Fourier Transform

$m_{i,e}$ = discrete values of the calibrated simulation time series of the existing building, $1 \leq i \leq K$

$M_{i,e}$ = DFT of the calibrated time series $m_{i,e}$

$s_{i,e}$ = discrete values of the uncalibrated simulation time series of the existing building, $1 \leq i \leq K$

$S_{i,e}$ = DFT of the uncalibrated time series $s_{i,e}$

r_j = discrete values of the response function (or of the Fourier filter), $1 \leq j \leq L$

R_j = the response function (the Fourier filter)

$s_{i,f}$ = discrete values of the uncalibrated simulation time series from a future building (a building being designed or a building that exist but it is not monitored), $1 \leq i \leq K$

$S_{i,f}$ = DFT of the uncalibrated time series $s_{i,f}$

$m_{i,f}$ = representation of the calibrated time series of the future building, $1 \leq i \leq K$

$M_{i,f}$ = DFT of the representation of calibrated time series $m_{i,f}$ of the future building

ε = error

N = number of data points

OVH=Other Victorian House

ACKNOWLEDGEMENT

Collaboration with Lime Technology Ltd; with Emission Zero R&D Ltd; and with Mr John Christophers of Birmingham Zero Carbon House is gratefully acknowledged. Monitoring of the Zero Carbon House was partially funded by the Higher Education Innovation Fund.

REFERENCES

- Carbon Trust (2011) *Closing the gap - Lessons learned on realising the potential of low carbon building design*. Carbon Trust. Available from: http://www.carbontrust.com/media/81361/ctg04_7-closing-the-gap-low-carbon-building-design.pdf. [Accessed in February 2013].
- Dhar, A., Reddy, T.A., Claridge, D.E., 1999. Generalization of the Fourier series approach to model hourly energy use in commercial buildings. *Journal of Solar Energy Engineering, Transactions of the ASME* 1999;121(1):54-60.
- Jankovic, L., 2012. *Designing Zero Carbon Buildings Using Dynamic Simulation Methods*. Routledge. London and New York.
- Jankovic, L., 1988. *Solar Energy Monitoring, Control and Analysis in Buildings*. PhD Thesis, The University of Birmingham.
- Jankovic, L. & Huws, H. 2012. Simulation Experiments with Birmingham Zero Carbon House and Optimisation in the Context of Climate Change. In: ENGLAND, I. (ed.) *Building Simulation and Optimisation 2012*. Loughborough: IBPSA.
- Lu, X., Viljanen, M., 2011. Analytical Model for Predicting Whole Building Heat Transfer. *World Academy of Science, Engineering and Technology* 76, 2011
- Luo, C., Moghtaderi, B., Page, A., 2010. Modelling of wall heat transfer using modified conduction transfer function, finite volume and complex Fourier analysis methods. *Energy and Buildings* 42 (2010) 605–617.
- Menezes, A. C., Cripps, A., Bouchlaghem, D., Buswell, R. (2012). Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post Occupancy Evaluation Data to Reduce the Performance Gap. *Applied Energy*, Volume 97, September 2012, Pages 355-364
- Press, W. H., Teukolsky, S. A., Vetterling, W. T., Flannery, B. P., 2007. *Numerical Recipes 3rd Edition: The Art of Scientific Computing*. Cambridge University Press, Cambridge.
- RIBA/CIBSE (2010) *Carbon Buzz*. Available from: http://www.carbonbuzz.org/docs/CarbonBuzz_Handbook.pdf. [Accessed in February 2013].
- Smith, S. W., 1997. *The Scientist and Engineer's Guide to Digital Signal Processing*. California Technical Publishing, San Diego, California.
- Weisstein, E. W., 2012. *Danielson-Lanczos Lemma*[online]. From MathWorld - A Wolfram Web Resource. Available from: <http://mathworld.wolfram.com/Danielson-LanczosLemma.html>. [Accessed October 2012].