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Direction and surface sampling in ray tracing for spacecraft radiative heat transfer

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ABSTRACT

This paper addresses the computation of radiative exchange factors through Monte Carlo ray tracing with the aim of reducing their computation time when dealing with the finite element method. Both direction and surface samplings are studied. The recently-introduced isocell method for partitioning the unit disk is applied to the direction sampling and compared to other direction sampling methods. It is then combined to different surface sampling schemes with either one or multiple rays traced per surface sampling point. Two promising approaches present better performances than standard spacecraft thermal analysis software. The first approach combines a Gauss surface sampling strategy with a local isocell direction sampling, whereas the second approach fires one ray per surface points using a global isocell direction sampling scheme. The advantages and limitations of the two methods are discussed, and they are benchmarked against a standard thermal analysis software using the entrance baffle of the Extreme Ultraviolet Imager instrument of the Solar Orbiter mission.

1. Introduction

The finite element method (FEM) is widely used in mechanical engineering, in particular for space structure design. However, it is not yet often exploited for thermal engineering of space structures for which the use of the finite difference method (lumped parameter or network-type method) is still commonplace [1,2]. When thermal and structural analyses are based on different meshes and methods, one limitation is that coupled analyses are not straightforward.

The main reason why FEM is not often used for heat transfer analysis of spacecraft systems is that the computation of the radiation couplings, which are necessary for radiative heat transfer, is extremely expensive. The radiation (or radiative) coupling $GR_{i,j}$ between face i and face j is equal to the radiative exchange factor (REF) $B_{i,j}$ between face i and face j multiplied by the area of face i and its emittance: $GR_{i,j} = A_i \epsilon_i B_{i,j}$. The radiative exchange factor $B_{i,j}$ is defined as the fraction of the total energy emitted by face i that is absorbed by face j either directly or after any number or type of reflections and/or transmissions. It generalizes the view factor $F_{i,j}$ which considers only the diffuse energy leaving face i that is directly intercepted by face j.

An additional difficulty is that classical reduction methods which rely on the superposition of thermal modes [3] cannot be applied in view of the nonlinear nature of heat transfers coupling conduction and radiation. Alternative projection methods were proposed in the literature. In [4,5], the linear reduced basis is enriched with, e.g., modal derivatives, but several iterations are required to converge to an adequate basis. There also exist other modal bases including nodal temperature derivatives [6] or trajectory piecewise linearization [7]. Proper orthogonal decomposition was also used to derive the optimal basis corresponding to a specific load case [8–12]. The main drawback of these reduction schemes is that simulations using the full model have to be carried out.

Instead of reducing *stricto sensu* FEM-based thermal models, another strategy for decreasing the computational burden is to focus specifically on the REFs. In this context, the most general method for REF computation is Monte Carlo ray tracing (MCRT) [13–15]. This method is, however, very computationally expensive due to the great number of elements composing a FE model. As a result, a great number of rays have to be fired to obtain meaningful REFs.

Monte Carlo methods were introduced in nuclear engineering during the 1940s and were first utilized for thermal radiation problems in the early 1960s by Fleck [16] and Howell [17,18]. In aerospace engineering, the MCRT method was introduced in the

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1970s with the NEVADA code [2]. Nowadays, it is part of most realistic radiative heat transfer software. The drawback of crude Monte Carlo techniques is their relatively low convergence rate τ which is the rate at which the error decreases as the number of traced rays increases: $error \propto N^{-\tau}$ with N the number of rays. For crude Monte Carlo techniques, the error is inversely proportional to the square root of the number of rays, i.e. $\tau = 0.5$ [19–22]. Many acceleration techniques were introduced in the different fields applying MCRT. This includes hardware acceleration using, e.g., graphics processing units. In [23], a broad classification of software acceleration techniques is given, namely computing faster ray-face intersections by reducing the number of intersections to compute or improving the intersection algorithms, firing fewer rays or firing generalized rays. We note that the latter approach is not suited for REF computation [24].

The main thrust of this study is to accelerate REF computation by firing less rays, which requires to improve the convergence rate of MCRT. One possible way for increasing the convergence rate is to consider quasi-Monte Carlo methods [19,25]. Unlike the classical Monte Carlo method which relies on a sequence of pseudo-random numbers, the quasi-Monte Carlo method exploits low-discrepancy sequences. Sobol and Halton sequences were for instance used in MCRT problems [26,27] to generate more uniform sampling directions.

Another quasi-Monte Carlo approach for generating more uniform samples over the integration domain is to use stratified sampling [19,25,28]. Stratified sampling consists in dividing the integration domain into *strata* which are randomly sampled independently to avoid aliasing. In [24], stratified sampling is applied to the hemisphere to generate more uniform directions. Each stratum in the method corresponds to the same view factor share of the hemisphere, but the strata do not exhibit the same shape, which can deteriorate the performance in particular configurations.

In this context, the first contribution of the paper is to improve the direction sampling of MCRT through the recently-developed isocell disc sampling method [29]. Specifically, more uniformly-shaped strata are sought. The second contribution of the paper is to study carefully the spatial sampling of the emitting face [30] and its interaction with direction sampling, something which has been rarely carried out in the literature.

The paper is organized as follows. The classical Monte Carlo method is briefly described in Section 2. Different direction sampling strategies are presented in Section 3, with a particular attention to the isocell method. The application of different direction sampling strategies to the computation of pointwise view factors concludes Section 3. The interaction between direction and surface samplings is studied in Section 4 with the aim to compute finite-surface-to-finite-surface REFs. Local (for each surface sample) and global (distributed among all surface samples) direction sampling strategies are analyzed. Section 5 presents the application of two selected combinations of direction and surface samplings to a real space structure. The conclusions of the paper are summarized in Section 6.

2. Monte Carlo ray tracing

MCRT consists in tracing the history of statistically meaningful samples of photons (or photon bundles called rays) from their point of emission to their final absorption. It can be used to compute the view factors, but the REFs can also be determined without adding too much complexity by taking into account multiple reflections/transmissions and real surface properties. Unlike classical analytical and numerical quadrature methods which become rapidly ineffective for complex geometries, the computational burden of Monte Carlo methods increases only linearly with the size and complexity of the problem.

The basic idea of Monte Carlo methods is that the number of rays must be large enough to be statistically meaningful so that the REF is accurately computed. If N_i rays are emitted from the surface i among which N_{ij} rays are absorbed by surface j either directly or after any type/number of reflections/transmissions, the REF $B_{i,j}$ between surfaces i and j is:

$$B_{i,j} = \lim_{N_i \to \infty} \frac{N_{ij}}{N_i} \cong \left. \frac{N_{ij}}{N_i} \right|_{N_i >> 1} \tag{1}$$

Because it is a stochastic method, the results exhibit some fluctuations, but the variance decreases as the number of samples increases. The inconvenience of crude Monte Carlo techniques is their relatively low convergence rate, i.e., the error is inversely proportional to the square root of the number of rays [19–22]. We note that the view factor $F_{i,j}$ is obtained by considering only direct absorption without any reflection or transmission of any kind.

3. Direction sampling

To compute the exchange factors between one specific surface and the surrounding surfaces, the rays must be distributed over the directions and over the emitting surface, in the same way that analytical view factor computation involves a double integration. Direction sampling of the unit hemisphere leads to the pointwise view factor F_{dA_i,A_j} between infinitesimal surface dA_i and finite surface A_j which is then integrated over the emitting surface A_i with surface sampling. This section focuses on direction sampling and compares the performance of different schemes, including the new isocell method which aims at increasing the convergence rate and accuracy of MCRT. The effect of spatial sampling is discussed in Section 4.

3.1. Sampling schemes

The most common direction sampling method is based on the cosine emission law (Lambert's cosine law [31]) for perfectly diffuse surfaces. The polar angle θ and azimuthal angle ϕ can be derived from two pseudo-random numbers R_θ and R_ϕ in $[0, 1]$ [15,21]:

$$\theta = \arcsin \sqrt{R_\theta} \quad \phi = 2\pi R_\phi \tag{2}$$

with the ray direction given by:

$$\boldsymbol{r}(\theta, \phi) = [\sin\theta \cos\phi \quad \sin\theta \sin\phi \quad \cos\theta]^\mathsf{T} \tag{3}$$

Based on Nusselt's analogy [32] which states that the pointwise view factor between a point P on surface i and a surface j is equal to the area of its orthographic projection[1] A'_j divided by π (ratio of the projected area to the area of the unit disc), Malley [33] proposed an equivalent method to generate the ray directions by sampling the unit disc with uniformly distributed pseudo-random numbers. Each point on the unit disc defines a direction by projecting it back to the unit hemisphere. With this method, the ray directions are

$$\boldsymbol{r}(r, \phi) = \left[r\cos\phi \quad r\sin\phi \quad \sqrt{1 - r^2} \right]^\mathsf{T} \tag{4}$$

where ϕ is given by Eq. (2). Eq. (4) is equivalent to Eq. (3) since $r = \sin\theta$. Crude Monte Carlo, which samples the unit disc randomly as in Fig. 1(a), is the technique used by the European Space Agency thermal analysis software ray tracing engine ESARAD [21,34].

[1] The orthographic projection is composed of a projection on the unit sphere centered on point P and an orthogonal projection onto the plane of tangent to the surface i and point P.