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Analytical Studies on Design Optimization of Movable Louvers for Space Use

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A systematic and generalized analysis has been made for evaluation of thermal control characteristics of movable louvers with a finite number of blades. The analysis is based on the assumption that the temperature of each blade is uniform and all blades are infinite in length. The modified radiosity approach is used to describe multiple reflections in a louver channel. The formulation is extended to include the radiant interchange due to one, two, or three intervening specular reflections. The image method is employed to estimate generalized view factors expressing fractions of radiant interchange due to specular reflections. A semigray spectral subdivision of surface properties is employed to account for differences in property values for solar and surface radiation. In each spectral interval a reflectance model with both diffuse and specular components is used to approximate the nondiffuse character of surface reflectance. An algorithm based on three-dimensional analytical geometry is developed for estimating the intensity of the solar field in a louver channel. The analysis yields closed-form expressions with which one can calculate effective emittance, solar rejection capability, and base surface temperature required for active thermal control. Numerical results of parametric studies are presented to aid the optimal design of movable louvers for space use. The results on effective absorptance and blade temperature are compared with experimental results obtained for thermal control louvers used on the ATS-F&G spacecraft. Agreement is good in spite of some differences between model and reality.

Nomenclature

a	= coefficient defined in Eqs. (10) or (30)
B	= dimensionless diffuse and specular coradiosity defined in Eqs. (8) or (28)
b	= coefficient defined in Eqs. (11) or (31)
D	= coefficient defined in Eq. (23)
E	= exchange factor defined in Eqs. (12) or (32)
F	= traditional or generalized view factor given in Appendix A or B
G	= dimensionless solar irradiance, defined in Eq. (40), due to both direct impingement and intervening specular reflections
H	= dimensionless solar irradiance, defined in Eq. (36), due to diffuse reflections
H_S	= coefficient defined in Eq. (27)
I_S	= solar constant
l	= half blade length normalized by blade spacing
ℓ, m, n	= directional cosines of specularly reflected solar flux, given in Eqs. (44b), (46b), (48b), or (50b)
M	= number of solar subfluxes
N	= number of louver channels ($N+1$ = number of blades)
p	= dimensionless distance given in Eqs. (44c), (46c), (48c), or (50c)
Q	= absorbed solar energy, given in Eq. (26)
Q_I	= electric heat generation on base surface
q	= dimensionless heat input defined in Eq. (21)
T	= absolute temperature
T_0^*	= reference temperature defined in Eq. (18)
$\boldsymbol{D}$	= directional cosine vector defined in Eq. (39)
$\boldsymbol{e}$	= unit or zero vector defined in Eq. (34)
$\boldsymbol{J}$	= vector defined in Eq. (37), used for calculating factors G_1, G_2, and G_3
$\boldsymbol{N}$	= surface normal vector defined in Eq. (38)
$\boldsymbol{n}$	= vector defined in the second expression of Eqs. (46a), (48a), or (50a), expressing N_1, N_2, or N_3
$\boldsymbol{R}$	= vector defined in Eq. (33), used for calculating factors H_1, H_2, and H_3
$\boldsymbol{r}$	= vector defined in Eq. (44a) or in the first expression of Eqs. (46a), (48a), or (50a), expressing $\boldsymbol{e}_1$, $\boldsymbol{e}_2$, $\boldsymbol{e}_3$, or $\boldsymbol{e}_4$
$\boldsymbol{r}_S$	= vector defined in Eq. (35), consisting of specular components of solar reflectances
α	= solar absorptance
β	= blade width normalized by blade spacing
Δ	= error index defined in Eq. (54), used for evaluating edge effect
ϵ	= infrared emittance
μ	= temperature ratio defined in Eq. (3) or dimensionless temperature defined in Eq (19)
ρ	= reflectance
σ	= Stefan-Boltzmann constant
θ	= blade opening angle
θ_S	= solar elevation angle shown in Fig. 1
φ_S	= solar azimuth angle shown in Fig. 1
τ_S	= rate of surface nondiffusiveness
η_S	= solar rejection effectiveness defined in Eq. (24)

Subscripts

0,3	= base surface
1	= inside blade surface
2	= outside blade surface
5	= surface set up to evaluate edge effect
D	= diffuse component
S	= specular component
mn	= nth specular reflection of mth solar subflux
eff	= effective
nsp	= not taking specular reflections into account

Superscripts

$(\ )^*$	= solar component of spectral subdivision
$(\ )^\infty$	= infinite louver array
$(\tilde{\ })$	= taking edge effect into account

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Introduction

TEMPERATURE control or thermal balance of a spacecraft is generally accomplished by passive means based on selection of coatings. But recently, active control over surface properties is required as spacecraft become larger and more complex. Movable louvers are one of the active means that have been developed and flight-tested. Temperature control by movable louvers is based on the simple law that louvers act as a thermal insulator in the closed position, while they allow heat to escape when in the open position. Thus thermal control characteristics of movable louvers should be presented as a function of blade opening angle for their design and construction.

Plamondon[1] was the first person to analyze thermal behavior of movable louvers in no solar radiation and express the result in terms of effective emittance. His analysis of an infinite louver array led to a simultaneous set of linear integral equations that yield numerical results showing good agreement with correlated Mariner II data. But his method of solution requires much computational time and some unreasonable assumptions, such as diffuse surfaces. For this reason his method is not practical for design purposes.

Ollendorf[2] pointed out that louvers lose their efficiency when subjected to high solar influx and proposed to apply a specular coating. Since then many studies were carried out to devise techniques for computer-aided design of a specular louver system in a solar vacuum environment. Parmer and Buskirk[3] and Parmer and Stipandic[4] analyzed the thermal control characteristics of movable louvers exposed to solar radiation. They presented some numerical results on the heat rejection capability. But the application of their method is restricted to one or two specular surfaces. Then Michalek, Stipandic, and Coyle[5] developed the ray trace method for evaluation of an all-specular louver system. They also presented solar simulation test results on effective absorptance and blade temperature to verify the method of calculation and the model.

However, the methods proposed up to now are only applicable to purely diffuse or purely specular surfaces irradiated by the sun in such a direction that the solar vector lies in the plane normal to the louver array. In addition, they require very large computational times for calculating total image view factors and solar radiosities. This results because closed-form expressions, helpful to reduce computational time, have not yet been found due to the difficulties of analytical treatment of specular reflections. It is therefore desirable to develop a new analytical approach for obtaining such closed-form expressions.

The purpose of this paper is to develop an analytical method to permit parametric studies for design optimization of movable louvers. The method proposed here is based on the so-called diffuse and specular coradiosity method. Here the dimensionless coradiosity B_{ij} is defined as the fraction of radiation emitted from surface i which is eventually absorbed at surface j directly or after any number of specular or diffuse reflections. This paper employs the image method[6-8] to analyze multiple intervening specular reflections and presents an algorithm to estimate the intensity of the solar field formed by specular reflections of the incident sun beam. This paper also presents some numerical results for practical application.

Effective Emittance

General Formulation

Figure 1 is a sketch of a louver array consisting of $N+1$ blades arranged at regular intervals, that is, N louver channels. Here the blade width and length are shown in dimensionless quantities, β and $2l$, normalized by the blade spacing. Then the assumption is made that all blades have the same opening angle θ. The coordinate system is shown in the figure.

In this model, end frames, side frames, and an actuator assembly are not included and the blades are pinned to the spacecraft surface. But in commonly used louvers the blades are usually centered on their rotation axes which are driven by the actuator. This actual configuration results in a gap between the blade lower edge and the mounting plate. There are further differences between model and reality in that the gap size varies as a function of blade opening angle and the fixed frames form nonuniform cavities at the ends. Since the existence of such a gap or cavity distorts local heat transfer characteristics in a louver channel, it may have a serious effect on the overall thermal characteristics of a louver system; however, their inclusion would greatly complicate the analysis. The model shown in Fig. 1 is therefore employed from necessity. The applicability of this model will be demonstrated later by comparing numerical results with the test results.[5]

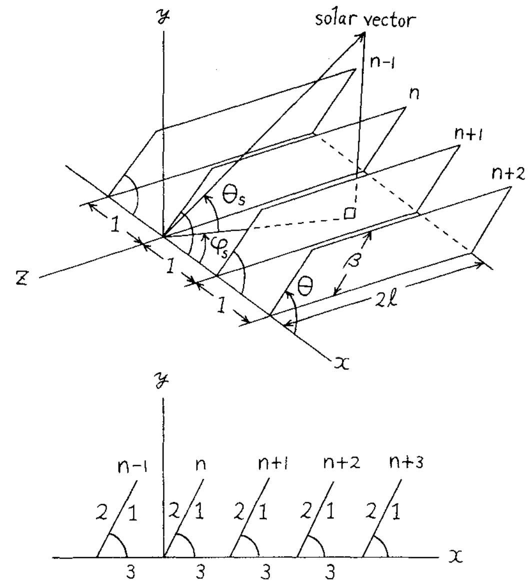

Fig. 1 Configuration of louver array.

In order to facilitate the mathematical treatment, the following assumptions are made: 1) the blades are infinite in length; 2) the internal conductance of the blades and base is infinite so that they are isothermal; 3) there is no conduction or convection between surfaces; 4) the surfaces are treated as semigray surfaces; 5) the surface properties of the inside and outside blade surfaces are equal; 6) the surfaces emit diffusively; and 7) the nondiffuse character of surface reflectance is approximated by dividing the reflectance into specular and diffuse components in both the infrared and solar wavelength regions.

The first assumption reduces the problem to two dimensions. Thus the mathematical model of a louver array may be represented by the schematic shown in Fig. 1. The second assumption leads to an $N+2$ node system where the base is regarded as a node specified by the temperature T_0 and the nth blade ($n=1,2,\ldots,N+1$) is regarded as a node specified by the temperature T_n. This assumption is demonstrated later with some numerical results. The third assumption is reasonable because the heat transfer in space takes place solely by radiation. The fifth assumption results from current louver design practice. The fourth, sixth, and seventh assumptions have been commonly used as a model of surface properties of real engineering materials and have yielded some successful results. This shows that they are reasonable assumptions for analytical formulation.

Since all louver channels have the same geometrical and optical properties, one has only to take one typical channel into account so far as the dimensionless coradiosity B_{ij} is concerned. For convenience, the inside blade surface is denoted by 1, the outside blade surface by 2, and the base surface by 3. The net heat transfer from the base to space is governed by the following equation from which the effective emittance $\epsilon_{\rm eff}$ is derived:

$$N\epsilon_{\rm eff}\sigma T_0^4 = N\epsilon_0\sigma T_0^4 - N\epsilon_0\sigma T_0^4 B_{33} - \beta\epsilon\sigma(T_1^4+T_2^4 + \cdots + T_N^4)B_{13} - \beta\epsilon\sigma(T_2^4+T_3^4+\cdots+T_{N+1}^4)B_{23} \tag{1}$$

The second term of Eq. (1) represents the radiation emitted from the base and absorbed there again. Then the third and fourth terms of Eq. (1) represent the radiant energy absorbed at the base but not originated from there. (The third term shows the contributions of inside blade surfaces, while the fourth term shows those of outside blade surfaces.) The blade temperatures are determined from the following equations expressing the thermal balance of this system:

$$2\beta\epsilon\sigma T_1^4 = \beta\epsilon\sigma T_1^4 B_{11} + \beta\epsilon\sigma T_2^4 B_{21} + \epsilon_0\sigma T_0^4 B_{31} \tag{2a}$$

$$2\beta\epsilon\sigma T_n^4 = \beta\epsilon\sigma T_{n-1}^4 B_{12} + \beta\epsilon\sigma T_n^4 (B_{11}+B_{22}) + \beta\epsilon\sigma T_{n+1}^4 B_{21} + \epsilon_0\sigma T_0^4 (B_{31}+B_{32}) \qquad (n=2,3,\ldots,N) \tag{2b}$$

$$2\beta\epsilon\sigma T_{N+1}^4 = \beta\epsilon\sigma T_N^4 B_{12} + \beta\epsilon\sigma T_{N+1}^4 B_{22} + \epsilon_0\sigma T_0^4 B_{32} \tag{2c}$$

The temperature ratio, defined as follows, lends itself to simplication of mathematical treatment:

$$\mu_n = \beta\epsilon T_n^4/\epsilon_0 T_0^4 \qquad (n=1,2,\ldots,N+1) \tag{3}$$

Equations (1) and (2) are rewritten as follows by using Eq. (3):

$$\epsilon_{\rm eff}/\epsilon_0 = 1 - B_{33} - N^{-1}[B_{13}(\mu_1+\mu_2+\cdots+\mu_N) + B_{23}(\mu_2+\mu_3+\cdots+\mu_{N+1})] \tag{4}$$

$$(2-B_{11})\mu_1 - B_{21}\mu_2 = B_{31} \tag{5a}$$

$$-B_{12}\mu_{n-1} + (2-B_{11}-B_{22})\mu_n - B_{21}\mu_{n+1} = B_{31}+B_{32} \qquad (n=2,3,\ldots,N) \tag{5b}$$

$$-B_{12}\mu_N + (2-B_{22})\mu_{N+1} = B_{32} \tag{5c}$$

Equation (4) is a general expression with which one can estimate the effective emittance. If $N=\infty$, then $\mu_1=\mu_2=\cdots=\mu_{N+1}=\mu\equiv\beta\epsilon T^4/\epsilon_0 T_0^4$ and $\epsilon_{\rm eff}=\epsilon_{\rm eff}^{\infty}$. Hence Eqs. (4) and (5) are reduced to simple expressions as follows:

$$\frac{\epsilon_{\rm eff}^{\infty}}{\epsilon_0} = 1 - B_{33} - \frac{(B_{13}+B_{23})(B_{31}+B_{32})}{(2-B_{11}-B_{12}-B_{21}-B_{22})} \tag{6}$$

$$\mu = (B_{31}+B_{32})/(2-B_{11}-B_{12}-B_{21}-B_{22}) \tag{7}$$

Representation of Coradiosity by Exchange Factors

Now attention is directed to the determination of dimensionless coradiosities. The exchange factor concept is available for this purpose. The exchange factor E_{ij} is defined as the fraction of radiation leaving surface i that arrives at surface j both directly and by all possible intervening specular reflections. The dimensionless coradiosity B_{ij} $(i, j=1, 2, 3)$ is therefore expressed as follows:

$$B_{ij} = \epsilon_j E_{ij} + \rho_D E_{i1} B_{1j} + \rho_D E_{i2} B_{2j} + \rho_{D0} E_{i3} B_{3j} \tag{8}$$

where the relations $\epsilon_1=\epsilon_2=\epsilon$ and $\epsilon_3=\epsilon_0$ are employed. In Eq. (8), the first term represents the portion of radiant energy absorbed without any experience of diffuse reflections, whereas the succeeding terms represent the portions involving diffuse reflections. Equation (8) can be easily solved, and one finds the following expressions:

$$B_{1j} = (b_{1j}a_{22} + b_{2j}a_{12})/(a_{11}a_{22} - a_{12}a_{21}) \tag{9a}$$

$$B_{2j} = (b_{1j}a_{21} + b_{2j}a_{11})/(a_{11}a_{22} - a_{12}a_{21}) \tag{9b}$$

$$B_{3j} = (\epsilon_j E_{3j} + \rho_D E_{31} B_{1j} + \rho_D E_{32} B_{2j})/(1-\rho_{D0}E_{33}) \tag{9c}$$

where the coefficients a_{11}, a_{12}, a_{21}, and a_{22} are defined as follows:

$$a_{11} = (1-\rho_D E_{11})(1-\rho_{D0}E_{33}) - \rho_{D0}\rho_D E_{13}E_{31} \tag{10a}$$

$$a_{12} = \rho_D[E_{12}(1-\rho_{D0}E_{33}) + \rho_{D0}E_{13}E_{32}] \tag{10b}$$

$$a_{21} = \rho_D[E_{21}(1-\rho_{D0}E_{33}) + \rho_{D0}E_{23}E_{31}] \tag{10c}$$

$$a_{22} = (1-\rho_D E_{22})(1-\rho_{D0}E_{33}) - \rho_{D0}\rho_D E_{23}E_{32} \tag{10d}$$

Then the coefficients b_{1j} and b_{2j} $(j=1, 2, 3)$ are defined as follows:

$$b_{1j} = \epsilon_j[E_{1j}(1-\rho_{D0}E_{33}) + \rho_{D0}E_{13}E_{3j}] \tag{11a}$$

$$b_{2j} = \epsilon_j[E_{2j}(1-\rho_{D0}E_{33}) + \rho_{D0}E_{23}E_{3j}] \tag{11b}$$

From the definition of the exchange factor, it is clear that the factor E_{ij} $(i, j=1, 2, 3)$ is expressible in the form of a series as follows:

$$E_{11} = \rho_S F_{1(2)1} + \rho_{S0}F_{1(3)1} + \rho_{S0}\rho_S F_{1(2,3)1} + \rho_{S0}\rho_S F_{1(3,2)1} + \rho_S^3 F_{1(2,1,2)1} + \rho_{S0}\rho_S^2 F_{1(2,1,3)1} + \rho_{S0}\rho_S^2 F_{1(2,3,2)1} + \rho_{S0}\rho_S^2 F_{1(3,1,2)1} + \rho_{S0}^2\rho_S F_{1(3,1,3)1} + \rho_{S0}^2\rho_S F_{1(3,2,3)1} + \cdots \tag{12a}$$

$$E_{12} = F_{12} + \rho_{S0}F_{1(3)2} + \rho_S^2 F_{1(2,1)2} + \rho_{S0}\rho_S F_{1(2,3)2} + \rho_{S0}\rho_S F_{1(3,1)2} + \rho_{S0}\rho_S^2 F_{1(2,1,3)2} + \rho_{S0}\rho_S^2 F_{1(2,3,1)2} + \rho_{S0}^2\rho_S F_{1(3,1,3)2} + \rho_{S0}\rho_S^2 F_{1(3,2,1)2} + \rho_{S0}^2\rho_S F_{1(3,2,3)2} + \cdots \tag{12b}$$

$$E_{13} = F_{13} + \rho_S F_{1(2)3} + \rho_S^2 F_{1(2,1)3} + \rho_{S0}\rho_S F_{1(3,1)3} + \rho_{S0}\rho_S F_{1(3,2)3} + \rho_S^3 F_{1(2,1,2)3} + \rho_{S0}\rho_S^2 F_{1(2,3,1)3} + \rho_{S0}\rho_S^2 F_{1(2,3,2)3} + \cdots \tag{12c}$$

$$E_{21} = F_{21} + \rho_{S0}F_{2(3)1} + \rho_S^2 F_{2(1,2)1} + \rho_{S0}\rho_S F_{2(3,2)1} + \rho_{S0}\rho_S F_{2(1,3)1} + \rho_{S0}\rho_S^2 F_{2(3,1,2)1} + \rho_{S0}\rho_S^2 F_{2(1,3,2)1} + \rho_{S0}^2\rho_S F_{2(3,1,3)1} + \rho_{S0}\rho_S^2 F_{2(1,2,3)1} + \rho_{S0}^2\rho_S F_{2(3,2,3)1} + \cdots \tag{12d}$$

$$E_{22} = \rho_S F_{2(1)2} + \rho_{S0}F_{2(3)2} + \rho_{S0}\rho_S F_{2(1,3)2} + \rho_{S0}\rho_S F_{2(3,1)2} + \rho_S^3 F_{2(1,2,1)2} + \rho_{S0}\rho_S^2 F_{2(1,2,3)2} + \rho_{S0}\rho_S^2 F_{2(1,3,1)2} + \rho_{S0}\rho_S^2 F_{2(3,2,1)2} + \rho_{S0}^2\rho_S F_{2(3,2,3)2} + \rho_{S0}^2\rho_S F_{2(3,1,3)2} + \cdots \tag{12e}$$

$$E_{23} = F_{23} + \rho_S F_{2(1)3} + \rho_S^2 F_{2(1,2)3} + \rho_{S0}\rho_S F_{2(3,2)3} + \rho_{S0}\rho_S F_{2(3,1)3} + \rho_S^3 F_{2(1,2,1)3} + \rho_{S0}\rho_S^2 F_{2(1,3,2)3} + \rho_{S0}\rho_S^2 F_{2(1,3,1)3} + \cdots \tag{12f}$$

$$E_{31} = F_{31} + \rho_S F_{3(2)1} + \rho_S^2 F_{3(1,2)1} + \rho_{S0}\rho_S F_{3(1,3)1} + \rho_{S0}\rho_S F_{3(2,3)1} + \rho_S^3 F_{3(2,1,2)1} + \rho_{S0}\rho_S^2 F_{3(1,3,2)1} + \rho_{S0}\rho_S^2 F_{3(2,3,2)1} + \cdots \tag{12g}$$

$$E_{32}=F_{32}+\rho_S F_{3(1)2}+\rho_S^2 F_{3(2,1)2}+\rho_{S0}\rho_S F_{3(2,3)2}+\rho_{S0}\rho_S F_{3(1,3)2}+\rho_S^3 F_{3(1,2,1)2}+\rho_{S0}\rho_S^2 F_{3(2,3,1)2}+\rho_{S0}\rho_S^2 F_{3(1,3,1)2}+\cdots \tag{12h}$$

$$E_{33}=\rho_S F_{3(1)3}+\rho_S F_{3(2)3}+\rho_{S0}\rho_S^2 F_{3(1,3,1)3}+\rho_{S0}\rho_S^2 F_{3(2,3,2)3}+\cdots \tag{12i}$$

The relations $\rho_{S1}=\rho_{S2}=\rho_S$ and $\rho_{S3}=\rho_{S0}$ are employed here. Factors such as $F_{i(l)j}$, $F_{i(l,m)j}$, $F_{i(l,m,n)j}$ are hereafter called generalized view factors because they play a role similar to that played by the traditional view factor F_{ij}. In the series of Eq. (12), the first-, second-, and third-power terms such as $\rho_{Sl}F_{i(l)j}$, $\rho_{Sl}\rho_{Sm}F_{i(l,m)j}$, $\rho_{Sl}\rho_{Sm}\rho_{Sn}F_{i(l,m,n)j}$ represent the indirect transport of radiant energy from surface i to surface j. For example, the term $\rho_{Sl}\rho_{Sm}\rho_{Sn}F_{i(l,m,n)j}$ shows the fraction of radiant energy leaving surface i and arriving at surface j with three intervening specular reflections. The subscripts l, m, and n appended to the factor $F_{i(l,m,n)j}$ specify the path of radiant interchange, that is, the sequence of specular reflections. Since all surfaces participating in radiant interchange are plane, no radiation impinges on the same surface in succession. It follows that there are no further paths of interchange involving one, two, or three intervening specular reflections except the paths shown explicitly in Eq. (12).

From reciprocity rules, one has the following relations:

$$F_{21}=F_{12},\ F_{2(3)1}=F_{1(3)2},\ F_{2(1,2)1}=F_{1(2,1)2},\ F_{2(3,2)1}=F_{1(2,3)2},\ F_{2(1,3)1}=F_{1(3,1)2},$$
$$F_{2(3,1,2)1}=F_{1(2,1,3)2},\ F_{2(1,3,2)1}=F_{1(2,3,1)2},\ F_{2(3,1,3)1}=F_{1(3,1,3)2},\ F_{2(1,2,3)1}=F_{1(3,2,1)2},\ F_{2(3,2,3)1}=F_{1(3,2,3)2} \tag{13a}$$

$$F_{31}=\beta F_{13},\ F_{3(2)1}=\beta F_{1(2)3},\ F_{3(1,2)1}=\beta F_{1(2,1)3},\ F_{3(1,3)1}=\beta F_{1(3,1)3},$$
$$F_{3(2,3)1}=\beta F_{1(3,2)3},\ F_{3(2,1,2)1}=\beta F_{1(2,1,2)3},\ F_{3(1,3,2)1}=\beta F_{1(2,3,1)3},\ F_{3(2,3,2)1}=\beta F_{1(2,3,2)3} \tag{13b}$$

$$F_{32}=\beta F_{23},\ F_{3(1)2}=\beta F_{2(1)3},\ F_{3(2,1)2}=\beta F_{2(1,2)3},\ F_{3(2,3)2}=\beta F_{2(3,2)3},\ F_{3(1,3)2}=\beta F_{2(3,1)3},$$
$$F_{3(1,2,1)2}=\beta F_{2(1,2,1)3},\ F_{3(2,3,1)2}=\beta F_{2(1,3,2)3},\ F_{3(1,3,1)2}=\beta F_{2(1,3,1)3} \tag{13c}$$

The fact that all blades are parallel to each other results in the following expressions:

$$F_{2(1)2}(\theta)=F_{1(2)1}(\pi-\theta),\ F_{2(3)2}(\theta)=F_{1(3)1}(\pi-\theta),\ F_{2(1,3)2}(\theta)=F_{1(2,3)1}(\pi-\theta),\ F_{2(3,1)2}(\theta)=F_{1(3,2)1}(\pi-\theta),$$
$$F_{2(1,2,1)2}(\theta)=F_{1(2,1,2)1}(\pi-\theta),\ F_{2(1,2,3)2}(\theta)=F_{1(2,1,3)1}(\pi-\theta),\ F_{2(1,3,1)2}(\theta)=F_{1(2,3,2)1}(\pi-\theta),$$
$$F_{2(3,2,1)2}(\theta)=F_{1(3,1,2)1}(\pi-\theta),\ F_{2(3,2,3)2}(\theta)=F_{1(3,1,3)1}(\pi-\theta),\ F_{2(3,1,3)2}(\theta)=F_{1(3,2,3)1}(\pi-\theta) \tag{14a}$$

$$F_{23}(\theta)=F_{13}(\pi-\theta),\ F_{2(1)3}(\theta)=F_{1(2)3}(\pi-\theta),\ F_{2(1,2)3}(\theta)=F_{1(2,1)3}(\pi-\theta),\ F_{2(3,2)3}(\theta)=F_{1(3,1)3}(\pi-\theta),$$
$$F_{2(3,1)3}(\theta)=F_{1(3,2)3}(\pi-\theta),\ F_{2(1,2,1)3}(\theta)=F_{1(2,1,2)3}(\pi-\theta),\ F_{2(1,3,2)3}(\theta)=F_{1(2,3,1)3}(\pi-\theta),\ F_{2(1,3,1)3}(\theta)=F_{1(2,3,2)3}(\pi-\theta) \tag{14b}$$

Furthermore, the following relations are deduced from the geometry shown in Fig. 1:

$$F_{1(3,1)2}(\theta)=F_{1(2,3)2}(\pi-\theta),\ F_{1(3,1,2)1}=F_{1(2,1,3)1} \tag{15a}$$

$$F_{2(1)2}=F_{1(2)1},\ F_{2(1,2,1)2}=F_{1(2,1,2)1} \tag{15b}$$

$$F_{3(1)3}=F_{1(3)1},\ F_{3(2)3}(\theta)=F_{1(3)1}(\pi-\theta) \tag{15c}$$

$$F_{3(1,3,1)3}=F_{1(3,1,3)1},\ F_{3(2,3,2)3}(\theta)=F_{1(3,1,3)1}(\pi-\theta) \tag{15d}$$

The following formulas are derived from Eqs. (12), (13), and (14)

$$E_{21}=E_{12},\ E_{31}=\beta E_{13},\ E_{32}=\beta E_{23} \tag{16a}$$

$$E_{22}(\theta)=E_{11}(\pi-\theta),\ E_{23}(\theta)=E_{13}(\pi-\theta) \tag{16b}$$

From Eqs. (13), (14), and (15), it is concluded that a basic requirement for the analysis is the knowledge of factors

F_{12}, F_{13}, $F_{1(2)1}$, $F_{1(3)1}$, $F_{1(3)2}$, $F_{1(2)3}$, $F_{1(2,3)1}$, $F_{1(3,2)1}$, $F_{1(2,1)2}$, $F_{1(2,3)2}$, $F_{1(2,1)3}$, $F_{1(3,1)3}$, $F_{1(3,2)3}$, $F_{1(2,1,2)1}$, $F_{1(2,1,3)1}$, $F_{1(2,3,2)1}$, $F_{1(3,1,3)1}$, $F_{1(3,2,3)1}$, $F_{1(2,1,3)2}$, $F_{1(2,3,1)2}$, $F_{1(3,1,3)2}$, $F_{1(3,2,1)2}$, $F_{1(3,2,3)2}$, $F_{1(2,1,2)3}$, $F_{1(2,3,1)3}$, and $F_{1(2,3,2)3}$. These factors are given in detail in Appendix A.

Calculation of Generalized View Factors

The image method can be used as a means of calculating generalized view factors because the blades and base are plane surfaces. This method is based on the principle that the radiant energy reflected from a plane mirror appears to come from an image located behind it at a distance identical to that from the participating surface to the mirror. The process of finding the factor $F_{1(2,3)2}$ is now presented as an example showing how the image method is applied. This process is divided into two steps. The first step is to construct the images of surface 1. The image 1(2) is the image surface of surface 1 formed by one specular reflection on surface 2. Then the image 1(2,3) is the image surface of surface 1 formed by two successive specular reflections on surfaces 2 and 3, that is, the image surface of the image 1(2) due to surface 3. The radiation from surface 1 which reflects specularly in surface 2 may, in turn, impinge on surface 3 and re-reflect there specularly. The re-reflected energy appears to originate at the image surface 1(2,3). The second step is to estimate the portion of this re-reflected energy that arrives at surface 2. This portion is equal to the view factor corresponding to interchange between surface 1(2,3) and surface 2.

Thus the problem is resolved into two parts. The first part is to find the geometrical condition which allows intervening specular reflections. The second part is attributed to the calculation of view factors between two segments of lines lying on the same plane. This calculation is easily carried out. The results are given in general forms shown in Eqs. (A27) and (A28) in Appendix A. Equation (A27) shows the portion of radiant interchange between two segments that intersect with each other at the angle γ. One is a distance a_1 away from the intersecting point, while the other is a distance a_2 away from it. The segment lengths are here specified by b_1 and b_2. Then Eq. (A28) shows the portion of radiant interchange between two segments parallel to each other at the interval h. One of them is a distance a_2 apart from the line crossing over

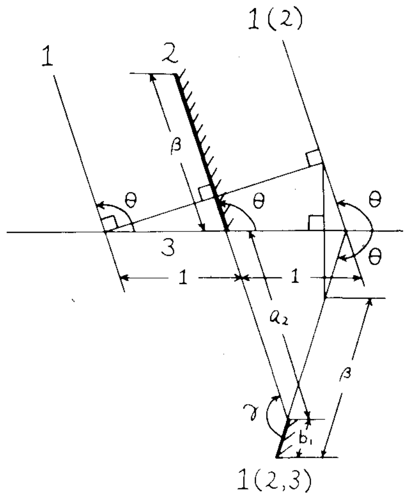

Fig. 2 Images formed by specular reflections.

the other perpendicularly at its end. The segment lengths are also specified by b_1 and b_2.

The configurations allowing double specular reflections related to $F_{1(2,3)2}$ are classified into three cases corresponding to θ. In the case of $0<\theta\leq\pi/2$, the image 1(2,3) does not face surface 2. This leads to $F_{1(2,3)2}=0$. Figure 2 shows a configuration corresponding to $\pi/2<\theta<2\pi/3$. It can be easily seen from Fig. 2 that there are two possibilities on double specular reflections. The first possibility corresponds to the case of $\pi/2<\theta<2\pi/3$ and $\beta>(4\cos^2\theta-1)/2\cos\theta$. In this case, only a part of the image 1(2,3) can be seen from surface 2. The factor $F_{1(2,3)2}$ is therefore given by Eq. (A27) with $a_1=0$, $b_1=\beta-(4\cos^2\theta-1)/2\cos\theta$, $a_2=-1/2\cos\theta$, $b_2=\beta$, $\gamma=2\pi-2\theta$. However, if $\pi/2<\theta<2\pi/3$ and $\beta\leq(4\cos^2\theta-1)\div 2\cos\theta$, then the image 1(2,3) cannot be seen from surface 2, that is, $F_{1(2,3)2}=0$. In the case of $2\pi/3\leq\theta<\pi$, the image 1(2,3) faces surface 2. The factor $F_{1(2,3)2}$ is therefore given by Eq. (A27) with $a_1=(1-4\cos^2\theta)/2\cos\theta$, $b_1=\beta$, $a_2=-1/2\cos\theta$, $b_2=\beta$, and $\gamma=2\pi-2\theta$. The other factors are also calculated in the manner mentioned above. The results are summarized in Appendix A.

Solar Rejection Capability

General Formulation

In general, solar radiation is the most significant heat input to spacecraft. Louvers installed on a spacecraft may serve as a solar insulator. This utilization is very attractive when the base temperature is required to be constant even if solar direction and intensity have changed. Thermal control characteristics to meet this requirement are called solar rejection capability. In analyzing this capability, it should be noted that there exist different kinds of radiation in a louver channel. One of them is thermal radiation characterized by B_{ij} defined in Eq. (9). The other is related to solar radiation for which the direction of incidence is specified by angles θ_S and φ_S, as shown in Fig. 1.

The thermal balance of a louver array irradiated by the sun is governed by the following equations:

$$N\epsilon_0\sigma T_0^4=NQ_0+\beta\epsilon\sigma(T_1^4+T_2^4+\cdots+T_N^4)B_{13}+\beta\epsilon\sigma(T_2^4+T_3^4+\cdots+T_{N+1}^4)B_{23}+N\epsilon_0\sigma T_0^4B_{33} \tag{17a}$$

$$2\beta\epsilon\sigma T_1^4=Q_1+\beta\epsilon\sigma T_1^4B_{11}+\beta\epsilon\sigma T_2^4B_{21}+\epsilon_0\sigma T_0^4B_{31} \tag{17b}$$

$$2\beta\epsilon\sigma T_n^4=Q+\beta\epsilon\sigma T_{n-1}^4B_{12}+\beta\epsilon\sigma T_n^4(B_{11}+B_{22})+\beta\epsilon\sigma T_{n+1}^4B_{21}+\epsilon_0\sigma T_0^4(B_{31}+B_{32})\quad(n=2,3,\ldots,N) \tag{17c}$$

$$2\beta\epsilon\sigma T_{N+1}^4=Q_{N+1}+\beta\epsilon\sigma T_N^4B_{12}+\beta\epsilon\sigma T_{N+1}^4B_{22}+\epsilon_0\sigma T_0^4B_{32} \tag{17d}$$

where Q_0, Q_1, Q, and Q_{N+1} show the solar energy absorbed at the base and blades, but the electric heat generation Q_I is added to Q_0. Equation (17a) is reduced to the following form in the special case when louvers are not installed on the base surface:

$$\epsilon_0\sigma T_0^{*4}=Q_0^*\equiv Q_I+I_S\alpha_0\sin\theta_S \tag{18}$$

The temperature T_0^* is used as the reference of dimensionless temperatures defined as follows:

$$\mu_0^*=(T_0/T_0^*)^4\qquad \mu_n^*=\beta\epsilon T_n^4/\epsilon_0T_0^{*4}\quad(n=1,2,\ldots,N+1) \tag{19}$$

Equation (17) is rewritten as follows, by using Eq. (19):

$$(1-B_{33})\mu_0^*-B_{13}\mu_1^*/N-(B_{13}+B_{23})(\mu_2^*+\mu_3^*+\cdots+\mu_N^*)/N-B_{23}\mu_{N+1}^*/N=q_0 \tag{20a}$$

$$-B_{31}\mu_0^*+(2-B_{11})\mu_1^*-B_{21}\mu_2^*=q_1 \tag{20b}$$

$$-(B_{31}+B_{32})\mu_0^*-B_{12}\mu_{n-1}^*+(2-B_{11}-B_{22})\mu_n^*-B_{21}\mu_{n+1}^*=q\quad(n=2,3,\ldots,N) \tag{20c}$$

$$-B_{32}\mu_0^*-B_{12}\mu_N^*+(2-B_{22})\mu_{N+1}^*=q_{N+1} \tag{20d}$$

where q_0, q_1, q, and q_{N+1} show dimensionless heat input defined as follows:

$$q=Q/Q_0^*\qquad q_n=Q_n/Q_0^*\qquad(n=0,1,N+1) \tag{21}$$

If $N=\infty$, then $\mu_1^*=\mu_2^*=\cdots=\mu_{N+1}^*=\mu^*\equiv\beta\epsilon T^4/\epsilon_0T_0^{*4}$. In this case Eqs. (20) are reduced to the following expressions:

$$\mu_0^*=q_0/\epsilon_{\text{eff}}^{\infty}+q(B_{13}+B_{23})/D \tag{22a}$$

$$\mu^*=[q_0(B_{31}+B_{32})+q(1-B_{33})]/D \tag{22b}$$

where the coefficient D is defined as follows:

$$D=(1-B_{33})(2-B_{11}-B_{12}-B_{21}-B_{22})-(B_{13}+B_{23})(B_{31}+B_{32}) \tag{23}$$

Since the difference between Q_0^* and Q_0 represents the portion of solar energy rejected by the louvers so that it does not impinge on the base surface, the following factor serves as a measure of solar rejection effectiveness:

$$\eta_S=1-(Q_0-Q_I)/(Q_0^*-Q_I) \tag{24}$$

The effective solar energy absorbed at the base is usually estimated in terms of effective absorptance defined as follows:

$$\alpha_{\text{eff}}=(\epsilon_{\text{eff}}\sigma T_0^4-Q_I)/I_S \tag{25}$$

The solar flux encountered in a louver channel consists of collimated flux and randomly distributed flux. The former is attributed to the flux impinging directly or after intervening specular reflections, while the latter is due to diffuse reflections. Their contributions to the solar irradiance on surface i are expressed in the coefficients G_i and H_i, which will be determined later. For example, the expression $I_S\alpha(G_1+G_2)\sin\theta_S$ shows the solar energy absorbed on blade $n(n\neq 1, N+1)$ without any experience of diffuse reflections. In regard to diffusely reflected solar energy, the dimensionless solar coradiosity B_{ij}^*, which is the same as B_{ij}, provides a means of analyzing its behavior. Thus one has the following expressions:

$$Q_0 = Q_1 + I_S(\alpha_0 G_3 + \rho_D^* H_1 B_{13}^* + \rho_D^* H_2 B_{23}^* + \rho_{D0}^* H_3 B_{33}^*)\sin\theta_S \tag{26a}$$

$$Q_1 = I_S[\alpha\beta H_S \eta(H_S) + (\alpha G_1 + \rho_D^* H_1 B_{11}^* + \rho_D^* H_2 B_{21}^* + \rho_{D0}^* H_3 B_{31}^*)\sin\theta_S] \tag{26b}$$

$$Q = I_S[\alpha(G_1+G_2) + \rho_D^* H_1(B_{11}^* + B_{12}^*) + \rho_D^* H_2(B_{21}^* + B_{22}^*) + \rho_{D0}^* H_3(B_{31}^* + B_{32}^*)]\sin\theta_S \tag{26c}$$

$$Q_{N+1} = I_S[-\alpha\beta H_S \eta(-H_S) + (\alpha G_2 + \rho_D^* H_1 B_{12}^* + \rho_D^* H_2 B_{22}^* + \rho_{D0}^* H_3 B_{32}^*)\sin\theta_S] \tag{26d}$$

where the coefficient H_S is defined as follows:

$$H_S = \cos\theta\sin\theta_S - \sin\theta\cos\theta_S\cos\varphi_S \tag{27}$$

Equation (27) shows the inner product between the solar vector and the vector normal to outside blade surface. Then the function $\eta(H_S)$ denotes a Heaviside unit step function which is 1 when $H_S \geq 0$ and 0 when $H_S < 0$.

Since the solar coradiosity $B_{ij}^*(i,j=1,2,3)$ plays a role similar to B_{ij} in the solar wavelength region, one finds the same expression as Eq. (8):

$$B_{ij}^* = \alpha_j E_{ij}^* + \rho_D^* E_{i1}^* B_{1j}^* + \rho_D^* E_{i2}^* B_{2j}^* + \rho_{D0}^* E_{i3}^* B_{3j}^* \tag{28}$$

where the relations $\alpha_1 = \alpha_2 = \alpha$ and $\alpha_3 = \alpha_0$ are employed. The solution of Eq. (28) has the same form as Eq. (9) and is written as follows:

$$B_{1j}^* = (b_{1j}^* a_{22}^* + b_{2j}^* a_{12}^*)/(a_{11}^* a_{22}^* - a_{12}^* a_{21}^*) \tag{29a}$$

$$B_{2j}^* = (b_{1j}^* a_{21}^* + b_{2j}^* a_{11}^*)/(a_{11}^* a_{22}^* - a_{12}^* a_{21}^*) \tag{29b}$$

$$B_{3j}^* = (\alpha_j E_{3j}^* + \rho_D^* E_{31}^* B_{1j}^* + \rho_D^* E_{32}^* B_{2j}^*)/(1-\rho_{D0}^* E_{33}^*) \tag{29c}$$

where the coefficients a_{11}^*, a_{12}^*, a_{21}^*, and a_{22}^* are defined as in Eq. (10):

$$a_{11}^* = (1-\rho_D^* E_{11}^*)(1-\rho_{D0}^* E_{33}^*) - \rho_{D0}^* \rho_D^* E_{13}^* E_{31}^* \tag{30a}$$

$$a_{12}^* = \rho_D^*[E_{12}^*(1-\rho_{D0}^* E_{33}^*) + \rho_{D0}^* E_{13}^* E_{32}^*] \tag{30b}$$

$$a_{21}^* = \rho_D^*[E_{21}^*(1-\rho_{D0}^* E_{33}^*) + \rho_{D0}^* E_{23}^* E_{31}^*] \tag{30c}$$

$$a_{22}^* = (1-\rho_D^* E_{22}^*)(1-\rho_{D0}^* E_{33}^*) - \rho_{D0}^* \rho_D^* E_{23}^* E_{32}^* \tag{30d}$$

The coefficients b_{1j}^* and b_{2j}^* $(j=1,2,3)$ are also defined as in Eq. (11):

$$b_{1j}^* = \alpha_j[E_{1j}^*(1-\rho_{D0}^* E_{33}^*) + \rho_{D0}^* E_{13}^* E_{3j}^*] \tag{31a}$$

$$b_{2j}^* = \alpha_j[E_{2j}^*(1-\rho_{D0}^* E_{33}^*) + \rho_{D0}^* E_{23}^* E_{3j}^*] \tag{31b}$$

The factor $E_{ij}^*(i,j=1,2,3)$ is the solar exchange factor similar to E_{ij}, and the following relations corresponding to Eqs. (12) and (16) are obtained:

$$E_{11}^* = \rho_S^* F_{1(2)1} + \rho_{S0}^* F_{1(3)1} + \rho_{S0}^* \rho_S^* F_{1(2,3)1} + \rho_{S0}^* \rho_S^* F_{1(3,2)1} + \rho_S^{*3} F_{1(2,1,2)1} + \rho_{S0}^* \rho_S^{*2} F_{1(2,1,3)1} + \rho_{S0}^* \rho_S^{*2} F_{1(2,3,2)1} + \rho_{S0}^* \rho_S^{*2} F_{1(3,1,2)1} + \rho_{S0}^{*2} \rho_S^* F_{1(3,1,3)1} + \rho_{S0}^{*2} \rho_S^* F_{1(3,2,3)1} + \cdots \tag{32a}$$

$$E_{12}^* = F_{12} + \rho_{S0}^* F_{1(3)2} + \rho_S^{*2} F_{1(2,1)2} + \rho_{S0}^* \rho_S^* F_{1(2,3)2} + \rho_{S0}^* \rho_S^* F_{1(3,1)2} + \rho_{S0}^* \rho_S^{*2} F_{1(2,1,3)2} + \rho_{S0}^* \rho_S^{*2} F_{1(2,3,1)2} + \rho_{S0}^{*2} \rho_S^* F_{1(3,1,3)2} + \rho_{S0}^* \rho_S^{*2} F_{1(3,2,1)2} + \rho_{S0}^{*2} \rho_S^* F_{1(3,2,3)2} + \cdots \tag{32b}$$

$$E_{13}^* = F_{13} + \rho_S^* F_{1(2)3} + \rho_S^{*2} F_{1(2,1)3} + \rho_{S0}^* \rho_S^* F_{1(3,1)3} + \rho_{S0}^* \rho_S^* F_{1(3,2)3} + \rho_S^{*3} F_{1(2,1,2)3} + \rho_{S0}^* \rho_S^{*2} F_{1(2,3,1)3} + \rho_{S0}^* \rho_S^{*2} F_{1(2,3,2)3} + \cdots \tag{32c}$$

$$E_{33}^* = \rho_S^* F_{3(1)3} + \rho_S^* F_{3(2)3} + \rho_{S0}^* \rho_S^{*2} F_{3(1,3,1)3} + \rho_{S0}^* \rho_S^{*2} F_{3(2,3,2)3} + \cdots \tag{32d}$$

$$E_{22}^*(\theta) = E_{11}^*(\pi-\theta),\ E_{23}^*(\theta) = E_{13}^*(\pi-\theta) \tag{32e}$$

$$E_{21}^* = E_{12}^*,\ E_{31}^* = \beta E_{13}^*,\ E_{32}^* = \beta E_{23}^* \tag{32f}$$

Determination of the Solar Field in a Louver Channel

Now the problem is to determine the coefficients G_i and H_i expressing the intensity of the solar field in a louver channel. For this purpose, it is necessary to follow the movement of a photon from incidence to absorption. The analysis is therefore carried out for one subflux of the M into which the incident flux is divided. The specular reflection history of the mth subflux can be described by means of the vector $\boldsymbol{R}_m$ defined as follows:

$$\boldsymbol{R}_m = \boldsymbol{r}_{m1} + (\boldsymbol{r}_S \boldsymbol{r}_{m1})\boldsymbol{r}_{m2} + (\boldsymbol{r}_S \boldsymbol{r}_{m1})(\boldsymbol{r}_S \boldsymbol{r}_{m2})\boldsymbol{r}_{m3} + \cdots \tag{33}$$

The vector $\boldsymbol{r}_{mj}$ specifies the surface on which the jth specular reflection of the mth subflux takes place. Hence the vector $\boldsymbol{r}_{mj}$ is equal to $\boldsymbol{e}_1$, $\boldsymbol{e}_2$, $\boldsymbol{e}_3$, or $\boldsymbol{e}_4$, which have been introduced to identify surfaces:

$$\boldsymbol{e}_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad \boldsymbol{e}_2 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad \boldsymbol{e}_3 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad \boldsymbol{e}_4 = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{34}$$

Then the vector $\boldsymbol{r}_S$ is defined as follows:

$$\boldsymbol{r}_S = \begin{pmatrix} \rho_S^* \\ \rho_S^* \\ \rho_{S0}^* \end{pmatrix} \tag{35}$$

Since the nth term of Eq. (33) represents the place and the rate of occurrence of the nth specular reflection, the coefficient H_i is given by the following expression:

$$H_i = \lim_{M\to\infty} \sum_{m=1}^{M} \boldsymbol{R}_m \boldsymbol{e}_i / M \tag{36}$$

In order to determine the coefficient G_i, it is necessary to introduce the vector $\boldsymbol{J}_m$ similar to $\boldsymbol{R}_m$, but including the knowledge on the direction of the nth specular reflection of the mth subflux:

$$\boldsymbol{J}_m = |\boldsymbol{D}_{m0}\boldsymbol{n}_{m1}|\boldsymbol{r}_{m1} + (\boldsymbol{r}_S \boldsymbol{r}_{m1})|\boldsymbol{D}_{m1}\boldsymbol{n}_{m2}|\boldsymbol{r}_{m2} + (\boldsymbol{r}_S \boldsymbol{r}_{m1})(\boldsymbol{r}_S \boldsymbol{r}_{m2})|\boldsymbol{D}_{m2}\boldsymbol{n}_{m3}|\boldsymbol{r}_{m3} + \cdots \tag{37}$$

The vector $\boldsymbol{n}_{mj}$ specifies the normal vector of the surface on which the jth specular reflection of the mth subflux takes place. Hence the vector $\boldsymbol{n}_{mj}$ is equal to $\boldsymbol{N}_1$, $\boldsymbol{N}_2$, or $\boldsymbol{N}_3$, defined as follows:

$$N_1 = \begin{bmatrix} \sin\theta \\ -\cos\theta \\ 0 \end{bmatrix} \quad N_2 = \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} \quad N_3 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{38}$$

The vector D_{mj} shows the direction of reflected radiation due to the jth specular reflection of the mth subflux, which is expressed as follows:

$$D_{mj} = \begin{bmatrix} \ell_{mj} \\ m_{mj} \\ n_{mj} \end{bmatrix} \quad D_{m0} = \begin{bmatrix} \cos\theta_S\cos\varphi_S \\ \sin\theta_S \\ -\cos\theta_S\sin\varphi_S \end{bmatrix} \tag{39}$$

where ℓ_{mj}, m_{mj}, and n_{mj} are direction cosines to the axes x, y, and z respectively. But the vector D_{m0} is equal to the solar vector. Thus one has the following expression similar to Eq. (36):

$$G_i = \lim_{M\to\infty} \sum_{m=1}^{M} J_m e_i / M \tag{40}$$

The last step of the analysis is to determine the vectors r_{mj}, n_{mj}, and D_{mj}. Three-dimensional analytical geometry is applicable to this problem. The inside and outside blade surfaces and the base surface are expressed in the following equations:

$$x\sin\theta - y\cos\theta = 0 \qquad (0<y<\beta\sin\theta) \tag{41a}$$

$$x\sin\theta - y\cos\theta = \sin\theta \qquad (0<y<\beta\sin\theta) \tag{41b}$$

$$y=0 \qquad (0<x<1) \tag{41c}$$

Then the reflected beam due to the nth specular reflection of the mth subflux is expressed as follows:

$$(x-x_{mn})/\ell_{mn} = (y-y_{mn})/m_{mn} = (z-z_{mn})/n_{mn} \tag{42}$$

Here the following parameter is introduced to specify the distance from the origin:

$$p_{mn} = m_{mn}x_{mn} - \ell_{mn}y_{mn} \tag{43}$$

Since the direction of incident flux is definite, one has the following relations:

$$r_{m0} = e_4 \tag{44a}$$

$$\ell_{m0} = \cos\theta_s\cos\varphi_S \quad m_{m0} = \sin\theta_S \quad n_{m0} = -\cos\theta_S\sin\varphi_S \tag{44b}$$

$$p_{m0} = \beta(\cos\theta\sin\theta_S - \sin\theta\cos\theta_S\cos\varphi_S) + (m - 1/2)\sin\theta_S/M \tag{44c}$$

Equations (44) provide the initial conditions of calculation.

The calculation is performed as follows. First, one has to find the points of intersection between the planes expressed in Eqs. (41) and the line expressed in Eq. (42). For convenience, one calls them P_1, P_2, and P_3. If the y coordinate of P_i ($i=1$, 2) satisfies the condition $0<y<\beta\sin\theta$, then the $n+1$th reflection occurs on surface i. But if the x coordinate of P_3 satisfies the condition $0<x<1$, then the $n+1$th reflection occurs on surface 3. Otherwise the nth reflected radiation escapes from the channel to space.

The analytical results are formulated as follows. First, if the conditions

$$0<p_{mn}/(m_{mn}\cos\theta - \ell_{mn}\sin\theta)<\beta \text{ and } r_{mn}e_1 = 0 \tag{45}$$

hold, then

$$r_{m(n+1)} = e_1 \qquad n_{m(n+1)} = N_1 \tag{46a}$$

$$\ell_{m(n+1)} = -\ell_{mn}\cos 2\theta - m_{mn}\sin 2\theta$$

$$m_{m(n+1)} = m_{mn}\cos 2\theta - \ell_{mn}\sin 2\theta \tag{46b}$$

$$p_{m(n+1)} = p_{mn} \tag{46c}$$

Second, if the conditions

$$0<(p_{mn} - m_{mn})/(m_{mn}\cos\theta - \ell_{mn}\sin\theta)<\beta \text{ and } r_{mn}e_2 = 0 \tag{47}$$

hold, then

$$r_{m(n+1)} = e_2 \qquad n_{m(n+1)} = N_2 \tag{48a}$$

$$\ell_{m(n+1)} = -\ell_{mn}\cos 2\theta - m_{mn}\sin 2\theta,$$

$$m_{m(n+1)} = m_{mn}\cos 2\theta - \ell_{mn}\sin 2\theta \tag{48b}$$

$$p_{m(n+1)} = p_{mn} - 2\sin\theta(\ell_{mn}\cos\theta + m_{mn}\sin\theta) \tag{48c}$$

Third, if the conditions

$$0<p_{mn}/m_{mn}<1 \quad \text{and} \quad r_{mn}e_3 = 0 \tag{49}$$

hold, then

$$r_{m(n+1)} = e_3 \qquad n_{m(n+1)} = N_3 \tag{50a}$$

$$\ell_{m(n+1)} = -\ell_{mn} \qquad m_{m(n+1)} = m_{mn} \tag{50b}$$

$$p_{m(n+1)} = p_{mn} \tag{50c}$$

If none of the conditions (45), (47), and (49) is satisfied, then

$$r_{m(n+1)} = e_4 \tag{51}$$

and the calculation comes to an end.

Numerical Results and Discussions

The primary objective of the following numerical computation is to acquire knowledge helpful in the design of movable louvers. The computation has been performed over a range of parameter values that characterize the geometrical and optical properties of interest. The principal results of the parametric studies are summarized in the form of tables and figures.

Table 1 shows the effective emittance at the almost closed position specified as $\theta = 10$ deg and at the full open position specified as $\theta = 90$ deg. The difference between them can be regarded as the dynamic range specifying the performance of louvers. In Table 1, the symbol τ_S is defined as $\tau_S = \rho_S/(\rho_S + \rho_D)$ and is called the rate of nondiffusiveness. For example, the column classified as $\tau_S = 1$ and $\tau_{S0} = 0$ in Table 1 represents the louvers with purely specular blades and a purely diffuse base. From Table 1, one finds that the nondiffuse character of blade surface exerts a considerable influence on effective emittance while that of the base exerts almost no influence. Table 1 also shows that the number of blades exerts a slight influence on the effective emittance and that the upper and lower limits of dynamic range are reduced slightly as N increases. The significant result seen from Table 1 is that a specular blade and diffuse base louver system is superior to other types of louvers in dynamic range.

The curves shown in Fig. 3 are plots of effective emittance vs blade opening angle for various values of the rate of blade surface nondiffusiveness. It is clearly seen that the nondiffuse

Table 1 Dynamic range of effective emittance

		$N=5$		$N=15$		$N=\infty$		$N=5$		$N=15$		$N=\infty$	
τ_S	τ_{SO}	10 deg	90 deg	10 deg	90 deg	10 deg	90 deg	10 deg	90 deg	10 deg	90 deg	10 deg	90 deg
		$\beta=1.1,\ \epsilon=0.05,\ \epsilon_0=0.50$						$\beta=1.1,\ \epsilon=0.10,\ \epsilon_0=0.50$					
0	0	0.158	0.410	0.157	0.410	0.157	0.409	0.170	0.411	0.169	0.410	0.168	0.409
0	1	0.154	0.407	0.153	0.407	0.153	0.406	0.166	0.408	0.165	0.407	0.164	0.406
1	0	0.117	0.495	0.114	0.495	0.113	0.495	0.089	0.491	0.083	0.490	0.080	0.490
1	1	0.196	0.495	0.195	0.495	0.194	0.495	0.182	0.491	0.178	0.490	0.176	0.489
		$\beta=1.1,\ \epsilon=0.30,\ \epsilon_0=0.50$						$\beta=1.1,\ \epsilon=0.50,\ \epsilon_0=0.50$					
0	0	0.215	0.415	0.212	0.411	0.211	0.409	0.257	0.418	0.253	0.412	0.252	0.409
0	1	0.212	0.412	0.210	0.408	0.208	0.406	0.255	0.416	0.252	0.410	0.250	0.406
1	0	0.043	0.473	0.024	0.470	0.015	0.469	0.114	0.457	0.095	0.452	0.086	0.450
1	1	0.138	0.471	0.126	0.468	0.120	0.466	0.157	0.453	0.141	0.447	0.133	0.444
		$\beta=1.1,\ \epsilon=0.05,\ \epsilon_0=0.85$						$\beta=1.1,\ \epsilon=0.10,\ \epsilon_0=0.85$					
0	0	0.181	0.620	0.181	0.618	0.180	0.618	0.197	0.622	0.196	0.619	0.195	0.618
0	1	0.180	0.618	0.179	0.616	0.179	0.616	0.196	0.620	0.194	0.617	0.194	0.616
1	0	0.129	0.837	0.126	0.836	0.124	0.835	0.096	0.824	0.089	0.821	0.085	0.820
1	1	0.149	0.837	0.146	0.836	0.144	0.835	0.121	0.823	0.114	0.821	0.111	0.820
		$\beta=1.1,\ \epsilon=0.30,\ \epsilon_0=0.85$						$\beta=1.1,\ \epsilon=0.50,\ \epsilon_0=0.85$					
0	0	0.261	0.630	0.257	0.622	0.255	0.618	0.326	0.638	0.320	0.625	0.318	0.618
0	1	0.260	0.629	0.256	0.620	0.254	0.616	0.325	0.637	0.319	0.623	0.317	0.616
1	0	0.046	0.775	0.025	0.767	0.015	0.764	0.127	0.733	0.104	0.720	0.093	0.714
1	1	0.070	0.773	0.051	0.766	0.041	0.762	0.137	0.730	0.114	0.717	0.103	0.710

Table 2 Maximum and minimum temperatures specifying thermal control limits

				$N=5$		$N=15$		$N=\infty$		$N=5$		$N=15$		$N=\infty$		$N=5$		$N=15$		$N=\infty$		$N=5$		$N=15$		$N=\infty$	
τ_S	τ_{SO}	τ_S^*	τ_{SO}^*	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
				$\beta=1.1,\epsilon=0.05,\epsilon_0=0.85$, $\alpha=0.10$, $\alpha_0=0.10$						$\beta=1.1,\epsilon=0.10,\epsilon_0=0.85$, $\alpha=0.10,\alpha_0=0.10$						$\beta=1.1,\epsilon=0.05,\epsilon_0=0.85$, $\alpha=0.20$, $\alpha_0=0.10$						$\beta=1.1,\epsilon=0.10,\epsilon_0=0.85$, $\alpha=0.20,\alpha_0=0.10$					
1	0	0	0	276	316	277	317	287	327	278	341	279	346	288	360	285	325	286	323	295	332	286	350	288	353	297	365
1	0	0	1	262	317	263	317	270	328	264	342	265	346	272	361	275	325	276	324	283	333	277	351	278	354	285	366
1	0	1	0	263	302	264	302	274	313	265	325	266	329	275	344	273	310	274	307	283	316	274	334	276	335	285	348
1	0	1	1	252	298	252	297	262	308	253	321	253	324	263	339	254	307	254	304	262	313	255	330	256	332	263	344
1	1	0	0	276	304	277	304	287	315	278	321	279	324	289	336	285	312	286	310	295	319	286	329	288	330	297	341
1	1	0	1	262	305	263	305	270	315	264	322	265	325	272	337	275	312	276	311	283	319	277	330	279	331	285	342
1	1	1	0	263	291	264	290	274	301	265	307	266	309	275	321	273	298	274	295	283	304	274	314	276	314	285	325
1	1	1	1	252	287	252	286	262	296	253	302	253	304	263	317	254	295	254	292	262	301	255	311	256	311	263	322
				$\beta=1.1,\epsilon=0.05,\epsilon_0=0.85$, $\alpha=0.30$, $\alpha_0=0.10$						$\beta=1.1,\epsilon=0.10,\epsilon_0=0.85$, $\alpha=0.30,\alpha_0=0.10$						$\beta=1.1,\epsilon=0.05,\epsilon_0=0.85$, $\alpha=0.10$, $\alpha_0=0.20$						$\beta=1.1,\epsilon=0.10,\epsilon_0=0.85$, $\alpha=0.10,\alpha_0=0.20$					
1	0	0	0	291	331	293	328	300	335	292	357	294	358	302	369	305	319	306	320	317	331	306	344	307	349	318	364
1	0	0	1	281	331	283	328	289	335	283	357	285	358	291	369	287	320	287	320	298	332	288	345	288	350	300	365
1	0	1	0	281	317	283	312	291	319	282	341	284	340	293	351	296	302	297	302	308	313	297	325	298	329	310	344
1	0	1	1	261	315	261	310	267	317	262	339	263	338	269	349	289	298	289	297	300	308	290	321	290	324	302	339
1	1	0	0	291	318	293	314	301	321	293	335	295	335	303	344	305	307	306	307	316	318	306	324	307	327	318	340
1	1	0	1	282	318	283	314	289	322	284	336	285	335	291	344	287	308	287	308	298	319	288	325	289	328	300	341
1	1	1	0	281	304	283	299	291	307	282	321	285	319	293	328	...	...	...	...	...	...	297	307	298	309	310	321
1	1	1	1	261	302	261	297	267	305	263	319	263	317	269	326	..	...	...	...	...	...	290	303	290	304	302	317

character of the blade greatly contributes to the expansion of dynamic range. The calculation is carried out with the same data as those of Plamondon[1] with a view to verifying the assumption that the blades and base are isothermal. This assumption can be regarded as reasonable because the curve specified as $\tau_S=0.0$ almost coincides with his curve. Figure 3 indicates negative effective emittance at almost closed positions for highly specular blades. This occurs because the analysis neglects an effect of the nonuniformity of radiosity distributions. Then there is another curve specified as $\beta=1.0$, $\epsilon=0.05$, $\epsilon_0=0.82$, $\tau_S=\tau_{SO}=1.0$, and $N=15$ in the figure. These parameters are the same as those Michalek et al.[5] employed to evaluate the performance of an all-specular louver system. This curve closely corresponds with their calculated values over the full range of blade opening angles. This demonstrates that the lack of a gap between blade and base in the model does not have a great influence on the predicted value of effective emittance.

The value estimated by Eq. (4) is different from the exact one calculated under the condition that blades are finite in length. This difference is caused by an edge effect. From the viewpoint of design practice, it is necessary to find an error index convenient to evaluate the edge effect. For simplicity, purely diffuse surfaces specified as $\rho_S=\rho_{SO}=0$ are now taken into consideration. In this case Eqs. (12) are reduced to the following expressions:

$$E_{11}=E_{22}=E_{33}=0, \qquad E_{12}=E_{21}=F_{12},$$

$$E_{13}=F_{13},\ E_{23}=F_{23},\ E_{31}=\beta F_{13},\ E_{32}=\beta F_{23} \tag{52}$$

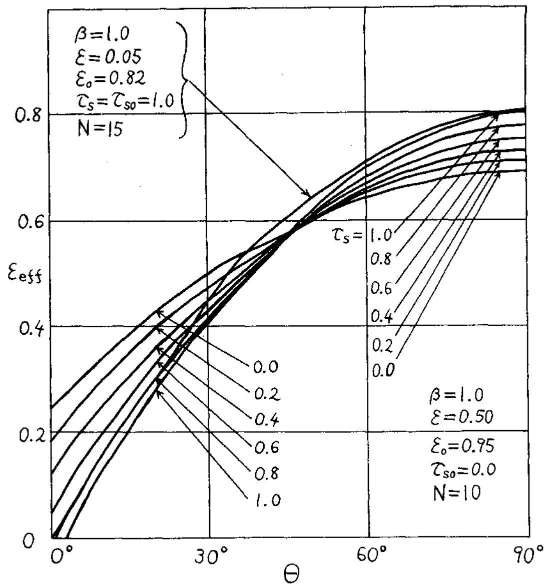

Fig. 3 Effect of nondiffuse surface reflectance on effective emittance.

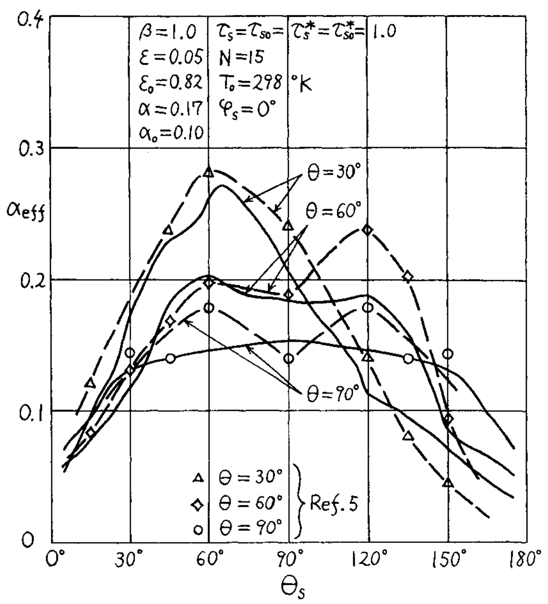

Fig. 4 Effective absorptance vs solar elevation angle.

Equation (52) is rewritten as follows provided that each blade is $2l$ in length.

$$E_{11}=E_{22}=E_{33}=0,\ E_{12}=E_{21}=\tilde{F}_{12},$$
$$E_{13}=\tilde{F}_{13}=1-\tilde{F}_{12}-\tilde{F}_{23}-\tilde{F}_{15},$$
$$E_{23}=\tilde{F}_{23},\ E_{31}=\beta\tilde{F}_{13},\ E_{32}=\beta\tilde{F}_{23} \tag{53}$$

where the subscript 5 appended to the factor $\tilde{F}_{15}$ represents two virtual surfaces parallel to the xy plane at the ends of a louver channel, that is, the so-called edge surfaces. The view factors $\tilde{F}_{12}$, $\tilde{F}_{23}$, and $\tilde{F}_{15}$ are given by double integrals shown in Appendix B. The error index Δ for evaluating the edge effect can now be defined as follows:

$$\Delta=(\widetilde{\epsilon^{\infty}_{\mathrm{eff,nsp}}}-\epsilon^{\infty}_{\mathrm{eff,nsp}})/\epsilon^{\infty}_{\mathrm{eff,nsp}} \tag{54}$$

where $\epsilon^{\infty}_{\mathrm{eff,nsp}}$ and $\widetilde{\epsilon^{\infty}_{\mathrm{eff,nsp}}}$ show the effective emittances calculated from Eq. (4) with Eqs. (52) and (52), respectively. As a result of numerical computation, one finds the approximate relation $\Delta\propto\tilde{F}_{15}$. Thus one can make a gross estimate of the edge effect.

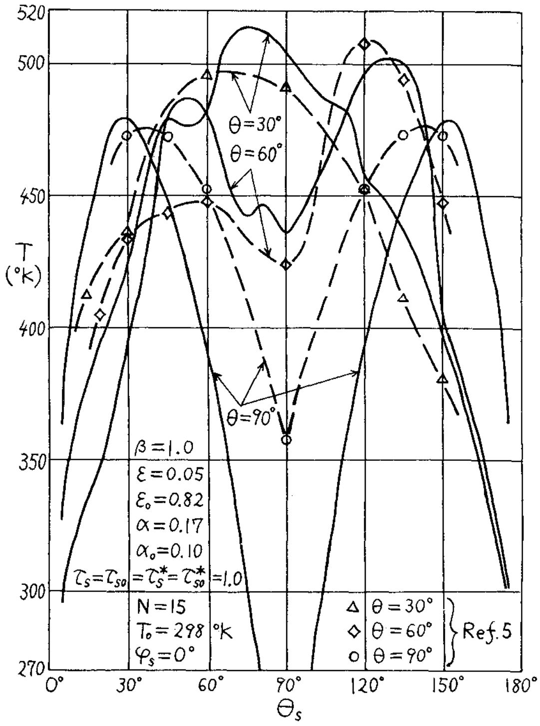

Fig. 5 Blade temperature vs solar elevation angle.

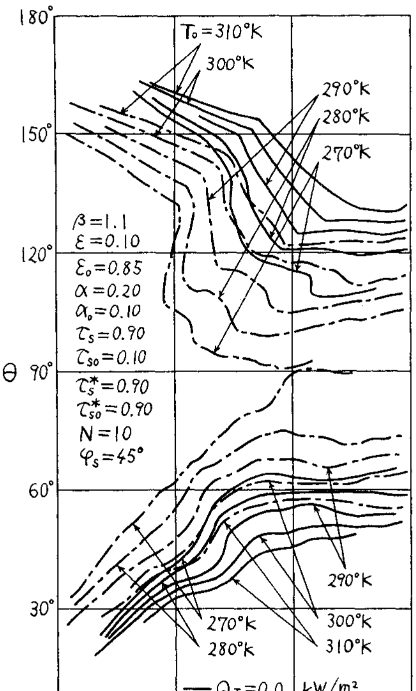

Fig. 6 Thermal control characteristics for specified values of base temperature.

Table 2 shows the maximum and minimum temperatures specifying the thermal control limits corresponding to the solar rejection capability of louvers. The base temperature must often be fixed at a specified value, no matter how the solar direction changes. In such cases it is possible to find preferred blade opening angles provided that the specified temperature is not beyond the limits shown in Table 2. The calculation is performed for the condition of $I_S=1.4\ \mathrm{kW/m^2}$,

$Q_I = 0.05$ kW/m^2, $10 \le \theta_S \le 90$ deg, and $0 \le \varphi_S \le 180$ deg. From Table 2, one has the following results: 1) the base surface nondiffusiveness specified by τ_{S0} in the infrared wavelength region hardly affects the thermal control limits; 2) the increase in surface nondiffusiveness specified by τ_S^* and τ_{S0}^* in the solar wavelength region makes the thermal control limits shift downward; 3) the large emittance of blade surface helps to expand the upper limit of thermal control; 4) the increase in solar absorptance of blade surface makes the thermal control limits shift upward; 5) the increase in solar absorptance of the base surface has almost no influence on the upper limit of thermal control, but it has a considerable effect on the lower limit; and 6) the thermal control limits of an infinite louver array are considerably different from those of louvers with a finite number of blades. In Table 2 dashes indicate that there is no temperature range within which active thermal control with louvers is possible.

Figures 4 and 5 present effective absorptance and average temperature of blades vs solar elevation angle for blade opening angles of 30, 60, and 90 deg. Solar simulation test results[5] of thermal control louvers used on the ATS-F&G spacecraft are also plotted in the figures for comparison with predictions. The shapes of the curves are generally in good agreement with the plots of the test results except for the full open position. Referring to the numerical results presented by Michalek et al.,[5] it is noted that there is no remarkable difference between their results and the author's predictions. Such agreements indicate that the model used in this paper is applicable to analytical studies of a louver system exposed to solar radiation.

Figure 6 is presented for the purpose of displaying optimal blade opening angles for two cases of heat generation in the base. The interesting feature of Fig. 6 is that there exist two optimal blade opening angles corresponding to a specified direction of solar incidence. Such characteristics should be taken into account in the design of the blade driving mechanism.

Concluding Remarks

An analytical method based on the diffuse and specular coradiosity representation has been presented for evaluation of effective emittance and solar rejection capability of movable louvers with a finite number of blades. The blades and base are treated as semigray surfaces of nondiffuse character that is approximated by subdivision of the reflectance into specular and diffuse components in both the solar and infrared wavelength regions. All possible specular reflections are taken into account to the extent of three intervening specular reflections. The matrix representation has been developed to follow specular reflection paths of a large number of subfluxes into which the solar flux incident on a louver channel is divided. The intensity of solar field formed by specular reflections is estimated by numerical means based on matrices with elements determined from three-dimensional analytical geometry. Analytical results have been applied to parametric studies for design optimization of movable louvers and to present some knowledge helpful to design practice.

Appendix A

$$\beta F_{12} = g(\beta, \cos\theta, \beta, \sin\theta) \tag{A1}$$

$$\beta F_{13} = f(0, \beta, 0, 1, \theta) \tag{A2}$$

$$\beta F_{1(2)1} = g(\beta, 0, \beta, 2\sin\theta) \tag{A3}$$

$$\beta F_{1(3)1} = f(0, \beta, 0, \beta, 2\theta) \quad \text{if } 0<\theta<\pi/2 \tag{A4a}$$

$$= 0 \quad \text{if } \pi/2 \le \theta < \pi \tag{A4b}$$

$$\beta F_{1(3)2} = f\left(0, \frac{1}{2\cos\theta}, \frac{1}{2\cos\theta}, \beta, \pi - 2\theta\right) \quad \text{if } 0<\theta<\frac{\pi}{2} \text{ and } \beta \ge \frac{1}{2\cos\theta} \tag{A5a}$$

$$= f\left(\frac{1}{2\cos\theta} - \beta, \beta, \frac{1}{2\cos\theta}, \beta, \pi - 2\theta\right) \quad \text{if } 0<\theta<\frac{\pi}{2} \text{ and } \beta < \frac{1}{2\cos\theta} \tag{A5b}$$

$$= g(\beta, \beta, \beta, 1) \quad \text{if } \theta = \pi/2 \tag{A5c}$$

$$= f\left(-\frac{1}{2\cos\theta}, \beta, 0, -\frac{1}{2\cos\theta}, 2\theta - \pi\right) \quad \text{if } \frac{\pi}{2}<\theta<\pi \text{ and } \beta \ge -\frac{1}{2\cos\theta} \tag{A5d}$$

$$= f\left(-\frac{1}{2\cos\theta}, \beta, -\frac{1}{2\cos\theta} - \beta, \beta, 2\theta - \pi\right) \quad \text{if } \frac{\pi}{2}<\theta<\pi \text{ and } \beta < -\frac{1}{2\cos\theta} \tag{A5e}$$

$$\beta F_{1(2)3} = f(0, \beta - 2\cos\theta, 1, 1, \pi - \theta) \quad \text{if } 0<\theta<\pi/2 \text{ and } \beta > 2\cos\theta \tag{A6a}$$

$$= 0 \quad \text{if } 0<\theta<\pi/2 \text{ and } \beta \le 2\cos\theta \tag{A6b}$$

$$= f(-2\cos\theta, \beta, 1, 1, \pi - \theta) \quad \text{if } \pi/2 \le \theta < \pi \tag{A6c}$$

$$\beta F_{1(2,3)1} = f\left(\frac{1}{\cos\theta}, \beta - 2\cos\theta, 0, \frac{1}{\cos\theta}, \pi - 2\theta\right) \quad \text{if } 0<\theta\le\frac{\pi}{4} \text{ and } \beta > 2\cos\theta \text{ or } \frac{\pi}{4}<\theta<\frac{\pi}{2} \text{ and } \beta \ge \frac{1}{\cos\theta} \tag{A7a}$$

$$= f\left(\frac{1}{\cos\theta}, \beta - 2\cos\theta, \frac{1}{\cos\theta} - \beta, \beta, \pi - 2\theta\right) \quad \text{if } \frac{\pi}{4}<\theta<\frac{\pi}{2} \text{ and } 2\cos\theta < \beta < \frac{1}{\cos\theta} \tag{A7b}$$

$$= g(\beta, \beta, \beta, 2) \quad \text{if } \theta = \pi/2 \tag{A7c}$$

$$=f\left(0,\frac{2\cos^2\theta-1}{\cos\theta},-\frac{1}{\cos\theta},\beta,2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta\geq\frac{2\cos^2\theta-1}{\cos\theta} \tag{A7d}$$

$$=f\left(\frac{2\cos^2\theta-1}{\cos\theta}-\beta,\beta,-\frac{1}{\cos\theta},\beta,2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta<\frac{2\cos^2\theta-1}{\cos\theta} \tag{A7e}$$

$$=0 \quad \text{if} \quad 0<\theta<\frac{\pi}{2} \quad \text{and} \quad \beta\leq 2\cos\theta \quad \text{or} \quad \frac{3\pi}{4}\leq\theta<\pi \tag{A7f}$$

$$\beta F_{1(3,2)1}=f\left(\frac{1}{2\cos\theta},\frac{1}{2\cos\theta},0,\beta-\frac{2\cos^2\theta-1}{\cos\theta},\pi-2\theta\right) \quad \text{if} \quad 0<\theta\leq\frac{\pi}{6} \quad \text{and} \quad \beta>\frac{2\cos^2\theta-1}{\cos\theta}$$

$$\text{or} \quad \frac{\pi}{6}<\theta<\frac{\pi}{4} \quad \text{and} \quad \beta\geq\frac{1}{2\cos\theta} \tag{A8a}$$

$$=f\left(\frac{1}{\cos\theta}-\beta,\beta,0,\beta-\frac{2\cos^2\theta-1}{\cos\theta},\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{6}<\theta<\frac{\pi}{4} \quad \text{and} \quad \frac{2\cos^2\theta-1}{\cos\theta}<\beta<\frac{1}{2\cos\theta} \tag{A8b}$$

$$=f\left(\frac{1}{2\cos\theta},\frac{1}{2\cos\theta},\frac{1-2\cos^2\theta}{\cos\theta},\beta,\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{4}\leq\theta<\frac{\pi}{2} \quad \text{and} \quad \beta\geq\frac{1}{2\cos\theta} \tag{A8c}$$

$$=f\left(\frac{1}{\cos\theta}-\beta,\beta,\frac{1-2\cos^2\theta}{\cos\theta},\beta,\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{4}\leq\theta<\frac{\pi}{2} \quad \text{and} \quad \beta<\frac{1}{2\cos\theta} \tag{A8d}$$

$$=g(\beta,\beta,\beta,2) \quad \text{if} \quad \theta=\pi/2 \tag{A8e}$$

$$=f\left(-\frac{1}{\cos\theta},\beta,0,\frac{2\cos^2\theta-1}{\cos\theta},2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta\geq\frac{2\cos^2\theta-1}{\cos\theta} \tag{A8f}$$

$$=f\left(-\frac{1}{\cos\theta},\beta,\frac{2\cos^2\theta-1}{\cos\theta}-\beta,\beta,2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta<\frac{2\cos^2\theta-1}{\cos\theta} \tag{A8g}$$

$$=0 \quad \text{if} \quad 0<\theta<\frac{\pi}{4} \quad \text{and} \quad \beta\leq\frac{2\cos^2\theta-1}{\cos\theta} \quad \text{or} \quad \frac{3\pi}{4}\leq\theta<\pi \tag{A8h}$$

$$\beta F_{1(2,1)2}=g(\beta,\cos\theta,\beta,3\sin\theta) \tag{A9}$$

$$\beta F_{1(2,3)2}=0 \quad \text{if} \quad 0<\theta\leq\frac{\pi}{2} \quad \text{or} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta\leq\frac{4\cos^2\theta-1}{2\cos\theta} \tag{A10a}$$

$$=f\left(0,\beta-\frac{4\cos^2\theta-1}{2\cos\theta},-\frac{1}{2\cos\theta},\beta,2\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta>\frac{4\cos^2\theta-1}{2\cos\theta} \tag{A10b}$$

$$=f\left(\frac{1-4\cos^2\theta}{2\cos\theta},\beta,-\frac{1}{2\cos\theta},\beta,2\pi-2\theta\right) \quad \text{if} \quad \frac{2\pi}{3}\leq\theta<\pi \tag{A10c}$$

$$\beta F_{1(2,1)3}=f(2\cos\theta,\beta,2,1,\theta) \quad \text{if} \quad 0<\theta\leq\frac{\pi}{2} \tag{A11a}$$

$$=f(0,\beta+2\cos\theta,2,1,\theta) \quad \text{if} \quad \pi/2<\theta<\pi \quad \text{and} \quad \beta>-2\cos\theta \tag{A11b}$$

$$=0 \quad \text{if} \quad \pi/2<\theta<\pi \quad \text{and} \quad \beta\leq-2\cos\theta \tag{A11c}$$

$$\beta F_{1(3,1)3}=f(0,\beta,0,1,3\theta) \quad \text{if} \quad 0<\theta<\pi/3 \tag{A12a}$$

$$=0 \quad \text{if} \quad \pi/3\leq\theta<\pi \tag{A12b}$$

$$\beta F_{1(3,2)3}=0 \quad \text{if} \quad 0<\theta\leq\pi/2 \tag{A13a}$$

$$=f\left(0,\frac{2\cos\theta}{4\cos^2\theta-1},\frac{1}{1-4\cos^2\theta},1,2\pi-3\theta\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta\geq\frac{2\cos\theta}{4\cos^2\theta-1} \tag{A13b}$$

$$=f\left(\frac{2\cos\theta}{4\cos^2\theta-1}-\beta,\beta,\frac{1}{1-4\cos^2\theta},1,2\pi-3\theta\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta<\frac{2\cos\theta}{4\cos^2\theta-1} \tag{A13c}$$

$$=g\left(\beta,\beta+\frac{1}{2},1,\frac{\sqrt{3}}{2}\right) \quad \text{if} \quad \theta=\frac{2\pi}{3} \tag{A13d}$$

$$=f\left(\frac{2\cos\theta}{1-4\cos^2\theta},\beta,\frac{2(2\cos^2\theta-1)}{1-4\cos^2\theta},1,3\theta-2\pi\right) \quad \text{if} \quad \frac{2\pi}{3}<\theta<\frac{3\pi}{4} \tag{A13e}$$

$$=f\left(\frac{2\cos\theta}{1-4\cos^2\theta},\beta,0,\frac{1}{4\cos^2\theta-1},3\theta-2\pi\right) \quad \text{if} \quad \frac{3\pi}{4}\leq\theta<\pi \tag{A13f}$$

$$\beta F_{1(2,1,2)1} = g(\beta,0,\beta,4\sin\theta) \tag{A14}$$

$$\beta F_{1(2,1,3)1} = f\left(\frac{2\cos^2\theta-1}{\cos\theta},\beta,\frac{1}{\cos\theta},\beta,2\theta\right) \quad \text{if} \quad 0<\theta\le\frac{\pi}{4} \tag{A15a}$$

$$= f\left(0,\beta-\frac{1-2\cos^2\theta}{\cos\theta},\frac{1}{\cos\theta},\beta,2\theta\right) \quad \text{if} \quad \frac{\pi}{4}<\theta<\frac{\pi}{2} \quad \text{and} \quad \beta>\frac{1-2\cos^2\theta}{\cos\theta} \tag{A15b}$$

$$= 0 \quad \text{if} \quad \frac{\pi}{4}<\theta<\frac{\pi}{2} \quad \text{and} \quad \beta\le\frac{1-2\cos^2\theta}{\cos\theta} \quad \text{or} \quad \frac{\pi}{2}\le\theta<\pi \tag{A15c}$$

$$\beta F_{1(2,3,2)1} = 0 \quad \text{if} \quad 0<\theta\le\frac{\pi}{2} \quad \text{or} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta\le\frac{4\cos^2\theta-1}{2\cos\theta} \tag{A16a}$$

$$= f\left(-\frac{1}{2\cos\theta},\beta-\frac{4\cos^2\theta-1}{2\cos\theta},-2\cos\theta,\beta,2\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta>\frac{4\cos^2\theta-1}{2\cos\theta} \tag{A16b}$$

$$= f(-2\cos\theta,\beta,-2\cos\theta,\beta,2\pi-2\theta) \quad \text{if} \quad 2\pi/3\le\theta<\pi \tag{A16c}$$

$$\beta F_{1(3,1,3)1} = f(0,\beta,0,\beta,4\theta) \quad \text{if} \quad 0<\theta<\pi/4 \tag{A17a}$$

$$= 0 \quad \text{if} \quad \pi/4\le\theta<\pi \tag{A17b}$$

$$\beta F_{1(3,2,3)1} = 0 \quad \text{if} \quad 0<\theta\le\pi/2 \quad \text{or} \quad 3\pi/4\le\theta<\pi \tag{A18a}$$

$$= f\left(-\frac{1}{2\cos\theta},\frac{2\cos\theta}{4\cos^2\theta-1},-\frac{1}{2\cos\theta},\beta,4\theta-2\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta>\frac{2\cos\theta}{4\cos^2\theta-1} \tag{A18b}$$

$$= f\left(-\frac{1}{2\cos\theta},\beta,-\frac{1}{2\cos\theta},\beta,4\theta-2\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{2\pi}{3} \quad \text{and} \quad \beta\le\frac{2\cos\theta}{4\cos^2\theta-1} \quad \text{or} \quad \frac{2\pi}{3}\le\theta<\frac{3\pi}{4} \tag{A18c}$$

$$\beta F_{1(2,1,3)2} = 0 \quad \text{if} \quad 0<\theta\le\pi/6 \quad \text{or} \quad \pi/2<\theta<\pi \quad \text{and} \quad \beta\le-2\cos\theta \tag{A19a}$$

$$= f\left(0,\frac{3-4\cos^2\theta}{2\cos\theta},\frac{3}{2\cos\theta},\beta,\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{6}<\theta<\frac{\pi}{2} \quad \text{and} \quad \beta\ge\frac{3-4\cos^2\theta}{2\cos\theta} \tag{A19b}$$

$$= f\left(\frac{3-4\cos^2\theta}{2\cos\theta}-\beta,\beta,\frac{3}{2\cos\theta},\beta,\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{6}<\theta<\frac{\pi}{2} \quad \text{and} \quad \beta<\frac{3-4\cos^2\theta}{2\cos\theta} \tag{A19c}$$

$$= g(\beta,\beta,\beta,3) \quad \text{if} \quad \theta=\pi/2 \tag{A19d}$$

$$= f\left(-\frac{3}{2\cos\theta},\beta+2\cos\theta,-\frac{3}{2\cos\theta}-\beta,\beta,2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{5\pi}{6} \quad \text{and} \quad -2\cos\theta<\beta<-\frac{3}{2\cos\theta} \tag{A19e}$$

$$= f\left(-\frac{3}{2\cos\theta},\beta+2\cos\theta,0,-\frac{3}{2\cos\theta},2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{5\pi}{6} \quad \text{and} \quad \beta\ge-\frac{3}{2\cos\theta}$$

$$\text{or} \quad \frac{5\pi}{6}\le\theta<\pi \quad \text{and} \quad \beta>-2\cos\theta \tag{A19f}$$

$$\beta F_{1(2,3,1)2} = 0 \quad \text{if} \quad 0<\theta\le\pi/6 \quad \text{or} \quad \pi/6<\theta<\pi/2 \quad \text{and} \quad \beta\le2\cos\theta \quad \text{or} \quad 3\pi/4\le\theta<\pi \tag{A20a}$$

$$= f\left(\frac{3}{2\cos\theta},\beta-2\cos\theta,0,\frac{3-4\cos^2\theta}{2\cos\theta},\pi-2\theta\right) \quad \text{if} \quad \frac{\pi}{6}<\theta\le\tan^{-1}\sqrt{\frac{5}{3}} \quad \text{and} \quad \beta>2\cos\theta$$

$$\text{or} \quad \tan^{-1}\sqrt{\frac{5}{3}}<\theta<\frac{\pi}{2} \quad \text{and} \quad \beta\ge\frac{3-4\cos^2\theta}{2\cos\theta} \tag{A20b}$$

$$= f\left(\frac{3}{2\cos\theta},\beta-2\cos\theta,\frac{3-4\cos^2\theta}{2\cos\theta}-\beta,\beta,\pi-2\theta\right) \quad \text{if} \quad \tan^{-1}\sqrt{\frac{5}{3}}<\theta<\frac{\pi}{2} \quad \text{and} \quad 2\cos\theta<\beta<\frac{3-4\cos^2\theta}{2\cos\theta} \tag{A20c}$$

$$= g(\beta,\beta,\beta,3) \quad \text{if} \quad \theta=\pi/2 \tag{A20d}$$

$$= f\left(-\frac{1}{2\cos\theta},\frac{2\cos^2\theta-1}{\cos\theta},\frac{4\cos^2\theta-3}{2\cos\theta},\beta,2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta\ge\frac{2\cos^2\theta-1}{\cos\theta} \tag{A20e}$$

$$= f\left(\frac{4\cos^2\theta-3}{2\cos\theta}-\beta,\beta,\frac{4\cos^2\theta-3}{2\cos\theta},\beta,2\theta-\pi\right) \quad \text{if} \quad \frac{\pi}{2}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta<\frac{2\cos^2\theta-1}{\cos\theta} \tag{A20f}$$

$$\beta F_{1(3,1,3)2} = f\left(0, \frac{1}{4\cos\theta(2\cos^2\theta-1)}, \frac{4\cos^2\theta-1}{4\cos\theta(2\cos^2\theta-1)}, \beta, \pi-4\theta\right) \quad \text{if } 0<\theta<\frac{\pi}{4} \text{ and } \beta \geq \frac{1}{4\cos\theta(2\cos^2\theta-1)} \tag{A21a}$$

$$= f\left(\frac{1}{4\cos\theta(2\cos^2\theta-1)} - \beta, \beta, \frac{4\cos^2\theta-1}{4\cos\theta(2\cos^2\theta-1)}, \beta, \pi-4\theta\right) \quad \text{if } 0<\theta<\frac{\pi}{4} \text{ and } \beta < \frac{1}{4\cos\theta(2\cos^2\theta-1)} \tag{A21b}$$

$$= 0 \quad \text{if } \pi/4 \leq \theta < \pi \tag{A21c}$$

$$\beta F_{1(3,2,1)2} = 0 \quad \text{if } 0<\theta<\frac{\pi}{6} \text{ and } \beta \leq \frac{4\cos^2\theta-3}{2\cos\theta} \text{ or } \frac{5\pi}{6} \leq \theta < \pi \tag{A22a}$$

$$= f\left(\frac{1}{\cos\theta}, \frac{1}{2\cos\theta}, 0, \beta - \frac{4\cos^2\theta-3}{2\cos\theta}, \pi-2\theta\right) \quad \text{if } 0<\theta<\frac{\pi}{6} \text{ and } \beta \geq \frac{1}{2\cos\theta} \tag{A22b}$$

$$= f\left(\frac{3}{2\cos\theta} - \beta, \beta, 0, \beta - \frac{4\cos^2\theta-3}{2\cos\theta}, \pi-2\theta\right) \quad \text{if } 0<\theta<\frac{\pi}{6} \text{ and } \frac{4\cos^2\theta-3}{2\cos\theta} < \beta < \frac{1}{2\cos\theta} \tag{A22c}$$

$$= f\left(\frac{1}{\cos\theta}, \frac{1}{2\cos\theta}, \frac{3-4\cos^2\theta}{2\cos\theta}, \beta, \pi-2\theta\right) \quad \text{if } \frac{\pi}{6} \leq \theta < \frac{\pi}{2} \text{ and } \beta \geq \frac{1}{2\cos\theta} \tag{A22d}$$

$$= f\left(\frac{3}{2\cos\theta} - \beta, \beta, \frac{3-4\cos^2\theta}{2\cos\theta}, \beta, \pi-2\theta\right) \quad \text{if } \frac{\pi}{6} \leq \theta < \frac{\pi}{2} \text{ and } \beta < \frac{1}{2\cos\theta} \tag{A22e}$$

$$= g(\beta, \beta, \beta, 3) \quad \text{if } \theta = \pi/2 \tag{A22f}$$

$$= f\left(-\frac{3}{2\cos\theta}, \beta, 0, \frac{4\cos^2\theta-3}{2\cos\theta}, 2\theta-\pi\right) \quad \text{if } \frac{\pi}{2} < \theta < \frac{5\pi}{6} \text{ and } \beta \geq \frac{4\cos^2\theta-3}{2\cos\theta} \tag{A22g}$$

$$= f\left(-\frac{3}{2\cos\theta}, \beta, \frac{4\cos^2\theta-3}{2\cos\theta} - \beta, \beta, 2\theta-\pi\right) \quad \text{if } \frac{\pi}{2} < \theta < \frac{5\pi}{6} \text{ and } \beta < \frac{4\cos^2\theta-3}{2\cos\theta} \tag{A22h}$$

$$\beta F_{1(3,2,3)2} = 0 \quad \text{if } 0<\theta \leq 2\pi/3 \tag{A23a}$$

$$= f\left(0, \frac{4\cos^2\theta-1}{4\cos\theta(2\cos^2\theta-1)}, \frac{1}{4\cos\theta(2\cos^2\theta-1)}, \beta, 3\pi-4\theta\right) \quad \text{if } \frac{2\pi}{3} < \theta < \frac{3\pi}{4} \text{ and } \beta \geq \frac{4\cos^2\theta-1}{4\cos\theta(2\cos^2\theta-1)} \tag{A23b}$$

$$= f\left(\frac{4\cos^2\theta-1}{4\cos\theta(2\cos^2\theta-1)} - \beta, \beta, \frac{1}{4\cos\theta(2\cos^2\theta-1)}, \beta, 3\pi-4\theta\right) \quad \text{if } \frac{2\pi}{3} < \theta < \frac{3\pi}{4} \text{ and } \beta < \frac{4\cos^2\theta-1}{4\cos\theta(2\cos^2\theta-1)} \tag{A23c}$$

$$= g(\beta, \beta+1/\sqrt{2}, \beta, 1/\sqrt{2}) \quad \text{if } \theta = 3\pi/4 \tag{A23d}$$

$$= f\left(\frac{4\cos^2\theta-1}{4\cos\theta(1-2\cos^2\theta)}, \beta, 0, \frac{1}{4\cos\theta(1-2\cos^2\theta)}, 4\theta-3\pi\right) \quad \text{if } \frac{3\pi}{4} < \theta < \pi \text{ and } \beta \geq \frac{1}{4\cos\theta(1-2\cos^2\theta)} \tag{A23e}$$

$$= f\left(\frac{4\cos^2\theta-1}{4\cos\theta(1-2\cos^2\theta)}, \beta, \frac{1}{4\cos\theta(1-2\cos^2\theta)} - \beta, \beta, 4\theta-3\pi\right) \quad \text{if } \frac{3\pi}{4} < \theta < \pi \text{ and } \beta < \frac{1}{4\cos\theta(1-2\cos^2\theta)} \tag{A23f}$$

$$\beta F_{1(2,1,2)3} = f(0, \beta-4\cos\theta, 3, 1, \pi-\theta) \quad \text{if } 0<\theta<\pi/2 \text{ and } \beta > 4\cos\theta \tag{A24a}$$

$$= 0 \quad \text{if } 0<\theta<\pi/2 \text{ and } \beta \leq 4\cos\theta \tag{A24b}$$

$$= f(-4\cos\theta, \beta, 3, 1, \pi-\theta) \quad \text{if } \pi/2 \leq \theta < \pi \tag{A24c}$$

$$\beta F_{1(2,3,1)3} = 0 \quad \text{if } 0<\theta<\pi/2 \text{ and } \beta \leq 2\cos\theta \text{ or } \pi/2 \leq \theta < \pi \tag{A25a}$$

$$= f\left(\frac{4\cos\theta}{4\cos^2\theta-1}, \beta-2\cos\theta, 0, \frac{2}{4\cos^2\theta-1}, \pi-3\theta\right) \quad \text{if } 0<\theta \leq \frac{\pi}{6} \text{ and } \beta > 2\cos\theta \tag{A25b}$$

$$= f\left(\frac{4\cos\theta}{4\cos^2\theta-1}, \beta-2\cos\theta, \frac{3-4\cos^2\theta}{4\cos^2\theta-1}, 1, \pi-3\theta\right) \quad \text{if } \frac{\pi}{6} < \theta < \frac{\pi}{3} \text{ and } \beta > 2\cos\theta \tag{A25c}$$

$$= g(\beta-1, \beta, 1, \sqrt{3}) \quad \text{if } \theta = \pi/3 \text{ and } \beta > 1 \tag{A25d}$$

$$= f\left(0, \frac{4\cos\theta}{1-4\cos^2\theta}, \frac{2}{1-4\cos^2\theta}, 1, 3\theta-\pi\right) \quad \text{if } \frac{\pi}{3} < \theta < \frac{\pi}{2} \text{ and } \beta \geq \frac{2\cos\theta(3-4\cos^2\theta)}{1-4\cos^2\theta} \tag{A25e}$$

$$= f\left(\frac{2\cos\theta(3-4\cos^2\theta)}{1-4\cos^2\theta} - \beta, \beta-2\cos\theta, \frac{2}{1-4\cos^2\theta}, 1, 3\theta-\pi\right) \quad \text{if } \frac{\pi}{3} < \theta < \frac{\pi}{2} \text{ and } 2\cos\theta < \beta < \frac{2\cos\theta(3-4\cos^2\theta)}{1-4\cos^2\theta} \tag{A25f}$$

$$\beta F_{1(2,3,2)3} = 0 \qquad \text{if} \quad 0<\theta\leq\frac{2\pi}{3}$$

$$\text{or} \quad \frac{2\pi}{3}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta\leq\frac{4\cos\theta(2\cos^2\theta-1)}{4\cos^2\theta-1} \tag{A26a}$$

$$= f\left(0,\beta-\frac{4\cos\theta(2\cos^2\theta-1)}{4\cos^2\theta-1},\frac{1}{4\cos^2\theta-1},1,3\pi-3\theta\right) \qquad \text{if} \quad \frac{2\pi}{3}<\theta<\frac{3\pi}{4} \quad \text{and} \quad \beta>\frac{4\cos\theta(2\cos^2\theta-1)}{4\cos^2\theta-1} \tag{A26b}$$

$$= f\left(\frac{4\cos\theta(1-2\cos^2\theta)}{4\cos^2\theta-1},\beta,\frac{1}{4\cos^2\theta-1},1,3\pi-3\theta\right) \qquad \text{if} \quad \frac{3\pi}{4}\leq\theta<\pi \tag{A26c}$$

where the functions $f(a_1, b_1, a_2, b_2, \gamma)$ and $g(b_1, a_2, b_2, h)$ are defined as follows:

$$f(a_1,b_1,a_2,b_2,\gamma) = f(a_2,b_2,a_1,b_1,\gamma)$$

$$= \tfrac{1}{2}\left[\sqrt{(a_1+b_1)^2+a_2^2-2(a_1+b_1)a_2\cos\gamma}-\sqrt{(a_1+b_1)^2+(a_2+b_2)^2-2(a_1+b_1)(a_2+b_2)\cos\gamma}\right.$$
$$\left.+\sqrt{a_1^2+(a_2+b_2)^2-2a_1(a_2+b_2)\cos\gamma}-\sqrt{a_1^2+a_2^2-2a_1\cos\gamma}\right] \tag{A27}$$

$$g(b_1,a_2,b_2,h) = g(b_2,-a_2,b_1,h) = g(b_2,a_2+b_2-b_1,b_1,h)$$

$$= \tfrac{1}{2}\left[\sqrt{(a_2-b_1)^2+h^2}-\sqrt{(a_2+b_2-b_1)^2+h^2}+\sqrt{(a_2+b_2)^2+h^2}-\sqrt{a_2^2+h^2}\right] \tag{A28}$$

Appendix B

$$\beta\tilde{F}_{12} = \frac{\sin^2\theta}{\pi}\int_0^\beta dy\int_0^\beta \frac{dz}{C^2}\left(\frac{2l}{C^2+4l^2}+\frac{l}{C}\tan^{-1}\frac{2l}{C}\right) \tag{B1}$$

where $C^2 = (y-z-\cos\theta)^2+\sin^2\theta$

$$\beta\tilde{F}_{23} = \frac{\sin^2\theta}{\pi}\int_0^1 dx\int_0^\beta dy\,\frac{xy}{C^2}\left(\frac{2l}{C^2+4l^2}+\frac{1}{C}\tan^{-1}\frac{2l}{C}\right) \tag{B2}$$

where $C^2 = x^2+y^2+2xy\cos\theta$

$$\tilde{F}_{15} = \frac{2l\sin^2\theta}{\pi}\int_0^1 dx\int_{-\beta}^\beta dy\,\frac{x}{C^2(C^2+4l^2)} \tag{B3}$$

where $C^2 = x^2+y^2+2xy\cos\theta$

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