IOP Conf. Series: Materials Science and Engineering **302** (2018) 012042 doi:10.1088/1757-899X/302/1/012042

Optimization Parameters of Air-conditioning and Heat Insulation Systems of a Pressurized Cabins of Long-distance Airplanes

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Abstract. The method for determination of an aircraft compartment thermal condition, based on a mathematical model of a compartment thermal condition was developed. Development of solution techniques for solving heat exchange direct and inverse problems and for determining confidence intervals of parametric identification estimations was carried out. The required performance of air-conditioning, ventilation systems and heat insulation depth of crew and passenger cabins were received.

1. Introduction

To find right solutions to various research problems in aircraft design and service, including the problem of effectiveness evaluation of air-conditioning, ventilation and heat insulation systems, it is required to determine thermal state of compartments.

A symbolic model of the system of a pressurized heat insulated compartment with air-conditioning systems and not pressurized and not insulated compartments can be represented by a system of one-dimensional equations of an insulating lining, windows and ordinary difference equations of convective heat transfer of the inner surface of the heat insulation of the lining and inner surface of the lining in not insulated compartments, seats, on-board equipment.

2. A symbolic model of the system of a pressurized

The equations of heat exchange of coverings we will present in the form of the one-dimensional equations of heat conductivity describing process of heat transfer in a multilayered structure:

$$C_{cv}(x)T_{cv,t} = (\lambda_{cv}(x,T_{cv})T_{cv,x})_x, \quad 0 < x < l; \tag{1}$$

$$\begin{aligned}\lambda_{cv}(x,T_{cv})\,F_{cv}\,T_{cv,x} = \alpha_{cv,out}(t)\,F_{cv}\,(T_e(t) - T_{cv}(t,x)) + Q_{cv,out} - \\ - c_0\,\varepsilon_{cv,out}\,F_{cv,out}\,T_{cv}^4(t), \qquad x = 0;\end{aligned} \tag{2}$$

$$\lambda_{cv}(x,T_{cv})F_{cv}T_{cv,x} = \alpha_{cv,in}(t)F_{cv}(T_{air}(t) - T_{cv}(t,x)) + \\ + \sum_j g_{j,cv}T_j^4 / T_{ms}^4 - c_0\,\varepsilon_{cv,in}F_{cv,in}T_{cv}^4(t) + Q_{cv,in}; \qquad x = l; \tag{3}$$

$$T_{cv}(0,x) = T_0(x), \quad 0 < x < l, \tag{4}$$

where $C_{cv}(x) = C_i$, $\lambda_{cv}(x,T_{cv}) = \lambda_{i,0} + \lambda_{i,1}T_{cv}$ at $l_{i-1} \le x < l_i$, $(i = 1,\ldots,k-1)$, $C_{cv}(x) = C_k$, $\lambda_{cv}(x,T_{cv}) = \lambda_{k,0} + \lambda_{k,1}T_{cv}$ at $l_{k-1} \le x \le l_k$,i.e. factors C_{cv}, λ_{cv} depend on in what layer heat transfer is being considered.

Thus $0 = l_0 < l_1 < \ldots < l_k = l.$

In the equations (1) - (4) the following designations are used:

$C_{cv}(x)$ - a volume thermal capacity of a multilayered structure (product of a specific thermal capacity on relative density); $\lambda_{cv}(l,T)$ - heat conductivity coefficient of a multilayered structure; $\alpha_{cv,out}$ – heat exchange coefficient in an outer surface of a covering; $\alpha_{cv,in}$ - heat exchange coefficient in an internal surface of a covering; F_{cv} - the covering area at outer and internal heat exchange; $Q_{cv,out}$ - thermal energy of external sources; c_0 - Stefan-Boltsman constant function; $\varepsilon_{cv,in}$ - radiation emissivity factor of an internal surface of a covering; m - quantity of blocks in a compartment; $g_{j,cv}$ - factor of a radiant exchange of system: j-element of a compartment - a covering; T_e - restoration temperature; t - time; T_{air} - temperature of the air environment in a compartment or regarding a compartment; $T_{cv}(x,t)$ - temperature of a multilayered structure; T_{ref} - reference temperature; T_j - temperature of j - element of a compartment; $T_{cv,x}$ - first derivative T_{cv} on x; $T_{cv,x,x}$ - second derivative T_{cv} on x; l - a thickness of a multilayered structure, $\varepsilon_{cov,\,out}$ - radiation emissivity factor of external surface of a covering.

Heat exchange coefficient $\alpha_{cv,out}$ an outer surface of a covering and heat exchange coefficient $\alpha_{cv,in}$ in an internal surface of a covering we will calculate by techniques, according to those described in [1] and [2].

The equations of heat exchange in pressurized heat-insulated partitions between pressurized heat-insulated compartments and not pressurized heat-insulated ones we will present in the form of one-dimensional equations of heat conductivity.

The equation of heat exchange of the onboard equipment we will present in the form of an ordinary differential equation describing its convective and radiant heat exchange.

Heat exchange coefficient of the onboard equipment at convective heat exchange we will calculate using the technique described in [3].

The equation of heat exchange of a person we will present in the form of an ordinary differential equation describing its convective and radiant heat exchange.

The equation of heat exchange of cargo we will present in the form of the ordinary differential equation describing its convective and radiant heat exchange.

The equation of heat exchange of designs we will present in the form of an ordinary differential equation describing its convective-radiant heat exchange

The equation of heat exchange of the air environment in a pressurized compartment we will present in the form of an ordinary differential equation describing convective heat exchange of an internal surface of a thermal protection of a covering of the onboard equipment, people, armchairs, luggage or cargo and enthalpy transfer from the air conditioning system:

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The equation of heat exchange of the air environment in a nonheat-insulated unpressurized compartment we will present in the form of an ordinary differential equation describing convective heat exchange of an internal surface of a covering, of a surface of heat-insulated pressurized partition and cargo.

The factor of a radiant exchange in the equations of heat exchange is defined by Monte-Carlo method [4].

3. Forward modelling of a thermal condition of compartments

For forward and inverse modelling of a thermal condition of compartments, the equation for a covering is sampled on a spatial variable based on Galerkin's method using piecewise-linear basis. As a result of application of this method the solution of the equations (1) - (4) and the equations of heat exchange in pressurized heat-insulated partitions is reduced to the numerical solution of system of ordinary differential equations where unknown values are ones of temperature in knots of the set grid on a piece [0, l_z]. The ordinary differential equations received thus for multilayered structures (1) - (4) and the equations of heat exchange in pressurized heat-insulated partitions, the equations for the onboard equipment, passengers, cargo, structures and air system make one system of ordinary differential equations which generally can be written down in the following way:

$$Y_t = F(Y(t,\Theta)),\, t \in (0,t_t); \quad Y_t = Y_\Theta,\, F, Y \in R^S; \quad \Theta \in R^r, \ldots \tag{5}$$

where $\mathbf{Y} = [T_1, T_2, T_i, T_\Theta, \ldots]^T$ - a vector of parameters of a thermal condition of a compartment; $\mathbf{Y}_t$ - a vector of first derivatives *Y* on *t*; $\Theta = [\vartheta_1, \vartheta_2, \ldots, \vartheta_5]^T$ - a vector of factors of model; *T* - the top index designating operation of transposing.

Let the vector of measured parameters of system (5) $Z = [Z_1, Z_2, \ldots, Z_i]^T$ be the function from the solution of system (5) $Z = Z(Y)$.

4. Inverse modelling of a thermal condition of compartments

The problem to evaluate factors Θ models is reduced to minimisation of the weighed sum of squares nonviscous between measured in a course of experiment by values *Z** to the corresponding values $Z(Y(t, \Theta))$, received in calculating on the model equations:

$$\Phi(\Theta) = \sum_{k=1}^{N}\sum_{i=1}^{S} \Gamma_{k,i}(Z^*_{k,i} - Z_i(Y(t_k, \Theta)))^2, \tag{6}$$

where $\Gamma_{k,i}$ - weight factors; t_k - time moments at *k* = 1,..., *N*.

As it has been noted in [4], for minimisation of function (17) it is expedient to use Brojdena-Fletchera-Goldfarba-Shenno's quasi-Newton method in a combination to Newton's method which is realised according to the formula:

$$\Theta_{j+1} = \Theta_j + b_j\, S(\Theta_j), \tag{7}$$

where b_j - the factor characterising length of a step on *j* - iterations; *S* - the parameter specifying a direction of search of a vector Θ of the valid values of factors Θ.

Next direction *S* of search of *j* vector Θ in this algorithm is defined from system of the equations:

$$\nabla^2 \Phi(\Theta_j) = -\nabla\Phi(\Theta_j)\ , \tag{8}$$

where $\nabla^2 \Phi - (r \times r)$ - the Gess matrix representing a square matrix of the second private derivatives of function Φ on a vector Θ_0:

Initial matrix $\nabla^2 \Phi(\Theta_k)$ in the equation (8) has been accepted by the individual.

For the decision of system of the equations (8) matrix $\nabla^2 \Phi(\Theta_j)$ is represented in the factorized to the form:

$$\nabla^2 \Phi(\Theta_j) = L(\Theta_j) D(\Theta_j) L^T(\Theta_j), \tag{9}$$

where $L(\Theta_j)$ - low triangle matrix with an individual diagonal; $D(\Theta_j)$ - a diagonal matrix.

Matrixes $L(\Theta_j)$, $D(\Theta_j)$ receive decomposition Holessky matrixes $\nabla^2 \Phi(\Theta_j)$ on the algorithm described in [5].

For the decision of the equation (8) it is offered to use the following numerical scheme of Rosenbrock type of the second order of approximation for on-line systems [6]

$$\vec{Y}_{n+1} = \vec{Y}_n + aK_1 + (1-a)K_2; \tag{10}$$

$$K_1 = h(I - a\,h\vec{\Psi}_Y(\vec{Y}_n, t_n, \Theta))^{-1}\vec{\Psi}(\vec{Y}_n, t_n + a\,h, \Theta); \tag{11}$$

$$\begin{aligned} &K_2 = h(I - a\,h\vec{\Psi}_Y(\vec{Y}_n, t_n, \vec{\Theta}))^{-1}\vec{\Psi}(\vec{Y}_n, t_n + a\,K_1, t_n + 2a\,h, \vec{\Theta}); \\ &a = 1 - 1/\sqrt{2}, \end{aligned} \tag{12}$$

where $\vec{Y}_n, \vec{Y}_{n+1}$ - the decision of the system received on *n* - and (*n* + 1) iterations, accordingly; $\vec{\Psi}$ - the right part of system; $\vec{\Psi}_Y$ – Yakobi matrix; *I* - an individual matrix; *h* - an integration step.

Confidential intervals of estimations of factors Θ nonlinear mathematical model of a thermal condition of a compartment of a kind (5) can be defined with the help dispersion matrix *P (Θ)* errors of estimations Θ required factors of model (the last characterise deviations of the calculated factors of model from the valid values). The method of displaying of joint confidential area of estimations on co-ordinate axes of space of factors [7] is thus used.

5. Object of research

As object of research the prototype of Brazilian main plane Embraer 190 has been accepted. Researches were spent according to Norms of flight validity Federal Aviation Regulations part 25, USA.

The basic criterion is achievement of temperature 290.15 – 298.15 K in a cabin of crew and salons of passengers no more, than through 1200 seconds with the ambassador of launch under condition of land preparation.

For cold type of a climate air reference temperature should correspond 283.15 K, for extreme warm dry – 315.15 K. Temperature of all elements of nonpressurized compartments is 228.15 K and 323.15 K. Temperature air on an exit from air central air in flight should not be more low 276.15 K and above 333.15 K.

There are 21 and 106 passengers accordingly.

Mass velocity of the air flow in pressurized heat insulated compartment was accepted as equal to 0.4 kg / (м^2 s), for nonpressurized compartments was calculated using the technique described in [8].

Parametrical identification or evaluation of a vector of factors Θ models of a thermal condition was spent on algorithm (6), (7).

Vector of factors of model

$$\Theta = [l_1, l_2, \ldots, l_5, G_1, G_2]^T \tag{13}$$

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includes required central air characteristics (the expense on an exit of a central air G_1 and G_2) and values of a thickness of a thermal protection of a cabin of crew and salon of passengers $l_1,\ l_2,\dots,l_5$ (Figure 1).

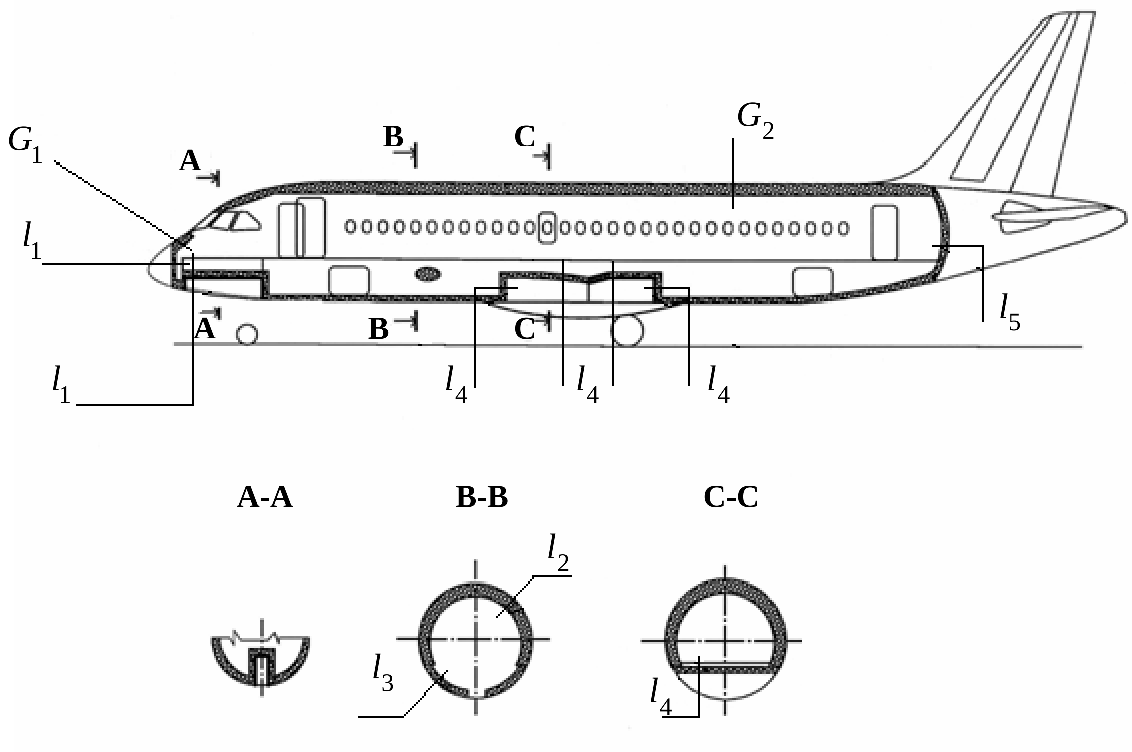

Figure 1 – Vector of factors of model: G_1 and G_2 – the expense on an exit of a central air; values of a thickness of a thermal protection of a cabin of crew and salon of passengers $l_1,\ l_2,\dots,l_5$

Estimations of factors of model for cold and extreme warm dry climate types are accordingly equal to:

$$\Theta = [0.062\ 0.058\ 0.043\ 0.039\ 0.050\ 0.090\ 0.761]^{T};$$

$$\Theta = [0.072\ 0.062\ 0.046\ 0.035\ 0.042\ 0.083\ 0.862]^{T}.$$

Confidential intervals of estimations of factors Θ make at confidential probability p = 0.99 accordingly

$$\Delta\,\Theta = [0.0001\ 0.0008\ 0.0006\ 0.0007\ 0.0009\ 0.0014\ 0.0122]^{T};$$

$$\Delta\,\Theta = [0.0009\ 0.0009\ 0.0007\ 0.0008\ 0.0007\ 0.0016\ 0.0137]^{T}.$$

Thus, the mathematical model of a thermal condition of compartments of the main plane is developed; working out of methods of the decision of direct and return problems of heat exchange and definition of confidential intervals of estimations of parametrical identification is passed; are received required characteristics of a central air conditioning and ventilation system, and also thickness of a thermal protection in a crew cabin and passenger salon of a prototype of Brazilian plane Embraer 190.

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