SIMULATION OF TILTROTOR MOTION

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Abstract

A computer model of a tiltrotor is under development for calculating performance and simulating control behaviour. A generic approach is assumed in the model building. An aircraft is composed of rigid elements: fuselage, wings, engine nacelles and rotors on which inertia, gravity and aerodynamic loads are calculated. In the paper the details of derivation of equation of motion and preliminary simulation results are presented.

Nomenclature

Indexes

a – aerodynamic, *b* – inertia, *f* – fuselage,
g, *G* – gravity, *h* – horizontal stabilizer,
i – inertia,
i=1 – element (wing, nacelle, rotor) on right side of aircraft
i=2 – element (wing, nacelle, rotor) on left side of aircraft
j=1,2,3 – rotor blade index of i-th rotor,
m – aerodynamic moment, moving element, mass,
n – nacelle,
p – aircraft, fuselage,
r – rotor

Matrices and Vectors

$\mathbf{A}$ - rotation matrix of moving element,
$\mathbf{A}_G$ - aircraft rotation matrix,
$\mathbf{A}_V$ - velocity matrix,
$\mathbf{I}_x$ - inertia matrix of x-th element,
$\mathbf{K}_x$ - angular momentum of x-th element,
$\mathbf{Q}_{xy}$ - y-th loads of x-th element, $\mathbf{Q}_{xy} = [\mathbf{F}_{xy}, \mathbf{M}_{xy}]^T$,
$\mathbf{V}$ - vector of linear speed in $O_p x_p y_p z_p$, $\mathbf{V} = [U, V, W]^T$,
$\mathbf{V}_a$ - motion speed of section,
$\mathbf{V}_c$ - vector of linear speed of three-dimensional body
$\mathbf{X}$ - vector of aircraft motion
$\mathbf{Y}_x$ - state vector of x-th element
$\mathbf{g}$ - vector of gravity acceleration
$\mathbf{g}_p$ - vector of gravity acceleration in $O_p x_p y_p z_p$
$\mathbf{r}_{CG}$ - position of C.G. in $O_p x_p y_p z_p$,
$\mathbf{r}_{nCG}$ - position of C.G. in moving element coordinate system,
$\mathbf{r}_n$ - position of moving element coordinate system in $O_p x_p y_p z_p$,
$\mathbf{\Omega}$ - vector of angular speed in $O_p x_p y_p z_p$, $\mathbf{\Omega} = [P, Q, R]^T$,
$\mathbf{\Omega}_x$ - vector of linear and angular speed of x-th element
$\mathbf{\Phi}$ - Euler's angles described in O_G as a vector, $\mathbf{\Phi} = [\Phi, \Theta, \Psi]^T$,

Scalars, constants

A_r - characteristic area,
$C_x(\alpha,\delta)$ - drag coefficient,
$C_z(\alpha,\delta)$ - lift coefficient,
$C_{my}(\alpha,\delta)$ - the coefficient of aerodynamic moment,
$C_{xc}(\alpha,\delta)$ - drag coefficient,
$C_{yc}(\alpha,\delta)$ - side force coefficient,
$C_{zc}(\alpha,\delta)$ - lift coefficient,
$C_{mxc}(\alpha,\delta)$ - coefficient of aerodynamic bank moment,
$C_{myc}(\alpha,\delta)$ - coefficient of aerodynamic slope moment,
$C_{mzc}(\alpha,\delta)$ - coefficient of aerodynamic yaw moment,
R_r - characteristic length,
V_a - the module of motion speed of section $V_a = |\mathbf{V}_a|$
$c(y)$ - chord (characteristic dimension),
g - gravity acceleration,
m_x - mass of x-th element,
α - the angle of attack
δ - the angle of inclination of steering element
ρ - the thickness of air

Introduction

Despite the expanding interest in development and applications of tilt-rotor aircraft, there are not many new available papers presenting comprehensive tilt-rotor modelling and simulation. [1, 2, 3]. At Warsaw University of Technology, a computer model of tiltrotor is

under development for analysis of stability and control in various flight conditions.
To construct the computer model of a tilt-rotor, the generic model of mobile objects developed in WUT is used.
The purpose of development of generic model of mobile objects was to simplify deriving and programming equations of motion of various air, water and land vehicles. This approach allows to obtain computer models of various vehicles in fast and easy way.
The background for the general approach forms the fact that on the vehicles considered the same type of loads: inertia, gravity and aerodynamic act. In the local coordinate systems these loads are described by the similar formulae.
The model of the vehicle consists of the base part (“fuselage”) to which the other parts are fixed or may rotate and/or translate. In this paper the elements of the vehicle are assumed to be rigid, although the approach may be applied also to vehicles with elastic parts. The damping forces may also be included into analysis.
Equations of motion are composed in the main system of coordinate fixed to the fuselage by adding all loads acting on all elements transformed from the local systems of coordinates fixed to each element.
The computer program is developed in the same way, by using predefined subroutines for each type of loads and the transformations of system of coordinates. It is easy to change the number of elements of model by increasing or decreasing the number of elements.
There are also some subroutines which perform other frequently needed operations as calculations of: inertia matrices, flow velocities in different coordinate systems and places of the vehicle, angles of attack, table–look procedures for searching aerodynamic coefficients etc.
Due to the approach used, despite that the aircraft configuration assumed for model construction is based on V-22 Osprey aircraft, there is a possibility of adjustment the model to other tilt-rotor concepts.

Tilt rotor model

The tiltrotor model (Fig.1) is composed of fuselage, two wings each with two trailing edge flaps, nacelles with rotors mounted at the wing tips, horizontal stabilizer composed of three parts and two vertical fins each with one rudder. The rotors have three blades fixed to the shaft with pitch hinges only. All components of the aircraft are modelled as rigid bodies.

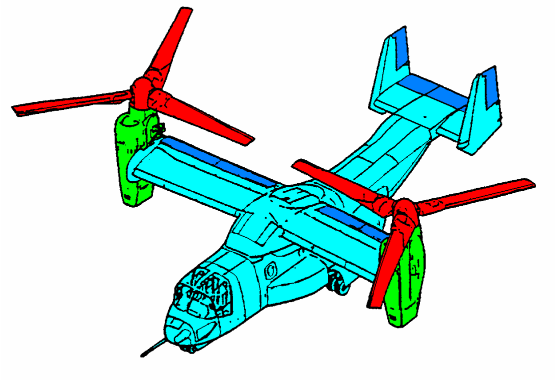

Fig. 1. Configuration of the tiltrotor

The loads acting on each of these elements are described in the subsequent parts of the paper.

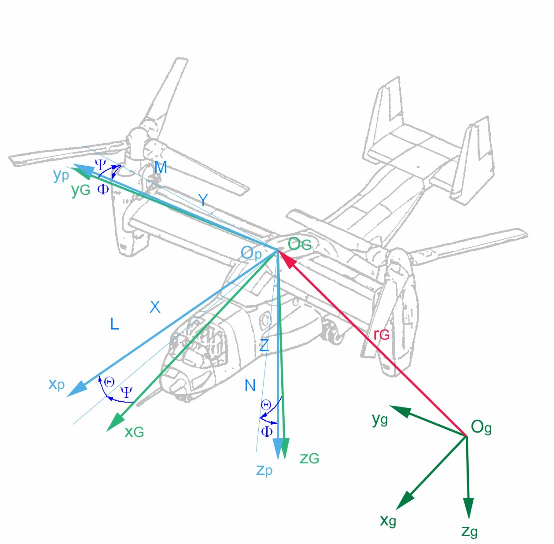

Fig. 2. Base systems of coordinates

The tiltrotor equations of motion are derived in the coordinate system $O_p x_p y_p z_p$ fixed to the fuselage of the aircraft (Fig. 2). The centre O_p of the system is placed in the connection point of rotor shafts in the fuselage plane of symmetry. The $O_p x_p$ axis lies in the longitudinal plane of symmetry of fuselage, parallel to the assembly (horizontal) plane of the aircraft and is directed "to the cockpit of aircraft”. The $O_p z_p$ axis lies in the longitudinal plane of symmetry of fuselage and is directed, down to the undercarriage. The $O_p y_p$ axis is pointing right, while looking along the $O_p x_p$ axis.
The two other important for the simulation of aircraft motion systems of coordinates (Fig. 2) are *inertia coordinate system* $O_g x_g y_g z_g$ related to the ground and *gravity coordinate system* $O_G x_G y_G z_G$ related to the gravity acceleration.

The centre of *inertia coordinate system* O_g may be placed in any selected point on surface of the ground (for instance it can be a selected point on the runway). The aircraft motion will be measured from this point. The $O_g z_g$ axis is vertical, lies along the Earth gravity acceleration and is directed according to its positive sign. Axis $O_g x_g$ and $O_g y_g$ lie in horizontal plane. The direction of $O_g x_g$ axis is placed in local geographical meridian, pointing north, and the $O_g y_g$ axis points east.

The centre O_G of gravity *system of coordinates is the same as the centre of fuselage* O_p and the axis of the system are parallel to the axis of inertia coordinate system when the motion of aircraft starts.

The gravity coordinate system is translated to the inertia system by the vector $\mathbf{x}_G(t)$; the relation between coordinates has the form:

$$\mathbf{x}_G = \mathbf{x}_G(t) + \mathbf{x}_g \qquad (1)$$

where the $\mathbf{x}_G(t) = [x_G(t), y_G(t), z_G(t)]^T$ is the function of time and describes translation of the tiltrotor.

The relation between the gravity and the aircraft systems of coordinates is described by Euler angles of rotation and has the form:

$$\mathbf{x}_p = \mathbf{A}_G(\Psi,\Theta,\Phi)\mathbf{x}_G \qquad (2)$$

where the rotation matrix has the form:

$$\mathbf{A}_G = \begin{bmatrix} \cos\Psi\cos\Theta & \sin\Psi\cos\Theta & -\sin\Theta \\ \cos\Psi\sin\Theta\sin\Phi - \sin\Psi\cos\Phi & \sin\Psi\sin\Theta\sin\Phi + \cos\Psi\cos\Phi & \cos\Theta\sin\Phi \\ \cos\Psi\sin\Theta\cos\Phi + \sin\Psi\sin\Phi & \sin\Psi\sin\Theta\cos\Phi - \cos\Psi\sin\Phi & \cos\Theta\cos\Phi \end{bmatrix} \qquad (3)$$

The aircraft motion is described by the vector:

$$\mathbf{X} = [U, V, W, P, Q, R, x_g, y_g, z_g, \Phi, \Theta, \Psi]^T \qquad (4)$$

obtained as the composition of four vectors, used in the description of aircraft motion:

$$\mathbf{X} = [\mathbf{V}, \mathbf{\Omega}, \mathbf{x}_g, \mathbf{\Phi}]^T \qquad (5)$$

where: $\mathbf{V} = [U, V, W,]^T$, $\mathbf{\Omega} = [P, Q, R]^T$,

$\mathbf{x}_g = [x_g, y_g, z_g]^T$, $\mathbf{\Phi} = [\Phi, \Theta, \Psi]^T$

Equation of motion

The aircraft equations of motion are derived using d'Alambert principle, summing up at the point O_p all loads (forces and moments) acting on the fuselage, wings, control surfaces, nacelles, and rotors. The system of equations of motion has the general form:

$$\mathbf{F}_p + \mathbf{F}_{n1} + \mathbf{F}_{n2} + \mathbf{F}_{r1} + \mathbf{F}_{r2} = 0 \qquad (6)$$

$$\mathbf{M}_p + \mathbf{M}_{n1} + \mathbf{M}_{n2} + \mathbf{M}_{r1} + \mathbf{M}_{r2} = 0 \qquad (7)$$

Inertia loads

The inertia loads are obtained from the momentum conservation according to the formulae:

$$\mathbf{F}_{pb} = m_p \frac{d\mathbf{V}}{dt} = m_p \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{\Omega} \times \mathbf{V} + \dot{\mathbf{\Omega}} \times \mathbf{r}_{CG} + \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}_{CG}) \right) \qquad (8a)$$

$$\mathbf{M}_{pb} = \frac{d\mathbf{K}_p}{dt} = \frac{\partial \mathbf{K}_p}{\partial t} + \mathbf{\Omega} \times \mathbf{K}_p + \mathbf{r}_{CG} \times m_p \frac{d\mathbf{V}}{dt} \qquad (8b)$$

After performing some mathematical manipulations, these equations are written in the matrix form:

$$\mathbf{Q}_{pb} = \mathbf{I}_p \dot{\mathbf{Y}}_p + \mathbf{\Omega}_p \mathbf{I}_p \mathbf{Y}_p \qquad (9)$$

where: the state vector is

$$\mathbf{Y}_p = [U, V, W, P, Q, R]^T$$

inertia matrix has the form

$$\mathbf{I}_p = \begin{bmatrix} m_p & 0 & 0 & 0 & S_{zp} & -S_{yp} \\ 0 & m_p & 0 & -S_{zp} & 0 & S_{xp} \\ 0 & 0 & m_p & S_{yp} & -S_{xp} & 0 \\ 0 & -S_{zp} & S_{yp} & I_{xp} & -I_{xyp} & -I_{xzp} \\ S_{zp} & 0 & -S_{xp} & -I_{xyp} & I_{yp} & -I_{yzp} \\ -S_{yp} & S_{xp} & 0 & -I_{xzp} & -I_{yzp} & I_{zp} \end{bmatrix} \qquad (9a)$$

and the velocity matrix is obtained as:

$$\mathbf{\Omega}_p = \begin{bmatrix} 0 & -R & Q & 0 & 0 & 0 \\ R & 0 & P & 0 & 0 & 0 \\ -Q & P & 0 & 0 & 0 & 0 \\ 0 & -W & V & 0 & -R & Q \\ W & 0 & -U & R & 0 & P \\ -V & U & 0 & -Q & P & 0 \end{bmatrix} \qquad (9b)$$

The expression (9) describes inertia loads acting on the fuselage and on the parts of airplane fixed to it, i.e. wings and control surfaces.

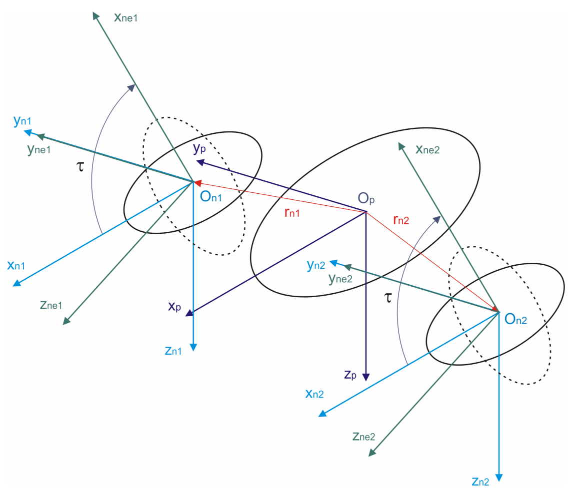

Fig.3. Nacelle coordinate systems

For the parts of aircraft rotating relative to the fuselage: nacelles (Fig. 3) and rotors, the inertia loads are calculated using (8) as:

$$\mathbf{Q}_{mb} = \mathbf{I}_m\left(\dot{\mathbf{Y}}_p + \dot{\mathbf{Y}}_m\right) + \left(\mathbf{\Omega}_p + \mathbf{\Omega}_m\right)\mathbf{I}_m\left(\mathbf{Y}_p + \mathbf{Y}_m\right) \tag{10}$$

where: the inertia matrices for these elements are calculated in fuselage system of coordinates:

$$\mathbf{I}_m = \begin{bmatrix} m_m & 0 & 0 & 0 & S_{zm} & -S_{ym} \\ 0 & m_m & 0 & -S_{zm} & 0 & S_{xm} \\ 0 & 0 & m_m & S_{ym} & -S_{xm} & 0 \\ 0 & -S_{zm} & S_{ym} & I_{xm} & -I_{xym} & -I_{xzm} \\ S_{zm} & 0 & -S_{xm} & -I_{xym} & I_{ym} & -I_{yzm} \\ -S_{ym} & S_{xm} & 0 & -I_{xzm} & -I_{yzm} & I_{zm} \end{bmatrix} \tag{10a}$$

and additional velocity matrices are added due to rotation of these elements (and in general case also velocities) relative to the fuselage:

$$\mathbf{\Omega}_m = \begin{bmatrix} 0 & -R_m & Q_m & 0 & 0 & 0 \\ R_m & 0 & P_m & 0 & 0 & 0 \\ -Q_m & P_m & 0 & 0 & 0 & 0 \\ 0 & -W_m & V_m & 0 & -R_m & Q_m \\ W_m & 0 & -U_m & R_m & 0 & P_m \\ -V_m & U_m & 0 & -Q_m & P_m & 0 \end{bmatrix} \tag{10b}$$

$$\mathbf{Y}_m = \left[U_m, V_m, W_m, P_m, Q_m, R_m\right]^T \tag{10c}$$

Gravity Loads

The gravity force is calculated in the centres of gravity of: fuselage and other aircraft elements and transformed to the centre O_p of the fuselage system of coordinates. The vector of gravity acceleration:

$$\mathbf{g} = \left[0, 0, g\right]^T \tag{11}$$

is rotated to the fuselage system of coordinates using transformation:

$$\mathbf{g}_p = \mathbf{A}_G(\Psi, \Theta, \Phi)\mathbf{g} \tag{12}$$

The masses of fuselage, wings and stabilizers are calculated together and gravity loads of these parts of aircraft are calculated as:

$$\mathbf{F}_{pg} = m_p \mathbf{g}_p = m_p \mathbf{A}_G \mathbf{g} \tag{13a}$$

$$\mathbf{M}_{pg} = \mathbf{r}_{CG} \times \mathbf{F}_{pg} = \mathbf{r}_{CG} \times m_p \mathbf{A}_G \mathbf{g} \tag{13b}$$

where $\mathbf{r}_{CG}$ is the position of fuselage C.G. relative to O_p.

The position of C.G. of other parts of airplane is described by the vector:

$$\mathbf{r}_{CG} = \mathbf{r}_n + \mathbf{A}(\alpha, \beta, \gamma)\mathbf{r}_{nCG} \tag{14}$$

and the gravity loads acting on other elements are transferred to the fuselage system of coordinates using formulae:

$$\mathbf{F}_{ng} = m_n \mathbf{g}_p = m_n \mathbf{A}_G \mathbf{g} \tag{15a}$$

$$\begin{aligned} \mathbf{M}_{ng} &= \left[\mathbf{r}_n + \mathbf{A}(\alpha, \beta, \gamma)\mathbf{r}_{nCG}\right] \times \mathbf{F}_{ng} = \\ &= \left[\mathbf{r}_n + \mathbf{A}(\alpha, \beta, \gamma)\mathbf{r}_{nCG}\right] \times \left[m_n \mathbf{A}_G \mathbf{g}\right] \end{aligned} \tag{15b}$$

Aerodynamics Loads

In the generic model developed, two quasi-steady methods of calculation of aerodynamic loads are used: 2D for elements composed of airfoils and 3D for solid bodies.

On wings, rotor blades, horizontal and vertical stabilizers two dimensional flow is assumed (Fig. 4).

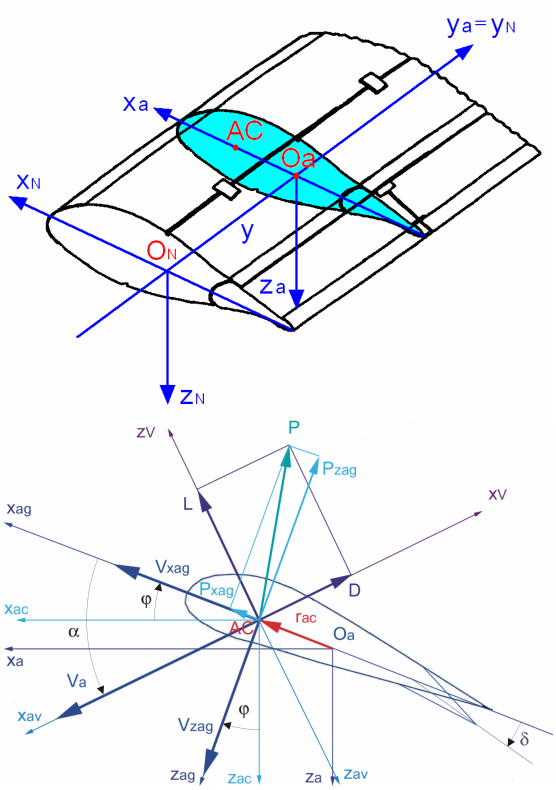

Fig. 4. Two-dimensional flow model

In each cross section along the span the instant, total flow velocity (Fig. 4) is calculated, taking into account velocities of:

a) airfoil motion resulting form motion of the fuselage and the aircraft elements in inertia coordinate system

b) air motion due to wind, gusts, etc

c) airfoil (rotor) induced velocity,

d) inflow due rotors.

Aerodynamic loads in each section *AC* are calculated using airfoil aerodynamic coefficients resulting from table look procedure for airfoil angle of attack α and flap (if exists) deflection δ. In the cross section the aerodynamic force and moment vectors are calculated as:

$$d\mathbf{P} = \left[dD, 0, dL\right]^T \quad d\mathbf{M} = \left[0, dM, 0\right]^T \tag{16a}$$

where

drag $$dD = \frac{1}{2}\rho c(y) V_a^2 C_x(\alpha, \delta) dy \tag{16b}$$

lift $$dL = \frac{1}{2}\rho c(y) V_a^2 C_z(\alpha, \delta) dy \tag{16c}$$

moment $dM = \frac{1}{2}\rho c^2(y)V_a^2 C_{my}(\alpha,\delta)dy$ (16d)

The loads (16) are integrated along the span and transferred to the fuselage system of coordinates:

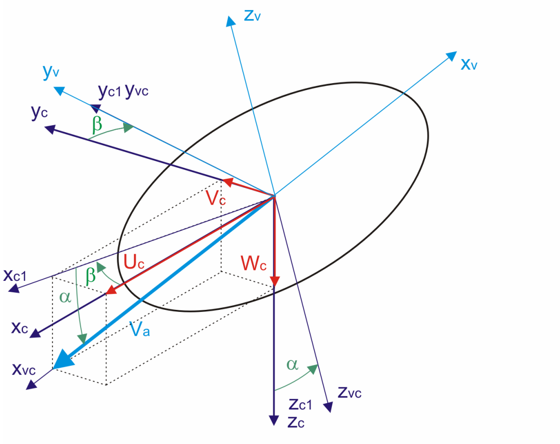

Fig. 5. Three-dimensional airflow

Fuselage and nacelles (Fig.5) are treated as three-dimensional bodies. Aerodynamics loads are calculated using local instant velocity $\mathbf{V}_c = [U_c, V_c, W_c]^T$ in the body aerodynamic centre. The angle of incidence α and angle of slip β are calculated as:

$$\alpha = a\sin\left[\frac{W_c}{\sqrt{U_c^2+V_c^2+W_c^2}}\right] \qquad \beta = a\sin\left[\frac{V_c}{\sqrt{U_c^2+V_c^2}}\right] \tag{17}$$

and table look procedure for aerodynamic coefficients is used.

Aerodynamic loads in the centre of coordinate system are calculated in the flow coordinate system first

$$P_{()a} = \frac{1}{2}\rho A_r V^2 C_{()c}(\alpha,\beta) \tag{18}$$

$$M_{()a} = \frac{1}{2}\rho A_r R_r V^2 C_{m()c}(\alpha,\beta)$$

and then transformed to the body local coordinate system using rotation matrix

$$\mathbf{A}_V = \begin{bmatrix} -\cos\beta\cos\alpha & -\sin\beta & \cos\beta\sin\alpha \\ -\sin\beta\cos\alpha & \cos\beta & \sin\beta\sin\alpha \\ -\sin\alpha & 0 & -\cos\alpha \end{bmatrix} \tag{19}$$

As in 2D case the loads are transformed from body local system of coordinates to the point O_p of the fuselage.

Details of loads modelling

Fuselage

The inertia loads acting on fuselage are calculated from (9), gravity loads from (11) and the aerodynamic loads from (18).

Wings

The tiltrotor wings have prescribed planform, twist and airfoil distribution along the span. Inertia and gravity loads of wings are included into loads calculated for fuselage by including their mass and inertia into fuselage inertia matrix. At each wing there are two flaps (ailerons) controlled individually. Flap angles of deflection are control variables in aircraft motion simulation. The aerodynamic loads are calculated using 2D model. Induced velocity of the rotors is included into wing airflow velocity in the proper sections along the span.

Horizontal stabilizer

The horizontal stabilizer is mounted at the fuselage tail. There are three flaps (elevators) at the trailing edge of the stabiliser, individually controlled. The horizontal stabilizer may have arbitrary airfoil shape and twist angle distributions along the span. Inertia and gravity loads on horizontal stabilizer are included into fuselage loads calculation by including their mass and inertia into fuselage inertia matrix. The aerodynamic loads are calculated using 2D model. Induced velocity of the rotors and the time delay is included into stabilizer airflow velocity in the proper sections along the span.

Vertical stabilizers

The vertical stabilizers are mounted at the tips of horizontal stabilizer. There is one flap (rudder) at the trailing edge of each of the stabilisers, individually controlled. The vertical stabilizers may have arbitrary airfoil shape and twist angle distributions along the span. Inertia and gravity loads of vertical stabilizer are included into fuselage loads including their mass and inertia into fuselage inertia matrix. The aerodynamic loads are calculated using 2D model. Induced velocity of the rotors and wings and the time delay is included into stabilizer airflow velocity calculations in the proper sections along the span.

Engine Nacelles

Nacelles are placed at the tip of each wing. They may rotate about axis perpendicular to the fuselage plane of symmetry. The inertia loads are calculated using (11), gravity using (15). Aerodynamic loads are calculating according to 3D model (18). The velocity of the airflow around the nacelles contains inflow from rotors and rotation of nacelles about fuselage axis.

Rotors.

Rotor rotation axis is perpendicular to the axis of nacelle rotation with respect to the fuselage. Looking from the rear art of fuselage, when the rotor axis are in horizontal position, right rotor rotates clockwise, and the left counter clockwise. For inertia load calculations the rotors are treated as rotating discs. Each rotor has three blades mounted to the shaft by pitch hinges. The pitch of the rotor blades is controlled by the swash-plate, resulting in collective and periodic control.

$$\theta_{ij} = \theta_{0i} + \theta_{1i}\cos\left(\Omega_i t + \frac{2\pi}{3} j\right) + \theta_{2i}\sin\left(\Omega_i t + \frac{2\pi}{3} j\right)$$

The blades may have arbitrary planform and twist along the span.
The aerodynamic loads are calculated using strip theory, with quasisteady aerodynamic loads using table-look procedure for airfoils aerodynamic coefficient calculations.
The induced flow is calculated using three state dynamic inflow model.

Data for simulation

Data used for simulation of tiltrotor motion were taken from open literature [4] for V-22 Osprey. If no information was available, the values of design parameters were assumed by analogy to similar parts of other aircraft. The base dimensions are given in Fig. 6. The data taken into the simulation of tiltrotor motion are given in Table 1.

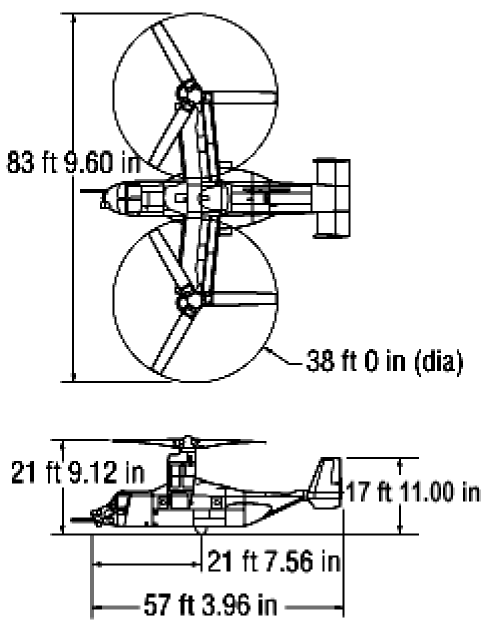

Fig. 6. Dimensions of V-22

Table 1. Tiltrotor data

Rotor System		
Blades per hub		3
Tip speed	fps (mps)	661.90 (201.75)
Diameter	ft (m)	38.00 (11.58)
Blade area	ft2 (m2)	261.52 (24.30)
Disc area	ft2, (m2)	2,268.00 (210.70)
Weights		
Takeoff	lbs (kg)	33,140 (15,032)
Dimensions		
Length, fuselage	ft (m)	57.33 (17.48)
Width, rotors turning	ft (m)	83.33 (25.55)
Width, horizontal stabilizer	ft (m)	18.42 (5.61)
Height, nacelles fully vertical	ft (m)	21.76 (6.63)
Height, vertical stabilizer	ft (m)	17.65 (5.38)

Preliminary results of numerical simulations

The model is designed performance and flying qualities evaluation in various flight conditions. The numerical simulations are in the progress.
The isolated rotor loads were calculated as functions of pitch control. The collective (Fig. 7) and cyclic pitch (Fig. 8-11) were applied giving the rotor loads reaction to control according to physical understanding of the phenomena.
The rotor loads due to lateral cyclic control is shown in (Fig. 8-9) and due to longitudinal in (Fig. 10-11).

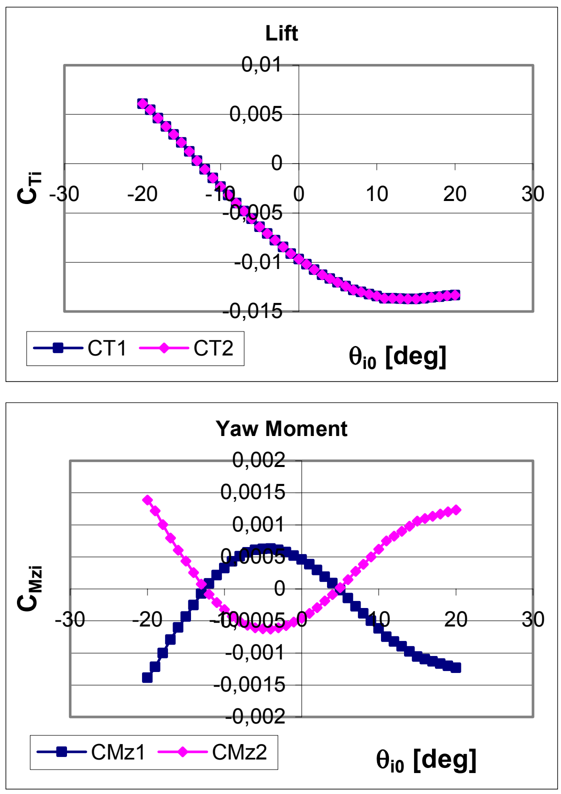

Fig. 7. Rotor loads due to collective control – no forward velocity

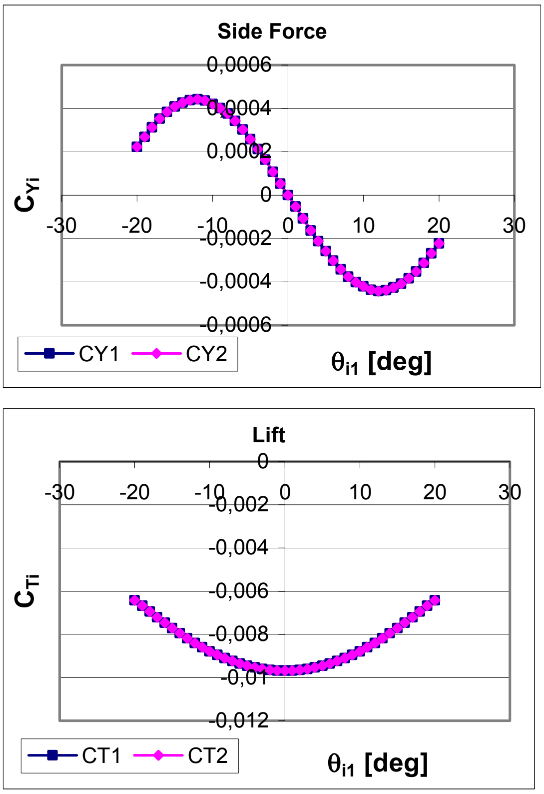

Fig. 8. Rotor loads due to lateral control – no forward velocity

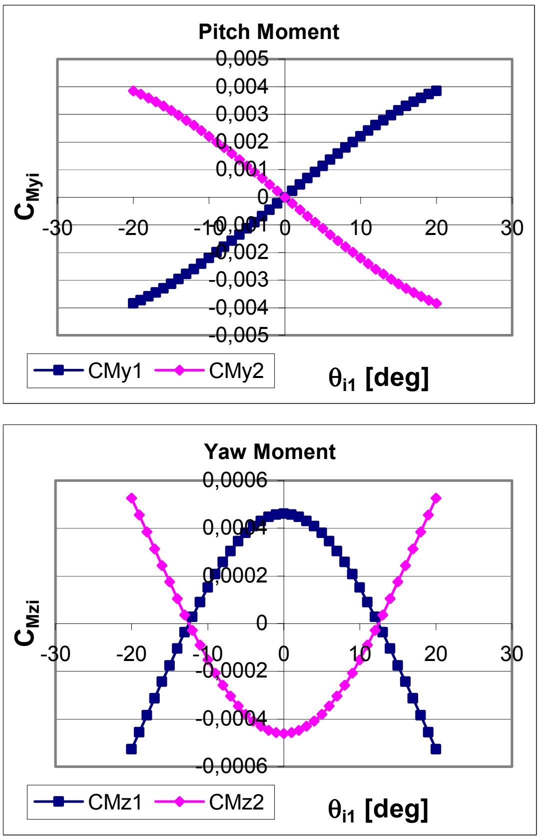

Fig. 9.. Rotor loads due to lateral control – no forward velocity

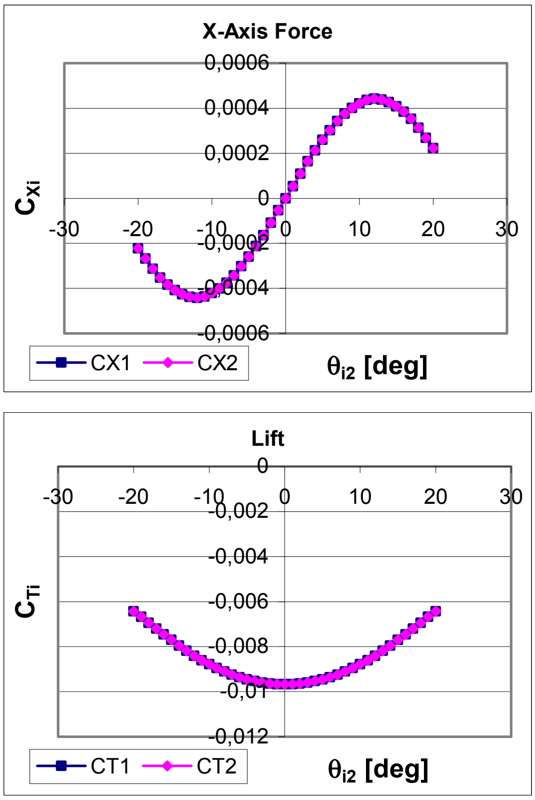

Fig. 10. Forces in Longitudinal Cyclic Control – no forward velocity

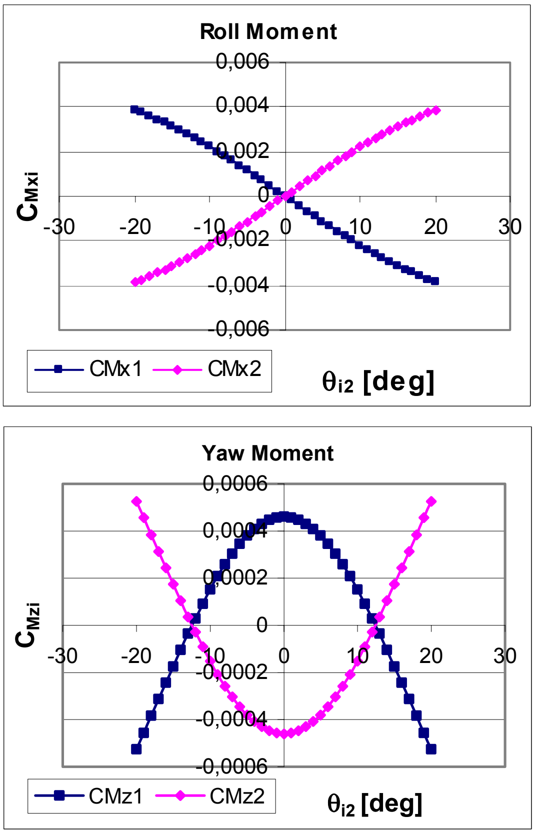

Fig. 11. Moments in Longitudinal Cyclic Control – no forward velocity

Vertical take off in helicopter mode was calculated as the function of collective control. Data taken into the simulation of vertical take off were given in Table 1 and Table 2. In Fig. 12 the vertical displacement from the simulation of that manoeuvre is presented. Displacement in y axis was omitted because of its very small values (5.0e-6) of translations.

Table 2 Data for simulation of vertical take off

Engine nacelle position	deg	90°
Rotor speed	rad/s	33
Flaps (2 x 2)	deg	0°
Elevators (3)	deg	0°
Rudders (2)	deg	0°
Blade pitch angle	deg	0°, 5°, 10°

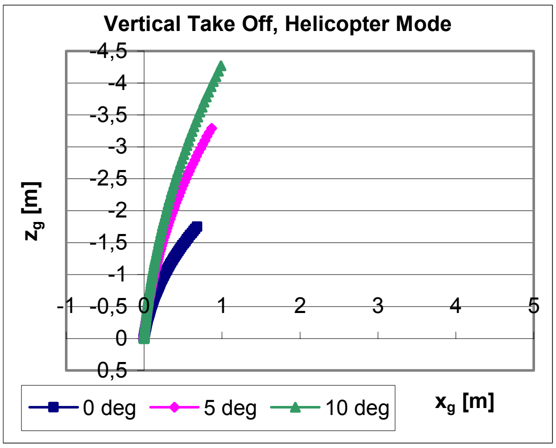

Fig. 12. Vertical Take Off in Helicopter Mode

Horizontal flight in aircraft mode was calculated as the function of blade collective control. Data taken into the simulation of horizontal flight are given in Table 1 and Table 3. In Fig. 13 data from the simulation of horizontal flight are presented. Displacement in y axis was omitted because of its very small values (5.0e-6).

Table 3. Data for simulation of horizontal flight

Engine nacelle position	deg	90°
Rotor speed	rad/s	33
Flaps (2 x 2)	deg	0°
Elevators (3)	deg	0°
Rudders (2)	deg	0°

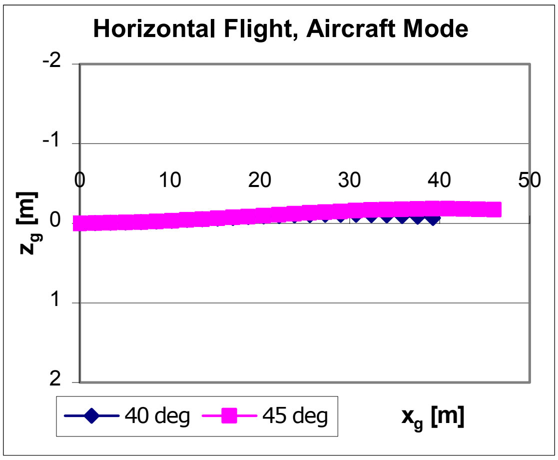

Fig. 13. Vertical translation in horizontal flight - aircraft mode

Conclusions

The tilt-rotor model developed is under tests. In the next phase controlled tiltrotor manoeuvres in helicopter, aircraft and transition modes will be tested.

Bibliography:

1. Miller M., Narkiewicz J., “Control of Tiltrotor Aircraft”, 4th National Rotorcraft Forum, October 19-20, 2001, Warsaw, Poland.
2. McVicar J. S. G., Bradley R., “A Generic Tilt-Rotor Simulation Model with Parallel Implementation and Partial Periodic Trim Algorithm”, 18th European Rotorcraft Forum, September 15-18, 1992, Avignon, France.
3. Srinivas V., Chopra I. “Validation of a Comprehensive Aeroelastic Analysis for Tiltrotor Aircraft”, AHS 52nd Annual Forum, June 4-6, 1996, Washington, D.C., USA.
4. V-22 Osprey Technical Specifications http://www.boeing.com/rotorcraft/military/v22/v22spec.htm

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