A VARIABLE, FULLY FLEXIBLE DYNAMIC RESPONSE TOOL FOR SPECIAL INVESTIGATIONS (VARLOADS)

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Abstract. A simulation environment is presented for special structural dynamics investigations. The environment is characterised by a modular software structure and an object-oriented data structure. The aircraft model and equation of motion can easily be adapted to the required level of detail. An integrated, fully flexible aircraft model is the basis for the simulations, which are carried out in the time-domain. The novelty of the approach lies in the combination of the above mentioned characteristics. This combination makes the software environment ideally suited for special studies ranging from the preliminary design stage on to in-flight incident investigations.

1. INTRODUCTION

In the structural dynamics department of a commercial aircraft manufacturer, most time is generally spent on the so-called loads loops for certification purposes. These loads loops cover a large number of flight conditions, mass configurations, excitation types (gust, manoeuvre, fatigue, failure cases, ground loads, etc.), and result in design envelopes for a high number of monitored properties (loads, accelerations) inside the aircraft structure. This resulting large number of load cases calls for computationally efficient and specialized software. This software is therefore generally developed for each type of excitation individually, and optimised for computational speed by taking into account only the relevant aspects for the considered excitation type.

However, special investigations are gaining more attention for the purpose of, e.g.:

- Loads prediction in the preliminary design phase.
- Calculation of sensitivities of loads with respect to, e.g., aerodynamic properties.
- Investigation of the effects of model simplifications such as linearisation.
- Design of load alleviation functions.

- Investigation of special load conditions.
- Real-time (in-flight) loads monitoring and investigation of incidents.

At Airbus Deutschland, a dedicated software denoted Variable Loads environment (VarLoads) has been developed[1] to facilitate such special investigations. The present paper gives an overview of some new features of this simulation environment, and is divided into three main parts. Firstly, the software structure and data structure are described in Section 2. Especially the modularity of the software and flexibility of the selected data structures are highlighted. Secondly, a pragmatic approach to the unified equation of motion is presented in Section 3. Thirdly, a parametric study is presented in Section 4 that demonstrates the advantages of the software environment. An outlook is given in Section 5.

2. MODULAR APPROACH

The data structure and software structure developed for VarLoads are presented in this section. The data structure is based on a physical consideration of the aircraft model and the various sub-models (aerodynamic, elastic, etc.) required for a structural dynamics response calculation. The smallest building blocks of the sub-models (boxes, grid points, etc.) are defined in a (mildly) object-oriented manner, which, among others, increases modularity of the software. Presently, VarLoads is based on MatLab/Simulink. The advantage of this development environment is that it allows for a modular, easily adaptable software structure, with all basic modules available in standard libraries and subroutines.

Aircraft model and data structure

A typical aircraft model for structural dynamics analyses is depicted in Fig.1. As mentioned, the aircraft model is built up from a set of sub-models reflecting the individual disciplines. On the one hand, an *elastic&inertia* sub-model is regarded (Fig.1a), while, on the other hand, a collection of sub-models (Fig.1b) is available for the external loads acting on the aircraft structure. It may be argued that every individual sub-model consists of a number of grid points (e.g., aerodynamic strips or boxes, lumped masses) with individual Degrees of Freedom (DoF) defined in their local coordinate systems. For a structural dynamics analysis, all aircraft sub-models are superimposed over one another, and the required coordinate transformations are carried out. The data structure is developed corresponding to this representation. A first step towards an object-oriented approach is taken, in which the lowest level building blocks are the grid points. For this so-called object class, a number of operators and functions can be defined such as coordinate transformations and visualisation tools. Consequently, these operators and tools can be applied to the grid points of all sub-models. In the following, the physical sub-models and data structure are explained in more detail.

For computational efficiency, the *elastic&inertia* properties are generally combined in a statically condensed model, as schematised in Fig.1a. The DoF for the full Finite Element (FE) model are reduced by, e.g., Guyan reduction. Lumped masses are connected to the grid points afterwards. This implies that merely one computationally expensive static reduction has to be carried out for the multitude of mass cases considered in a structural dynamic analysis. The DoF for a resulting structural grid point are depicted in Fig.1a for the left outer engine. Output from the aeroservoelastic simulation are the loads and accelerations at certain cut-outs in the aircraft structure. The grid points corresponding to this internal loads sub-model are the so-called monitoring stations, which generally exhibit other DoF and are defined in other local coordinate systems as the condensed model. For example, for the forward fuselage monitoring station depicted in Fig.1a, only the bending moment (M_z), torsion moment (M_x), and shear force (Q_y) are recorded, as would typically be the case for anti-symmetric aircraft response.

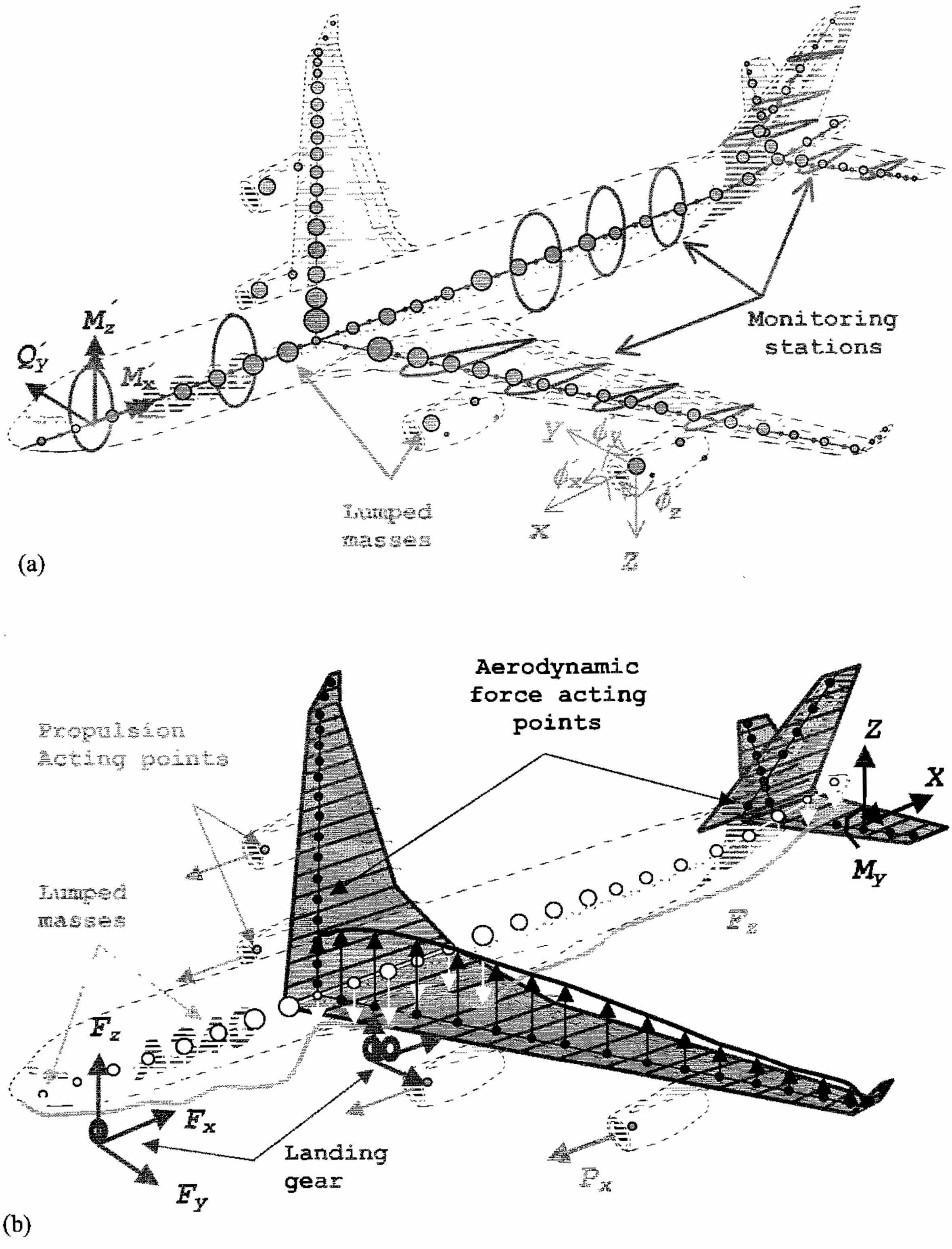

Fig.1: Aircraft sub-models. (a) Condensed model and sub-model for monitoring stations. (b) Sub-models for external loads due to airflow, propulsion, landing/impact, and gravity.

External loads sub-models are depicted in Fig.1b. The *gravity* loads act on the individual lumped masses that are connected to the condensed structural grid. Although the grid point locations for this sub-model in a body-fixed coordinate system will thus be identical to those of the condensed model, the DoF for the gravity loads are defined as the z-direction of a geodetic coordinate system. The *aerodynamic* sub-model contains the lifting surfaces, which in turn consist of a number of elements (boxes, strips,…). A grid of downwash control points and force acting points is available on the aerodynamic elements. Generally, these grids are assigned a restricted number of DoF as well. For example, wing strip force acting points will typically exhibit 3 DoF, i.e., drag (X), lift (Z) and pitching moment (M_y). Further sub-models are the *propulsion* systems and *landing gear*. Again, a grid with corresponding DoF can be defined for these sub-models. For example, the *propulsion* sub-model may simply consist of a single grid point at the engine with a single DoF corresponding to the direction of the propulsion force (P_x).

For a classical flight mechanics analysis, the *elastic&inertia* sub-model may be represented by a single lumped mass (i.e., the centre of gravity), while an *aerodynamic* sub-model may, e.g., be represented by strips at the mean aerodynamic chords of the wing and tails. Extending the software environment to a multi-body simulation, the control surfaces, interior (passengers, cargo) and landing gears can be viewed as further sub-models of the aircraft[1]. Presently, however, the aircraft is regarded as a single elastic body with rigid transformations between the sub-models. This is acceptable when the structural deformations are sufficiently small. Aerodynamic properties of the control surfaces are reflected by the corresponding wing or tail strips, while the interior and landing gears are represented by lumped masses rigidly connected to the condensed structural grid.

model.aero{i_{fc}}.M		- Mach number
model.aero{i_{fc}}.Qkj		- aerodynamic influence coefficient matrix
model.geom.aerogrid.*		- aerodynamic grid point data with fields:
	offset	- (1 x n_grid) aerodynamic grid point offsets
	CP_ID	- (1 x n_grid) coordinate system IDs for grid offsets
	k_set	- (1 x n_grid) force acting point DoF numerators
	j_set	- (1 x n_grid) downwash control point DoF numerators
	CD_ID	- (1 x n_grid) coordinate system IDs for DoF
	CompKey	- {1 x n_grid} component keys (e.g. 'WR' for right wing)
	…	
model.geom.coord.*		- local coordinate system data (all sub-models) with fields:
	ID	- (1 x n_coord) coordinate system IDs
	dircos	- (1 x n_coord) direction cosines w.r.t. global
	offset	- (1 x n_coord) offsets of origin w.r.t. global
	…	

Fig.2: Data-structure for VarLoads; aerodynamic properties.

The data-structure within VarLoads (as well as other recently developed software at Loads & Aeroelastics, Airbus Deutschland) reflects the modularity of the aircraft model as treated above. All model data is collected in a tree (MatLab structure array), of which some examples for the aerodynamic sub-model are shown in Fig.2. An aerodynamic sub-model is defined for every considered flight condition, denoted with index i_{fc} in Fig.2. Correspondingly, a modal model will be available for every combination of mass and landing gear configuration, etcetera. As mentioned, the building blocks for the aerodynamic model are the grid points, which are stored in a fixed data-structure with fields for the IDs of the coordinate systems applied for the definition of the grid point offsets (coordinates), the DoF and the IDs of the local coordinate systems in which the DoF are defined, the aircraft component (e.g., wing, fuselage,...) that the grid point belongs to, etcetera. Coordinate system data is defined relative to an arbitrary body-fixed reference coordinate system in a parallel sub-structure. In order to save storage space, the grid point, local coordinate systems, and transformation data between the body-fixed systems, which are independent of the flight condition, are stored only once in the (load case independent) sub-structure 'geom'.

The flexibility of this data structure for model updating purposes will be demonstrated in Section 4. Subroutines such as animation functions and operators such as coordinate transformations can be applied to the building blocks of all sub-models. Furthermore, it is emphasised that half- and full aircraft models, as well as any (unconventional) aircraft configuration can be reflected without adapting the data-structure.

Dynamic response simulation and software structure

Sub-systems of VarLoads are depicted for a representative model in Fig.3. The aeroelastic response is calculated within the *aircraft* sub-system. This sub-system is further divided into a number of modules. The *elastic&inertia* module basically contains the left hand side of the Equation of Motion (EoM), which will be treated in Section 3, i.e., the structural stiffness, structural damping, and mass properties. The right hand side of the EoM, i.e., the external loads (*aerodynamic*, *propulsion*,...) that act on the structure, are reflected by further modules within the aircraft sub-system. Interactions between the modules representing the external loads, on the one hand, and the *elastic&inertia* module, on the other hand, are represented by feed-back loops in Simulink.

Starting from a defined initial condition, typically the aircraft is either excited by a change in its *environment* (e.g., an atmospheric disturbance defined in FAR25), or by some given input (e.g., a checked manoeuvre defined in FAR25). In addition, outer feed-back loops transport the aircraft states (rigid body motion, elastic vibrations) back to the *sensor* sub-system, where the relevant signals for the flight *controls* sub-system are selected and transformed. The controls sub-system may include load alleviation functions[6]. Certain aircraft states may trigger the *pilot* into action as well. The *sensor* signals and the *pilot* commands constitute the input for the flight control systems. Control surface deflections and engine settings are the typical output from the flight control system. These signals are fed through the *actuators* sub-system, which reflect the dynamic behaviour of the actuation systems, back to the *aircraft/aerodynamic* and *aircraft/propulsion* sub-systems, where they are transformed into incremental loads. Finally, the *post-processing* sub-system computes the internal forces at the monitoring stations. For the present work, this is carried out with the method of force summation.

Alternatively, the initial equilibrium state itself may be the focus of the investigation, for example when determining the structural deformation and loads for a level flight condition or a balanced manoeuvre. For numerical computation of (equilibrium) initial conditions, a trim algorithm from DLR, based on non-linear system and non-linear least-squares solvers from the MINPACK library, is used.

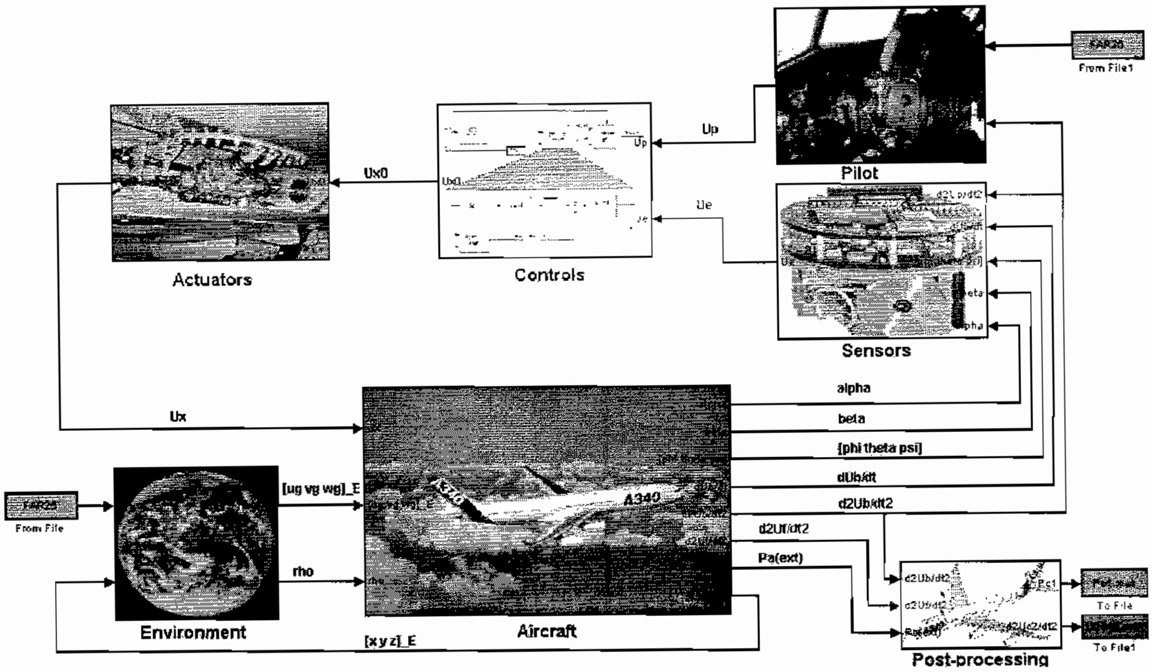

Fig.3: Representation of VarLoads sub-systems in a MatLab/Simulink environment.

Time histories for all variables can very easily be monitored in the Simulink model. On the one hand, this eases de-bugging while, on the other hand, increased physical insight for the user will result. Every sub-system in Fig.3 is built up from standard Simulink blocks and subsystems that been collected in an in-house library. The advantage of this modular software structure is three-fold. Firstly, the individual building blocks can be obtained from different sources. This eases cooperation with research partners, who are typically specialists in a specific field. Secondly, the building blocks may reflect a varying level of refinement. For example, the aerodynamic method may be steady strip theory or a more refined approach such as vortex lattice. Modules can easily be down-sized for real-time applications by replacing refined with lower-order systems. This characteristic makes the software environment suitable for analyses along the aircraft development axis, i.e., for aircraft models evolving continuously from the preliminary design stage on to the certification stage and beyond.

3. INTEGRATED MODEL

For the computation of different kinds of loads, generally different types of aircraft models are used. For example, loads resulting from large amplitude manoeuvres are computed using a 6 DoF non-linear flight dynamics model, while gust loads are predicted using aeroelastic models representing (small amplitude) vibrations of the airframe structure. For preliminary design and special investigations, frequently a single model representation will be preferable. In order to predict various types of loads of an elastic aircraft using a single model representation, an integrated aircraft model has to be developed, combining non-linear flight dynamics and linear elastic structural dynamics. The basis for an integrated model are the Equations of Motion (EoM) for an aeroelastic flight vehicle[2—5].

Equations of motion

As an initial step, the EoM as proposed by Waszak and Schmidt[4] are implemented. These equations consist of the non-linear Newton-Euler EoM of the rigid aircraft (as used in flight mechanics) and the linear elastic EoM in modal form (known from structural dynamics). By making a number of simplifying assumptions in the derivation[2], one obtains:

$$
\begin{aligned}
&\begin{bmatrix} \mathbf{M}_{b1b1}\left(\dot{\mathbf{V}}_{b1}+\mathbf{\Omega}_{b2}\times\mathbf{V}_{b1}\right) \\ \mathbf{I}_{b2b2}\dot{\mathbf{\Omega}}_{b2}+\mathbf{\Omega}_{b2}\times\left(\mathbf{I}_{b2b2}\mathbf{\Omega}_{b2}\right) \end{bmatrix} = \mathbf{T}_{rb}^{\mathrm{T}}\mathbf{\Phi}_{ar}^{\mathrm{T}}\mathbf{P}_{a}^{\mathrm{ext}}, \\
&\Phi_{af}^{\mathrm{T}}\mathrm{M}_{aa}\Phi_{af}\left(\ddot{\mathrm{u}}_{f}+2\left[\zeta_{f}\right]\left[\omega_{f}\right]\dot{\mathrm{u}}_{f}+\left[\omega_{f}\right]^{2}\mathrm{u}_{f}\right)=\Phi_{af}^{\mathrm{T}}\mathrm{P}_{a}^{\mathrm{ext}},
\end{aligned}
\tag{1}
$$

where:

$\mathbf{M}_{b1b1}$	$\mathbf{M}_{b1b1}$ =[m_{AC} 0 0;0 m_{AC} 0; 0 0 m_{AC}], with m_{AC} the aircraft mass
$\mathbf{I}_{b2b2}$	mass moment of inertia matrix for the rigid a/c in body axes; $\mathbf{I}_{b2b2}$=[I_{xx} I_{xy} I_{xz}; I_{yx} I_{yy} I_{yz}; I_{zx} I_{zy} I_{zz}]
$\mathbf{V}_{b1} = [u\ v\ w]^{\mathrm{T}}$	normal velocity vector for the rigid a/c in body axes
$\mathbf{\Omega}_{b2} = [p\ q\ r]^{\mathrm{T}}$	rotational velocity vector for the rigid a/c in body axes
$\mathbf{T}_{rb}$	transformation matrix from centre of gravity to reference grid point
$\mathbf{\Phi}_{ar}$	modal matrix for rigid body modes
$\mathbf{\Phi}_{af}$	modal matrix for flexible modes
$\mathbf{P}_{a}^{\mathrm{ext}}$	vector of external forces on structural grid points
$\mathbf{M}_{aa}$	physical mass matrix
$\mathbf{u}_{f}$	generalized coordinates for flexible modes
$[\zeta_{f}]$	structural damping of flexible modes (diagonal)
$[\omega_{f}]$	frequencies of flexible modes (diagonal)

In order to obtain the correct physical total aircraft loads from the rigid body modes, the rigid body modes ($\mathbf{\Phi}_{ar}$) are normalised with respect to a reference grid point DoF. Rather than the actual centre of gravity, a reference grid point is applied for this load transformation in order to enable the definition of a single structural DoF set (a-set) for all mass cases. Coupling between the rigid body modes and the elastic modes stems solely from the external forces. The EoM have been derived using Lagrangian dynamics and the Principle of Virtual Work under the following assumptions[2,4]:

1. The structure is comprised of lumped mass elements.
2. Linear elastic theory is valid, i.e. the structural deformations are small.
3. A set of orthogonal modes resulting from "free-free" modal analysis is available.
4. Deformation and rate are sufficiently small or collinear so that their cross product is small.

As the body reference frame, a floating reference system, so called "mean axes", have been chosen. Mean axes are not physically attached to the airframe. Their origin is in the momentary centre of gravity and their directions are determined using so-called practical mean axis constraints. By making the (reasonable) Assumption 3, the flexible modes are orthogonal with respect to the rigid body modes, automatically fulfilling these constraints[2]. The 4th assumption implies that the inertial cross terms resulting from Coriolis and centrifugal forces are neglected and the inertia tensor is constant.

The presented EoM have been adopted as a first step. In case one or more of the assumptions above are no longer valid, more refined equations, as for example derived by Buttrill *et al.*[3], will be implemented.

External loads

The external forces and moments ($\mathbf{P}_a^{\mathrm{ext}}$) that actually drive the EoM mainly result from the airflow and propulsion. For the present EoM formulation, gravity loads are applied as external forces as well. The scheme presently used for calculation of aerodynamic and gravity loads is treated in the following. Once more, it is emphasised that the presented approach is to be regarded as a building block, which will be replaced by a more refined (or less refined) approach when this is called for in light of the intended application.

One of the most important aspects of the loads calculation is the application of aerodynamic loads to the structure. The number of theories available to calculate aerodynamic loads is abundant, ranging from simple Lifting Line Theory to sophisticated Navier-Stokes solvers. However, the choice of a method and its trade-offs with respect to accuracy and computational cost has to be considered in light of the application. In the case where the design process is in an advanced stage, aerodynamic databases with wind tunnel and/or flight test results are available, whereas during the preliminary design phase, one must rely solely on CFD data.

The forces during the simulation resulting from rigid body movement, elastic vibrations, control surface deflections, and atmospheric disturbances can be calculated separately and subsequently be superimposed. The individual contributions to the aerodynamic force can be expressed as

$$\mathbf{P}_a^{\mathrm{aero}} = q_{\mathrm{dyn}} \mathbf{TP}_{ka}^{\mathrm{T}} \left[\mathbf{Q}_{kj}^{\alpha} (\boldsymbol{\alpha}_j - \boldsymbol{\varepsilon}_j) + \mathbf{Q}_{kj}^{\beta} (\boldsymbol{\beta}_j - \boldsymbol{\sigma}_j) + \mathbf{Q}_{kb2}^{\Omega} \boldsymbol{\Omega}_{b2} \frac{l_{\mathrm{A}}}{V_{\mathrm{TAS}}} + \mathbf{Q}_{kx}^{\delta} \mathbf{u}_x \right], \tag{2}$$

where:

q_{dyn}	dynamic pressure
$\mathbf{TP}_{ka}$	transformation matrix for loads from aerodynamic force acting point DoF to structural grid point DoF
$\mathbf{Q}_{kj}^{\alpha} = (1/q_{\mathrm{dyn}}) \mathrm{d}\mathbf{P}_k / \mathrm{d}\boldsymbol{\alpha}_j$	Aerodynamic Influence Coefficient (AIC) matrix with strip loads ($\mathbf{P}_k$) due to strip angles of attack ($\boldsymbol{\alpha}_j$)
$\boldsymbol{\alpha}_j = \boldsymbol{\alpha}_j^{0} + \Delta\boldsymbol{\alpha}_j^{\mathrm{gust}} + \Delta\boldsymbol{\alpha}_j^{\mathrm{r}} + \Delta\boldsymbol{\alpha}_j^{\mathrm{f}}$	strip angle of attack, with contributions for zero lift ($\boldsymbol{\alpha}_j^{0}$), gust ($\Delta\boldsymbol{\alpha}_j^{\mathrm{gust}}$), rigid body motion ($\Delta\boldsymbol{\alpha}_j^{\mathrm{r}}$), and flexible modes ($\Delta\boldsymbol{\alpha}_j^{\mathrm{f}}$)
$\boldsymbol{\varepsilon}_j = \boldsymbol{\varepsilon}_j^{0} + \Delta\boldsymbol{\varepsilon}_j$	strip downwash angle (only for tail), with contributions for zero lift ($\boldsymbol{\varepsilon}_j^{0}$) and increment with angle of attack ($\Delta\boldsymbol{\varepsilon}_j$)
$\mathbf{Q}_{kj}^{\beta} = (1/q_{\mathrm{dyn}}) \mathrm{d}\mathbf{P}_k / \mathrm{d}\boldsymbol{\beta}_j$	Aerodynamic Influence Coefficient (AIC) matrix with strip loads ($\mathbf{P}_k$) due to strip angles of sideslip ($\boldsymbol{\beta}_j$)

$\beta_j=\beta_j^0+\Delta\beta_j^{\mathrm{gust}}+\Delta\beta_j^{\mathrm{r}}+\Delta\beta_j^{\mathrm{f}}$	strip sideslip angles, with contributions for zero lift (β_j^0), gust ($\Delta\beta_j^{\mathrm{gust}}$), rigid body motion ($\Delta\beta_j^{\mathrm{r}}$), and flexible modes ($\Delta\beta_j^{\mathrm{f}}$)
$\sigma_j=\sigma_j^0+\Delta\sigma_j$	strip sidewash angle (only for tails), with contributions for zero lift (σ_j^0) and increment with sideslip angle ($\Delta\sigma_j$)
$\mathrm{Q}_{kb2}^{\Omega}=(1/q_{\mathrm{dyn}})\mathrm{dP}_k/\mathrm{d}\Omega_{b2}l_{\mathrm{A}}/V_{\mathrm{TAS}}$	AIC matrix with strip loads (P_k) due to rotational velocities of the rigid a/c in body axes (Ω_{b2}), normalised with mean aerodynamic chord length (l_{A}) and true air speed (V_{TAS})
$\mathbf{Q}_{kx}^{\delta}=(1/q_{\mathrm{dyn}})\mathrm{d}\mathbf{P}_k/\mathrm{d}\mathbf{u}_x$	AIC matrix with strip loads ($\mathbf{P}_k$) due to control surface deflections ($\mathbf{u}_x$)

For compatibility with the in-house aerodynamic database, as a first step the AIC matrices in (2) are related directly to the angle of attack (α) and the angle of sideslip (β) of the local strips. The local coordinate systems for the strip downwash control points are chosen such that α and β correspond to the strip ϕ_y and ϕ_z DoF, respectively. Incremental angles $\Delta\alpha$ and $\Delta\beta$ due to local normal motion of the strips are obtained by dividing with the true air speed. Furthermore, the physical control surface deflections and the angular rates of an aerodynamic reference point are represented by individual DoF-sets.

The aerodynamic loads on the empennage due to a change of the angle of attack of the aircraft are modelled with a so-called lag-in-downwash approach, i.e., the change of the downwash is delayed by the time the free-stream velocity propagates the change from the wing to the tail. Analogously, during a gust encounter the forces start acting on the structure when each individual strip penetrates the gust. To model the unsteady build up of lift and moment, a Wagner function for a rapid change in angle of attack respectively a Küssner function for the gust penetration are applied.

The loads due to gravity are calculated from

$$\mathbf{P}_a^{\mathrm{grav}}=\mathbf{M}_{aa}\mathbf{g}_a,$$

where:

$\mathbf{M}_{aa}$	physical mass matrix
$\mathbf{g}_a$	vector containing the components of acceleration of gravity

The components of $\mathbf{g}_a$ are obtained by a coordinate transformation for every time step from geodetic axes to the local structural grid point coordinate systems corresponding to the a-set DoF.

Finally, propulsion loads may be derived from engine settings provided by the flight control system or pilot model. Alternatively, for a steady trim analysis, engine loads will be derived from equilibrium, with the aircraft drag following from the trim angle of attack. For the direction of the propulsion loads with respect to the mean axes, the momentary elastic deformation at the engine may be taken into account.

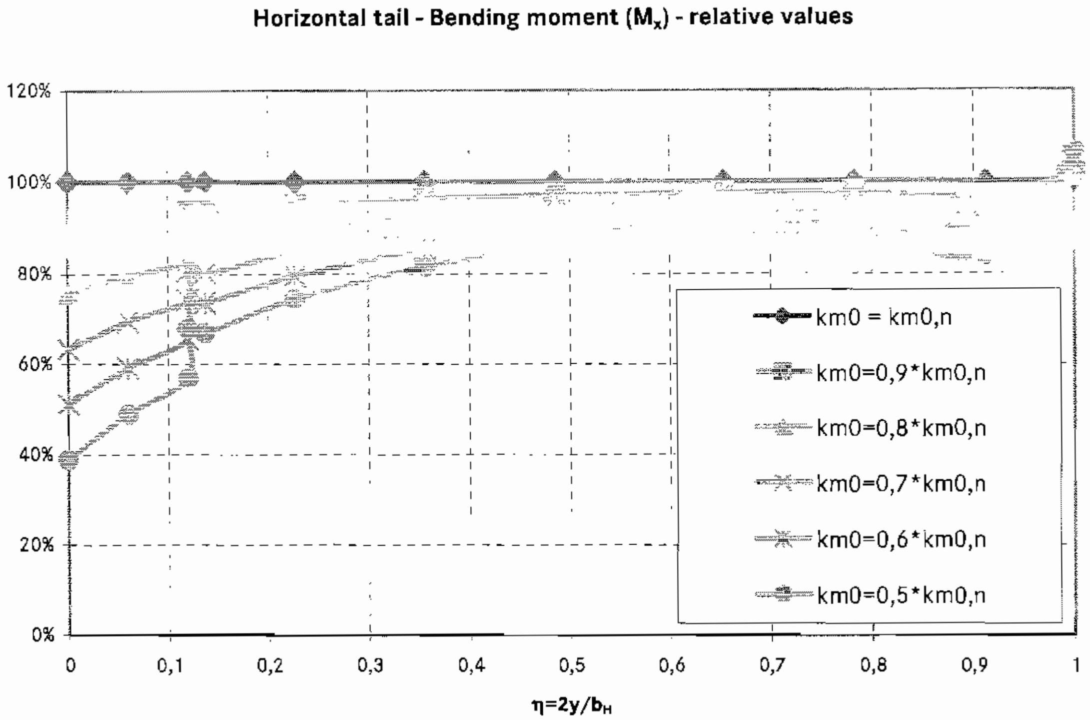

Fig.4: Horizontal tail span-wise bending moment for a change in zero-lift pitching moment of the wing, with C_{m0} the nominal value.

The presented EoM are an extension to the unified approach by Waszak *et al.*[2] in the sense that gravity is assumed to act on every individual lumped mass rather than applying it in an average sense to the aircraft centre of gravity. Here, starting from the wing jig shape and corresponding zero-lift distributions, the momentary elastic deformation of the aircraft and the corresponding load increments are determined automatically for every time-step.

4. EXAMPLE APPLICATION

In the following, a typical parametric investigation is presented using the approach from Section 2 and Section 3. Rather than presenting a numerical example, the intention is to show the advantages of the data and software structure presented in the preceding sections.

A parametric study is carried out to establish the effect of an uncertainty in the wing pitching moment coefficient for zero lift (C_{m0}) on 1g loads of the horizontal tail. Results for the horizontal tail bending moment (M_x) are depicted in Figure 4. Data for a generic passenger transport aircraft are used. The Mach number and altitude correspond to a flight condition at V_D. The wing zero-lift pitching moment distribution (k_{m0}) is scaled. Equilibrium for steady level flight and the corresponding structural deformation is calculated by trimming the integrated, flexible model.

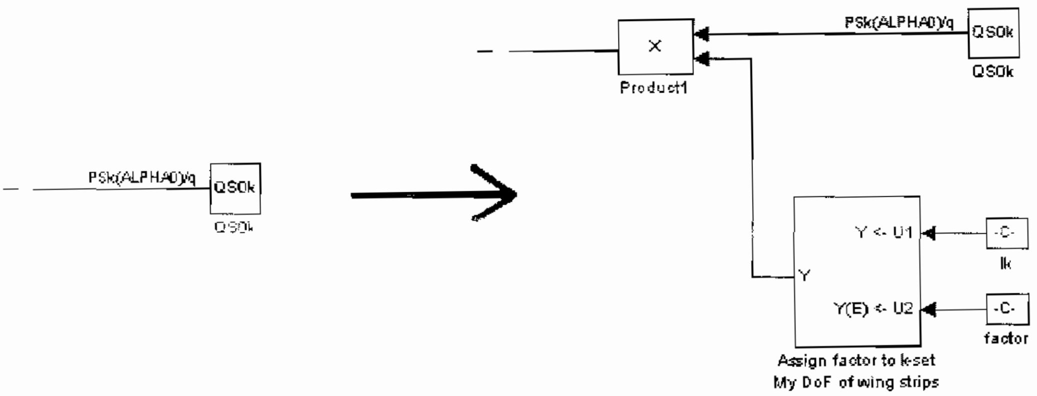

Fig.5: Manipulation of VarLoads/Simulink model required to change the pitching moment distribution of the wing.

This parametric investigation can be achieved by a few straightforward manipulations of the Simulink model. These manipulations are depicted in Fig.5. The signal containing the zero-lift strip loads (normalised w.r.t. the free-stream dynamic pressure) for all aerodynamic force DoF ($\mathbf{Q}^{S0}{}_{k}$), which is normally a constant input vector for the simulation, is manipulated by adding four standard Simulink blocks. Two additional inputs are a unit vector with dimension of the k-set as well as the factor by which the nominal local wing zero-lift pitching moment coefficient ($k_{m0,n}$) is scaled. This factor is assigned only to the M_y-DoF of the wing strips. These DoF are easily obtained from the data structure in Fig.2 by selecting the strips with component keys 'WR', for the right wing, and 'WL', for the left wing, and subsequently reading the 5th row (i.e., the M_y-DoF) of the k-set for these elements. Finally, the adapted vector $\mathbf{Q}^{S0}{}_{k}$ is obtained by multiplication.

Thus, the parametric study can be carried out with a minor adaptation of the Simulink model, without the need to load new aircraft model data from database. The subsequent trimming analysis is computationally efficient as well, resulting in a computation time of a few seconds (Pentium III processor) for the presented investigation.

5. OUTLOOK

A simulation environment was presented for special structural dynamics investigations. The environment is characterised by a modular software structure and an object-oriented data-structure. The aircraft model and equation of motion can easily be adapted to the required level of detail. An integrated, fully flexible aircraft model is the basis for the simulations. The novelty of the approach lies in the combination of the above mentioned characteristics. It was demonstrated that the model can easily be adapted for parametric investigations. These features make the software environment ideally suited for special studies ranging from the preliminary design stage on to in-flight incident investigations.

Extensions to the software environment will include more refined approaches towards the unified equation of motion and (unsteady) aerodynamics modelling. Furthermore, the addition of ground (or impact) loads to the time domain simulation can be achieved in a straightforward manner. Applications of the VarLoads environment currently focus on, among others, preliminary design, design of loads control functions[6], and real-time models[1].

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