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DYLOFLEX: A Computer Program for Flexible Aircraft Flight Dynamic Loads Analyses with Active Controls

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This paper describes and illustrates the capabilities of the DYLOFLEX computer program system. DYLOFLEX is an integrated system of computer programs for calculating dynamic loads of flexible airplanes with active control systems. A brief discussion of the engineering formulation of each of the nine DYLOFLEX programs is described. The capabilities of the system are illustrated by the analyses of two example configurations.

Nomenclature

$\bar{A}$	= root-mean square (rms) value per unit rms gust velocity
ΔC_p	= difference of pressure coefficients
C_3	= generalized aerodynamic matrix due to gust
$\bar{C}_3$	= load coefficient matrix due to gust aerodynamics
c	= local chord of lifting surface
$\bar{c}$	= reference length
D	= matrix of normalwash factors, doublet lattice
F	= matrix of normalwash factors, relating slender body pressures to thin body and interference body normalwash
$F(\omega)$	= Fourier transform of discrete excitation function
$f(t)$	= discrete excitation function
$H(\omega)$	= frequency response function
$h(t)$	= impulsive response function
$K_1,...,K_6$	= feedback gains, Fig. 10
k	= reduced frequency, $\omega\bar{c}/2V_T$
M_1,M_2,M_3	= generalized structural stiffness, damping, and mass matrices
M_4,M_5	= generalized aerodynamic stiffness and damping matrices
$\bar{M}_1,\bar{M}_2,\bar{M}_3$	= structural load coefficient matrices
$\bar{M}_4,\bar{M}_5$	= load coefficient matrices due to motion aerodynamics
N_0	= number of zero crossings with positive slope per unit distance
q	= vector of generalized coordinates
s	= Laplace variable
t,τ	= time
V_T	= true velocity
v_g	= lateral gust velocity
w,w_B	= normalwash vector
w_g	= vertical gust velocity
x	= chordwise coordinate
$x(t)$	= response due to discrete excitation
$X(\omega)$	= Fourier transform of response
z	= vertical displacement, positive down
α_g	= gust angle of attack, w_g/V_T
δ_{col}	= deflection of control column, positive for pull-up
ζ	= damping ratio
η_f	= nondimensional fin spanwise coordinate
θ	= pitch angle, positive nose up
Φ	= indicial-lift-growth function due to motion
$\Phi(\omega)$	= atmospheric turbulence power spectrum
Ψ	= indicial-lift-growth function due to gust
ψ	= yaw angle
ω	= circular frequency
$*$	= convolution
$\cdot$	= time derivative

Subscripts

aero	= aerodynamic panel load
max	= the maximum value of a quantity
net	= net panel load
root	= evaluated at the root of a lifting surface

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Introduction

LARGE, flexible flight vehicles and control configured vehicles necessitate improved analytical techniques for determining aeroelastic effects on the stability and control characteristics, gust design loads, and ride qualities. Because of the complexity of these aeroelastic analyses, a computerized method is required to analyze these vehicles.

DYLOFLEX is an integrated system of stand-alone computer programs which performs dynamic loads analyses of flexible airplanes with active controls. DYLOFLEX incorporates a wide range of analysis capabilities which include calculating dynamic loads due to continuous atmospheric turbulence, discrete gusts, and discrete control inputs. The output of DYLOFLEX consists of statistical quantities of the dynamic loads and time histories of the dynamic loads.

The DYLOFLEX documentation consists of an Engineering and Usage Document for each program, a System Design and Maintenance Document for each program, and a Summary Document describing the entire system.[1] These documents are published as NASA contractor reports. The individual computer progams are available for purchase through the Computer Software Management and Information Center (COSMIC) at the University of Georgia.

The purpose of this paper is to present an engineering description of the DYLOFLEX computer program system and to show typical results. Emphasis is on the capabilities of DYLOFLEX, using two sample configurations for illustration.

DYLOFLEX Features and Capabilities

In designing the DYLOFLEX computer program system, the design philosophy was to allow for maximum versatility in the types of structural and aerodynamic models it permits and in the types of analyses it performs. The following is a brief description of the DYLOFLEX features and capabilities which resulted from this design philosophy.

Structural Model

DYLOFLEX accepts externally generated structural data (mode shapes, generalized mass and stiffness matrices, lumped masses at structural nodes) from either a finite element or a lumped-mass-beam analysis. It accepts either free-free or cantilever modes, which may be appended with both rigid body and cantilever control-surface modes. DYLOFLEX can process a maximum of 70 modes.

Aerodynamic Model

The aerodynamics generated within DYLOFLEX may represent either subsonic or supersonic flow. The degree of unsteadiness ranges from quasi-steady (steady flow modified with indicial-lift-growth functions) to fully unsteady (for subsonic flow only). The aerodynamics due to gusts include the effects of gradual gust penetration. DYLOFLEX permits up to 400 aerodynamic singularities, which may be distributed over lifting surfaces, slender bodies, and interference bodies.

Equations of Motion

The equations of motion are linearized small perturbation equations which describe airplane motions and active control system perturbations about a trimmed, straight and level, 1 g flight condition. The longitudinal and lateral equations are decoupled. Within DYLOFLEX, the equations of motion may be written for a maximum of 70 deg of freedom (which includes flexible, rigid body, control surface, and active control system degrees of freedom in any combination).

Dynamic Loads

The loads equations are written using the method of summation of forces. Loads may be calculated at any location (e.g., wing, tail, fuselage, nacelle) and about any arbitrary axis on the vehicle. Dynamic loads are calculated for the following types of disturbances:

1) Continuous atmospheric turbulence. Root-mean-square values and zero crossings per unit length of the dynamic loads are calculated using random harmonic analysis techniques. The input power spectrum may be von Karman, Dryden, or user specified.

2) Discrete gust. Time histories of dynamic loads are calculated using Fourier transform techniques. The input gust forcing function may be one-minus-cosine, singularity functions, or user specified.

3) Discrete control input. Time histories of dynamic loads are calculated using Fourier transform techniques. The input control surface motion may be defined by the same types of forcing functions that define the discrete gust. Several control surfaces may be deflected simultaneously.

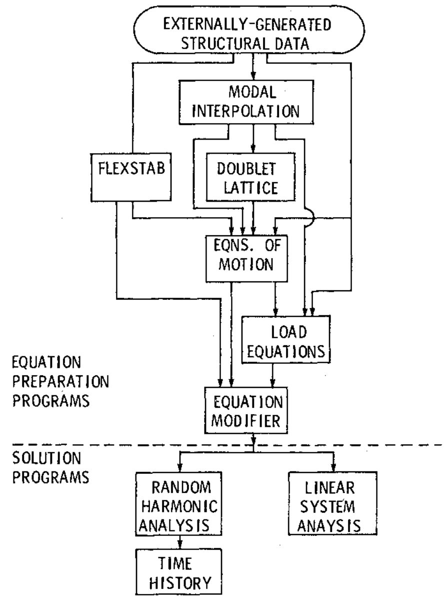

Fig. 1 Flow chart of DYLOFLEX system.

Parameter Studies

DYLOFLEX is ideally suited for performing numerous types of parametric analyses. Once the equations of motion and loads equations have been created, modifying these equations and then solving them in the solution programs may be done for a small fraction of the computational effort required to create them initially. Cycling into the left-hand and right-hand solution paths in Fig. 1 permits parametric studies to be performed, of which the following are typical examples:

1) Effects of active control system variables on loads and stability.

2) Effects of control surface stiffness or inertia on loads and stability.

3) At a constant Mach number, finding the flight condition which results in maximum loads.

Implementation on Computer

DYLOFLEX is written to execute on the CDC-6600 series computer using the CDC Network Operating System (NOS). Generally, separate execution of the individual DYLOFLEX programs is preferred so that inspection of intermediate results can be made. However, it is possible to execute several DYLOFLEX programs in a single sequential run by using the appropriate NOS control commands.

DYLOFLEX Engineering Formulation

A flow chart of DYLOFLEX is shown in Fig. 1. The individual programs communicate with each other via files, and externally generated structural data are required as input. The DYLOFLEX programs fall into two categories: equation preparation programs and solution programs. The dashed line in Fig. 1 separates these categories. The six upstream computer programs create the equations of motion and load equations of a flexible airplane with active control systems. The three downstream programs solve these equations. The engineering formulation of each of the computer programs is given in this part of the paper. The programs are discussed in the same order that they would be executed when performing a dynamic loads analysis.

Modal Interpolation Program

The Modal Interpolation Program (INTERP) accepts externally generated mode shapes as input and 1) forms arrays of interpolation coefficients (used in the Doublet Lattice Program and the Equations of Motion Program) for determining the aerodynamic boundary conditions, and 2) prepares the modal input (for use in the Loads Equation Program) for calculating inertia loads. Structural nodes and modal degrees of freedom may be added to or deleted from the basic set of data. INTERP has the capability of adding degrees of freedom which represent rigid rotations about control surface hinge lines.

Five different interpolation methods within INTERP give the analyst the capability of matching the type of vibration data (beam or finite element) with the particular aerodynamic bodies used in the aerodynamic idealization. The five interpolation methods are:

1) Motion point. This method uses modal displacements and rotations defined at a single input point to determine the motion at any output point.
2) Motion axis. This method uses modal information defined along a series of straight line segments which lie in the plane of its corresponding aerodynamic body.
3) Surface spline. This method uses modal displacements defined normal to a planar surface to determine motion at any output point on that surface.[2]
4) Beam spline. This method uses modal displacements and rotations defined along several (intersecting or nonintersecting) straight line segments defined in a plane.
5) Polynomial. This method requires no modal input. The user defines the order and the coefficients of a polynomial which describes the surface deflections.

Doublet Lattice Unsteady Aerodynamic Program

The Doublet Lattice Unsteady Aerodynamic Program (DUBFLX) is one of the two aerodynamic programs in DYLOFLEX. The doublet lattice method used in DUBFLX is that developed by Giesing, et al.[3] with changes made for increased computational efficiency and ease of maintainability. The doublet lattice method has as its basis a finite element concept used to evaluate the integral equations relating pressure and normalwash on lifting surfaces, which in matrix form is

$$\left\{\frac{w}{V_T}\right\} = [D]\{\Delta C_p\} \tag{1}$$

Streamlined closed body aerodynamics are represented by Miles's slender body theory[4] and Woodward's method of interference surfaces[5] is applied to determine the interaction effects between slender bodies and lifting surfaces. Equation (2) relates the slender body lifting pressures to the normalwash on lifting surfaces and interference surfaces.

$$\left\{\frac{w_B}{V_T}\right\} = [F]\{\Delta C_p\} \tag{2}$$

There are two options within DUBFLX: the generalized aerodynamic forces and lifting pressure (GAF) option and the aerodynamic influence coefficient (AIC) option. The user may select fully unsteady aerodynamics (with aerodynamic parameters defined at several reduced frequencies, k) with either option, or he may select quasi-steady aerodynamics (with the parameters defined at $k=0$ only) for the AIC option only.

FLEXSTAB Computer Program System

FLEXSTAB is a system of compatible computer programs which performs several types of analyses of flexible airplanes.[6] When it is used as part of DYLOFLEX, FLEXSTAB serves the following functions: 1) it generates a steady-state AIC matrix, and 2) it calculates rigid and elastic stability derivatives. In generating the steady-state AIC matrix, FLEXSTAB serves as the second aerodynamic program in DYLOFLEX. FLEXSTAB uses a linear finite element aerodynamic method developed by Woodward but extended to include both subsonic and supersonic flow about wing-body combinations.[5] The stability derivative calculations are especially important if forward speed effects are to be included. Because the aerodynamic formulation in DUBFLX cannot account for velocity changes in the direction of flight, the speed derivative from FLEXSTAB is the only method of including these aerodynamic effects.

Equations of Motion Program

The Equations of Motion Program (EOM) formulates a set of second-order linear differential equations which describe the motions of an airplane relative to its level equilibrium flight condition. The differential equations are formed (using the Lagrangian approach) under the restrictions that all motions are small and that the airplane is initially in trimmed, unaccelerated, straight and level flight. EOM generates the structural and aerodynamic matrices contained in Eq. (3).

$$([M_1]\{q\}+[M_2]\{\dot{q}\}+[M_3]\{\ddot{q}\}) + ([M_4]\{q\}+[M_5]\{\dot{q}\}) = \{C_3\}\alpha_g \tag{3}$$

where M_1, M_2, and M_3 are the structural matrices, M_4, M_5, and C_3 are the aerodynamic matrices, q is the vector of generalized coordinates, and α_g is the gust angle of attack.

Structural Matrices

The generalized stiffness (M_1) and generalized mass (M_3) are considered to be externally generated structural data. The generalized damping (M_2) is computed with DYLOFLEX in either of the two forms: structural damping (assumed proportional to displacement and in phase with velocity) or equivalent viscous damping. EOM has the capability of augmenting the generalized stiffness, damping, and mass matrices to include control surface degrees of freedom which may have been added in INTERP and are, therefore, not included in the basic set of vibration modes. The coupling is accomplished by augmenting the basic generalized mass matrix to include the inertial coupling terms between the original vibrational degrees of freedom and the added control surface degrees of freedom.

Aerodynamic Matrices

The aerodynamic matrices due to airplane motion (M_4 and M_5) and the aerodynamic vector due to gust (C_3) are computed in EOM. Aerodynamic data are input from either DUBFLX or FLEXSTAB (Fig. 1) and interpolation arrays are read in from INTERP. Together, the two aerodynamic methods offer four options for forming the aerodynamic matrices:

1) Doublet lattice GAF (fully unsteady).
2) Doublet lattice AIC (fully unsteady).
3) Doublet lattice AIC (quasisteady).
4) FLEXSTAB AIC (quasisteady).

Options 2, 3, and 4 allow for the effects of gradual penetration of the gust. Option 1 does not. When options 3 or 4 are chosen, the form of the equations of motion differs slightly from Eq. (3). The structural portion of the equation is unchanged, but the aerodynamic portion is altered. Unsteady aerodynamic effects are approximated by convoluting the instantaneous incidence angle with indicial-lift-growth functions (Kussner- and Wagner-type functions):

$$([M_1]\{q\}+[M_2]\{\dot{q}\}+[M_3]\{\ddot{q}\}) + ([M_4]\{q\}^*\Phi+[M_5]\{\dot{q}\}^*\Phi)=\{C_3\}\alpha_g{}^*\Psi \tag{3}$$

In Eq. (3), the elements of the M_4 and M_5 matrices are frequency dependent. In Eq. (4) they are constant, but unsteady effects are approximated by the indicial-lift-growth functions.

Loads Equation Program

The Loads Equation program (LOADS) generates load coefficient matrices using the method of summation of forces. Input to LOADS includes generalized aerodynamic forces from EOM, modal information from INTERP, and externally generated structural mass properties (Fig. 1). The dynamic load equations are in the same format as the equations of motion. For fully unsteady aerodynamics

$$\{\text{LOAD}\}=[\bar{M}_1]\{q\}+[\bar{M}_2]\{\dot{q}\}+[\bar{M}_3]\{\ddot{q}\} + [\bar{M}_4]\{q\}+[\bar{M}_5]\{\dot{q}\})+\{\bar{C}_3\}\alpha_g \tag{5}$$

For quasisteady aerodyamics

$$\{\text{LOAD}\}=[\bar{M}_1]\{q\}+[\bar{M}_2]\{\dot{q}\}+[\bar{M}_3]\{\ddot{q}\} + [\bar{M}_4]\{q\}^*\Phi+[\bar{M}_5]\{\dot{q}\}^*\Phi+\{\bar{C}_3\}\alpha_g{}^*\Psi \tag{6}$$

There are four different types of dynamic loads and for each type there is a module within LOADS for the formation of the appropriate load coefficient matrices.

Accelerations, Velocities, Displacements (AVD)

This module generates M_1, M_2, and M_3 matrices which define accelerations, velocities, and displacements at user specified locations on the airplane. A primary use of AVD is to create sensor equations which are used downstream as feedback signals in active control systems.

Aerodynamic Panel Loads (PLDS)

This module generates $\bar{M}_4$, $\bar{M}_5$, and $\bar{C}_3$ matrices which define aerodynamic forces (due to vehicle motion and gust) on user selected aerodynamic panels.

Net Panel Loads (NPLDS)

This module generates $\bar{M}_4$, $\bar{M}_5$, and $\bar{C}_3$ matrices which define aerodynamic panel forces and an $\bar{M}_3$ matrix which defines inertia panel forces. When combined, the aerodynamic and inertia panel forces result in a net panel force on user specified panels.

Shears, Bending Moments, Torsions (VBMT)

This module generates $\bar{M}_3$, $\bar{M}_4$, $\bar{M}_5$, and $\bar{C}_3$ matrices which define shears and moments at user specified locations on the airplane.

Equation Modifying Program

The Equation Modifying Program (EQMOD) provides many ways to modify both the equations of motion and the load equations. By using EQMOD the analyst can modify any element of the matrices in Eqs. (3-6) and add rows and columns to these matrices. Brief descriptions of the types of modifications performed by EQMOD are listed.

Addition of Active Control Systems

Active control system (ACS) equations are written as second-order (or less) linear differential equations. The ACS equations include sensor equations (formed in the AVD module of LOADS) which express feedback quantities (such as acceleration, yaw rate, etc.) to the control surfaces initially added in INTERP.

Replace Matrix Elements

This capability permits any element of any matrix to be changed to a different value. There are two important uses for this capability: 1) to add "backup" stiffness to a control surface degree of freedom, and 2) to modify the equations of motion so that the right-hand side becomes the excitation due to a control-surface displacement.

Stability Derivative Overwrite

If stability derivatives from FLEXSTAB or from external sources (such as wind-tunnel tests or flight tests) are available, they may be placed into the appropriate elements of the M_4, M_5, and C_3 matrices and used in place of the derivatives calculated in EOM.

Matrix Scalar Multiplication

This capability permits all elements of any matrix to be multiplied by the same scalar constant. An important use for the capability is to modify the elements of the M_4, M_5, and C_3 matrices to reflect changes in forward speed and dynamic pressure while holding Mach number constant.

Increment Matrix Elements

This capability permits the addition of some user selected value to any element of any matrix.

Axes Transformation

This capability transforms the equations of motion and loads equations from the inertia axes system to a body-fixed axes system.

Linear System Analysis Program

The Linear System Analysis Program (QR) is included in DYLOFLEX to determine the roots of the equations of motion. In QR, the equations of motion are reduced from a system of second-order differential equations with frequency-dependent coefficients to a system of constant-coefficient algebraic equations in the Laplace variable, s. These equations are solved using the QR algorithm to obtain the eigenvalues (roots). If the equations of motion are defined at several values of reduced frequency, the roots may be calculated at each of the reduced frequencies.

Random Harmonic Analysis Program

The Random Harmonic Analysis Program (RHA) is included in DYLOFLEX to perform power-spectral-density analyses of the dynamic loads due to continuous atmospheric turbulence. RHA solves the equations of motion (generated in EOM) and the dynamic loads equations (generated in LOADS) with either constant-coefficient matrices (quasisteady aerodynamics) or frequency-dependent-coefficient matrices (fully unsteady aerodynamics). RHA computes frequency response functions of the generalized coordinates (for a unit sinusoidal gust velocity) which are used to obtain the load frequency response functions. These are then used to calculate the statistical quantities $\bar{A}$ (rms value) and N_0 (number of zero crossings per distance) according to the following expressions

$$\bar{A}=\left[\frac{\int_0^\infty |H(\omega)|^2\Phi(\omega)\mathrm{d}\omega}{\int_0^\infty \Phi(\omega)\mathrm{d}\omega}\right]^{1/2} \tag{7}$$

$$N_0 = \frac{1}{2\pi}\left[\frac{\int_0^\infty \omega^2 |H(\omega)|^2 \Phi(\omega)\,\mathrm{d}\omega}{\int_0^\infty |H(\omega)|^2 \Phi(\omega)\,\mathrm{d}\omega}\right]^{1/2} \tag{8}$$

where $H(\omega)$ is the load frequency response function and $\Phi(\omega)$ is the atmospheric turbulence power-spectral-density function. The integrals in Eqs. (7) and (8) are evaluated numerically using trapezoidal integration at a maximum of 250 solution frequencies. If the equations of motion have been modified in EQMOD for control surface input rather than turbulence input, the load and generalized coordinate frequency response functions are those due to a unit sinusoidal control surface displacement.

Time History Solution Program

The Time History Solution Program (THS) is included in DYLOFLEX to calculate time histories of dynamic loads due to discrete excitations (gust and control-surface). The inputs to THS are the load and generalized coordinate frequency response functions from RHA (Fig. 1). THS computes time histories by Fast Fourier Transform techniques using the Cooley-Tukey algorithm.[7] In this method, the Fourier transform of the discrete gust forcing function $F(\omega)$ is computed and then multiplied by the frequency response function of the dynamic load $H(\omega)$. This product is expressed in the frequency domain as

$$X(\omega) = H(\omega)F(\omega) \tag{9}$$

where $X(\omega)$ is the output frequency response function. The dynamic load output time history is obtained by taking the inverse Fourier transform of $X(\omega)$. These steps are equivalent to evaluating the convolution integral in the time domain.

$$x(t) = \int_0^t h(t-\tau)f(\tau)\,d\tau \tag{10}$$

where $x(t)$ is the load output time history, $h(t-\tau)$ is the load impulsive response, and $f(\tau)$ is the discrete excitation.

Applications

System capabilities and major options and solution paths in DYLOFLEX are illustrated in this section of the paper by using two airplane configurations, both flexible vehicles with active control systems. The two analyses incorporate: lumped-mass-beam and finite element structural models; FLEXSTAB aerodynamics and two of the three types of doublet lattice aerodynamics; all four types of dynamic loads; and continuous turbulence, discrete gust, and discrete control surface disturbances.

Gust Loads Analysis

To illustrate the capabilities of the DYLOFLEX system in a typical design loads situation, a lateral gust analysis is performed on the configuration shown in Fig. 2. The analysis conditions are Mach number = 0.64, altitude = 2743 m (9000 ft).

The structural representation is an elastic-axis model consisting of 117 lumped masses representing the wing,

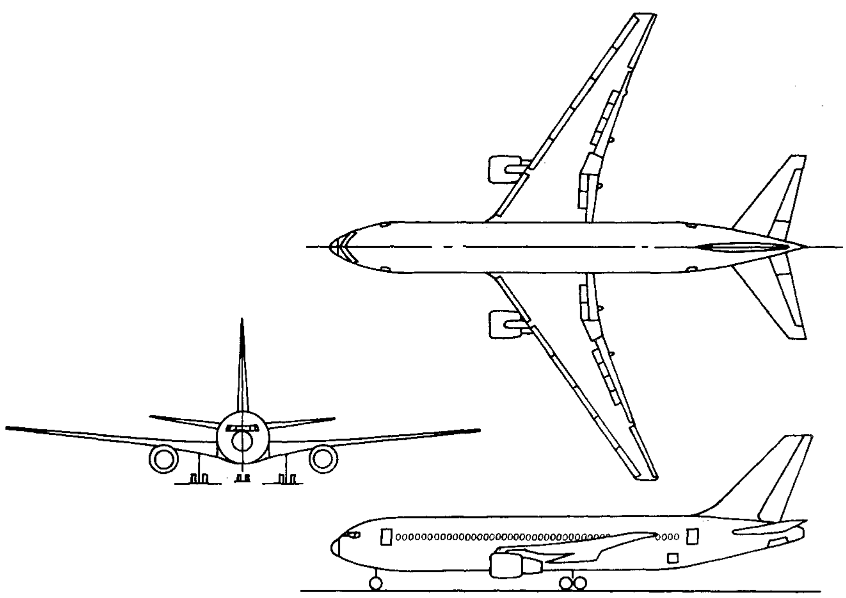

Fig. 2 Study configuration.

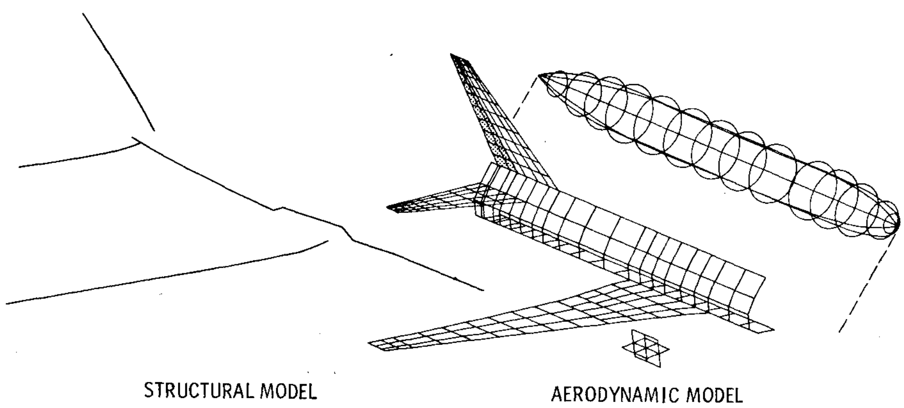

Fig. 3 Structural and aerodynamic idealizations of study configuration.

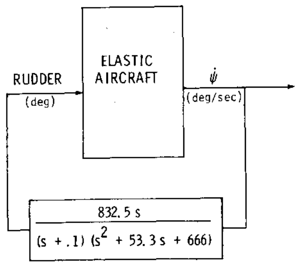

Fig. 4 Block diagram of assumed yaw damper

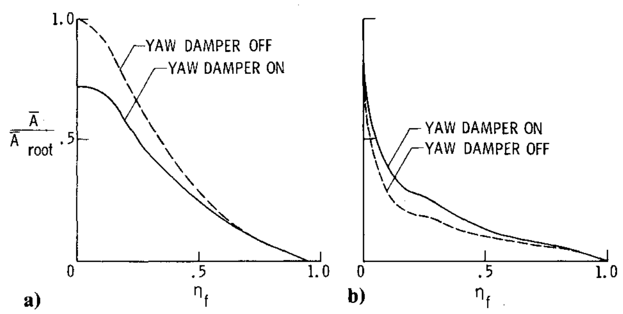

Fig. 5 Normalized fin loads a) bending moment; b) torsion.

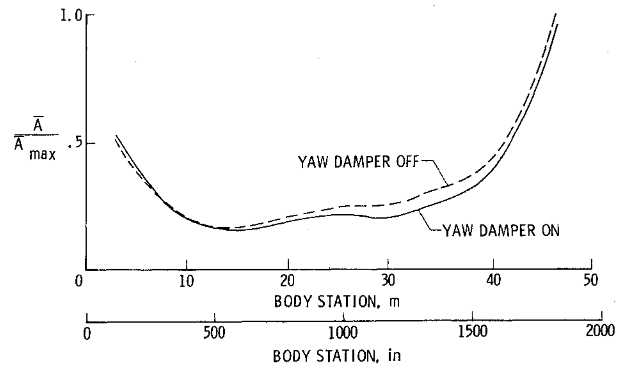

Fig. 6 Normalized fuselage lateral acceleration.

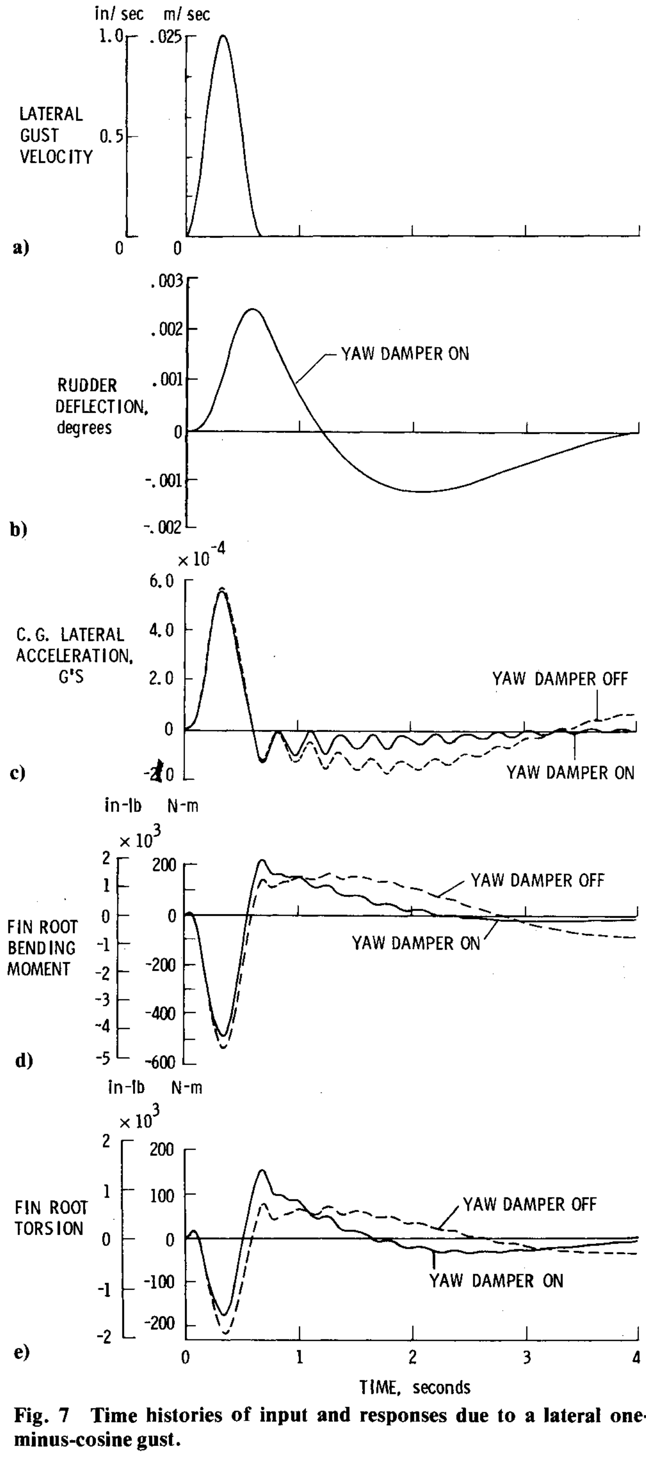

Fig. 7 Time histories of input and responses due to a lateral one-minus-cosine gust.

fuselage, nacelle, and horizontal and vertical tails. The elastic-axis configuration is shown on the left side of Fig. 3. Twenty-five free-free elastic modes are used. To these are added three rigid body modes representing side translation, roll, and yaw which make up the basic set of 28 airplane modes. A rigid notation about the rudder hinge line is added as the 29th mode. The aerodynamic model of the airplane is shown on the right side of Fig. 3. The model consists of lifting surfaces, interference bodies, and slender bodies which have a total of 290 singularities. The doublet lattice quasi-steady AIC option is the aerodynamic method chosen.

The basic airplane is augmented with the assumed yaw damper shown in Fig. 4. Airplane characteristic roots (obtained from the QR program with yaw damper on and off) indicate that the effect of the yaw damper is to significantly increase the damping of the Dutch roll mode (from $\zeta = 0.181$ to $\zeta = 0.519$) with almost no changes in the other roots. Normalized plots of rms values of fin bending moment and fin torsion due to a unit lateral rms gust velocity (obtained from the RHA program) are presented in Fig. 5. Fin root bending moment is reduced almost 30% due to the assumed yaw damper. Normalized rms fuselage lateral accelerations (also obtained from RHA) are plotted as a function of body station in Fig. 6. Lateral accelerations are shown to be reduced up to 25% due to the assumed yaw damper. The responses due to a unit one-minus-cosine discrete gust (obtained from the THS program) are presented in Fig. 7. Part a) shows the time history of the lateral gust velocity and part b) shows the time history of rudder deflection for the assumed yaw damper on. Parts c) and d) show the beneficial effects of the yaw damper on lateral acceleration at the vehicle center of gravity (c.g.) and on fin root bending moment. Part e) shows the time histories of fin root torsion.

Assessment of Active Load Alleviation Systems

The NASA Drones for Aerodynamic and Structural Testing Project uses a modified Firebee II target drone to test several research wings. One of the wings (designated ARW-2) is designed to incorporate multiple active control concepts simultaneously. The Firebee with the ARW-2 wing is shown in Fig. 8. For the DYLOFLEX analyses described in this section of the paper, the aerodynamic and structural models illustrated in Fig. 9 are used. The aerodynamic model of the entire vehicle is represented by 252 singularities on the wing

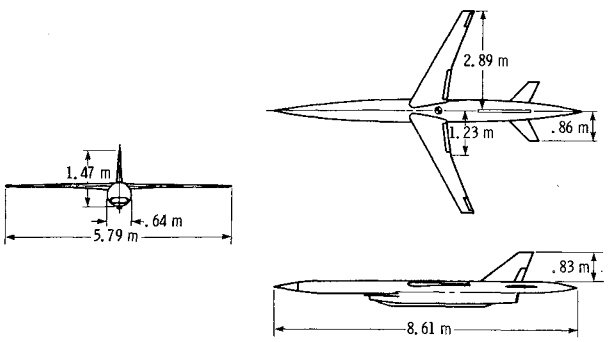

Fig. 8 ARW-2 configuration.

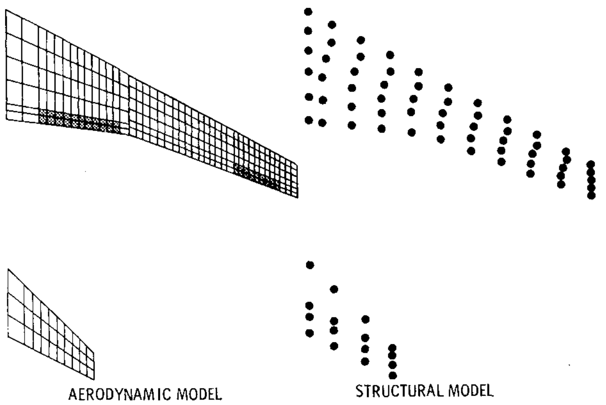

Fig. 9 Aerodynamic and structural idealizations of ARW-2 configuration.

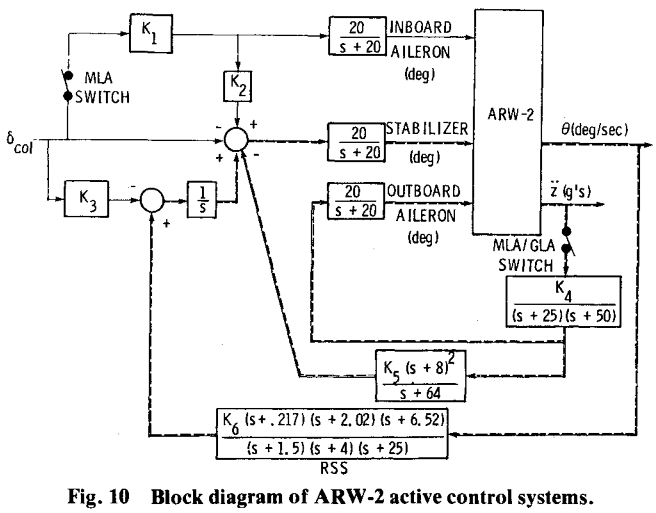

Fig. 10 Block diagram of ARW-2 active control systems.

and 27 on the tail. The structural representation contains 59 lumped masses on the wing and 16 on the tail. The block diagram in Fig. 10 contains relaxed-static-stability (RSS), gust-load-alleviation (GLA) and maneuver-load-alleviation (MLA) active control functions. The first DYLOFLEX analysis assesses the performance of the GLA system in continuous turbulence. The second analysis assesses the performance of the MLA system during a pull-up maneuver.

Assessment of GLA System

The portion of the block diagram (Fig. 10) represented by the dashed lines are the GLA and RSS systems. In this analysis, aerodynamic panel loads (PLDS) and net panel loads (NPLDS) due to continuous vertical turbulence are calculated for GLA on and GLA off. The flight condition for this analysis is Mach number = 0.6, altitude = 2134 m (7000

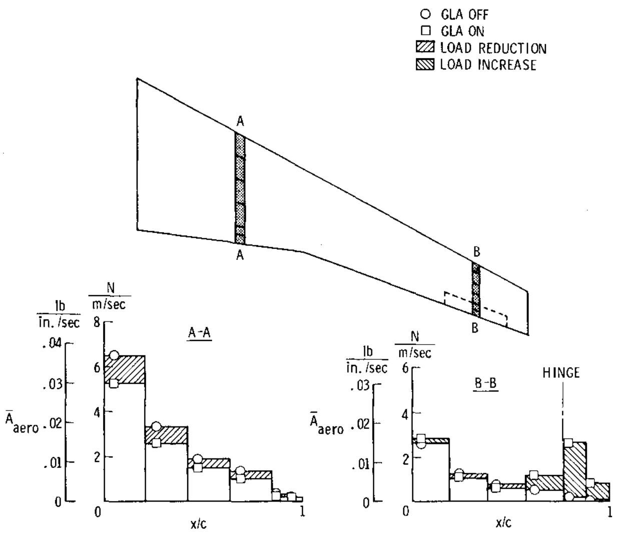

Fig. 11 Aerodynamic panel loads

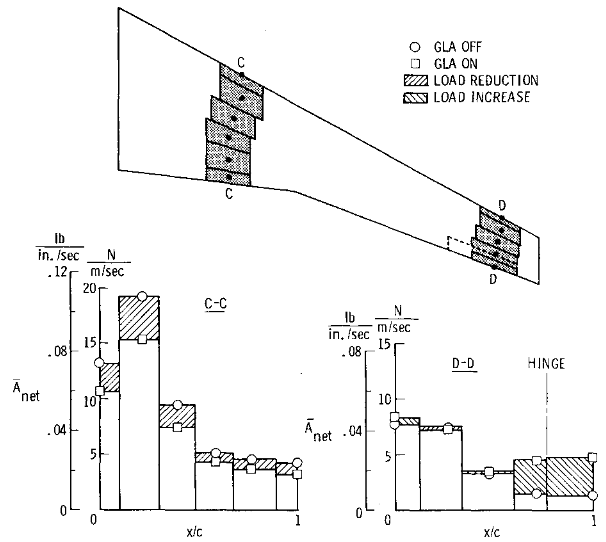

Fig. 12 Net panel loads.

ft). Two control surface modes (outboard aileron and horizontal stabilizer) are added to the two rigid body modes (plunge and pitch) and nine flexible modes for a total of 13 modes. The doublet lattice fully unsteady AIC option (at 11 values of reduced frequency) is the aerodynamic method chosen. To more accurately represent an airplane flying in atmospheric turbulence, the gradual gust-penetration option is exercised.

Airplane characteristic roots (obtained from QR with GLA on and GLA off) indicate a factor-of-two increase in the frequency of the short period mode and a factor-of-three increase in damping with GLA on. Root-mean-square values of the aerodynamic panel loads and net panel loads (obtained from the RHA program) are presented in Figs. 11 and 12 for GLA on and GLA off. Both figures show planforms of the wing illustrating the two chordwise rows (one of which passes over the active outboard aileron) on which the loads are calculated. The plots in both figures are of rms values of the appropriate load on each panel as functions of nondimensional chord. The direction of the cross-hatch indicates whether the GLA system results in a reduction or an increase in the load on each panel. For sections A-A and C-C, the GLA system results in roughly 20% reductions in both aerodynamic panel loads and net panel loads. For sections B-B and D-D, the GLA system causes substantial increases in both types of

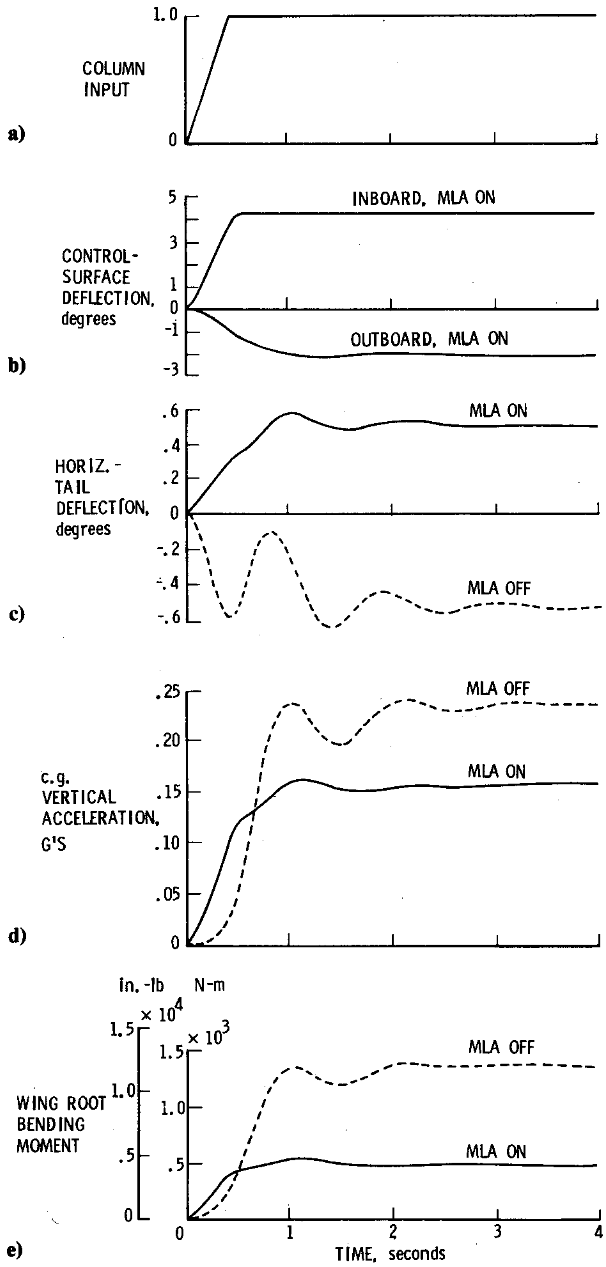

Fig. 13 Time histories of input and responses due to ramp-hold column deflection.

loads on the control surface and immediately forward of the hinge line on the wing.

Assessment of MLA System

The entire block diagram represents the MLA and RSS systems. The MLA system incorporates the GLA system, but, in addition, uses an inboard aileron on the wing. For a pull-up maneuver, the MLA system is designed to reduce the wing-root bending moment due to the maneuver. The flight condition for this analysis is Mach number = 0.35, altitude = sea level. In addition to the 13 deg of freedom used in the assessment of the GLA system, an additional control surface degree of freedom is added to account for the rotation of the inboard aileron about its hinge line. For this analysis the FLEXSTAB quasi-steady AIC option is executed and indicial-lift-growth functions are added to approximate unsteady effects. No gradual penetration effects are included. Using EQMOD, the equations of motion are modified to change the disturbance quantity on the right-hand side of the equations from vertical gust velocity to column input, δ_{col} (Fig. 10).

Airplane characteristic roots (obtained from QR with MLA on and MLA off) indicate an increase in short-period damping (from $\zeta = 0.442$ to $\zeta = 0.561$). Time histories (calculated in THS) due to a discrete ramp-hold column input are presented in Fig. 13, for MLA on and MLA off. The column input is shown at the top of the figure, and is the same for MLA on and MLA off. Part b) shows the time histories of the deflections (positive trailing edge down) of the inboard and outboard ailerons for MLA on. They deflect as expected (inboard down, outboard up) for MLA on. These surfaces do not deflect for MLA off. Part c) shows the horizontal tail deflection for MLA on and MLA off. As indicated, the horizontal tail deflects trailing edge down for MLA on, which is opposite that for a conventional (MLA off) pull-up maneuver. Parts d) and e) illustrate the alleviating effect of the MLA system on the incremental c.g. acceleration and the incremental wing root bending moment experienced during the maneuver. Peak accelerations are reduced by about ⅓ and peak bending moments are reduced by about ½.

Conclusions

DYLOFLEX is a system of stand-alone computer programs which performs dynamic loads analyses of flexible airplanes with active control systems. It is the first generally available documented dynamic loads program to incorporate the capability to include the effects of active control systems. DYLOFLEX features a wide range of analysis capabilities which include calculating dynamic loads due to the following types of disturbances: continuous atmospheric turbulence, discrete gusts, and discrete control surface inputs. The applications of DYLOFLEX presented in this paper illustrate its ability to perform each of these types of analyses. Depending upon the level of sophistication of the structural and aerodynamic models, DYLOFLEX is suitable for either preliminary or final design studies.

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