HIGH SPEED RESEARCH - AIRFRAME TECHNOLOGIES

TASK 20 - TECHNOLOGY INTEGRATION

NASA CONTRACT NAS1-20220

WBS 2.1.3 AEROELASTIC CONCEPT ENGINEERING

REPORT ON

PRELIMINARY AEROELASTIC CONCEPT

Prepared By

The Boeing Company

November 25, 1997

PREPARED FOR NASA LANGLEY RESEARCH CENTER
HAMPTON, VA

[redacted]

HIGH-SPEED RESEARCH PROGRAM
HSR II - AIRFRAME TASK 20 (WBS 2.1 Technology Integration)
SUB-TASK 2.1.3 AEROELASTIC CONCEPT ENGINEERING

REPORT ON

PRELIMINARY AEROELASTIC CONCEPT

Prepared Date: November 25, 1997

Prepared by :

Bala K. Bharadvaj
Advanced Transports & Tankers
Long Beach, CA

Christopher J. Borland
Boeing Commercial Airplane Group
Seattle, WA

Reviewed by :

H. R. Welge
Advanced Transports & Tankers
Long Beach, CA

Ronald J. Pera
Boeing Commercial Airplane Group
Seattle, WA

PREPARED FOR NASA LANGLEY RESEARCH CENTER

NASA CONTRACT NAS1-20220

PRELIMINARY AEROELASTIC CONCEPT

Foreword

The work reported here is part of the effort in Aeroelastic Concept Engineering (WBS 2.1.3) which is one of the subtasks under Technology Integration. This report is based on the coordinated efforts of several members of the Aeroelastic Concept Engineering (ACE) Team and different ACE Working Groups consisting of various experts from NASA and industry.

This document is being submitted to satisfy the deliverable "Preliminary Aeroelastic Concept" for WBS 2.1.3 under Task 20 of the High Speed Research II - Airframe Technologies Contract NAS1-20220. It is organized in four major sections. Section 1 provides an overview and a summary of the total effort. Section 2 provides details of work related to Aerodynamic Performance. Section 3 documents work done in the area of Weights & Structures. Section 4 summarizes activities related to Nonlinear Aeroelastic Loads.

The report is presented in the form of presentation charts with notes to help highlight and/or clarify the main points of interest.

Many individuals from several different organizations have directly contributed to the Preliminary Aeroelastic Concept and the contents of this report. The names of the key contributors are listed in the table below in alphabetic order.

Several other engineers have also contributed by providing input data, debating the alternatives, and making suggestions for improvement. The ACE Team thanks all these colleagues as well.

Key Contributors to the Preliminary Aeroelastic Concept

Name	Organization	Area of Contribution
Abdi, Frank	Alpha-Star Corp	Structures
Adamson, Eric	Boeing-Seattle	Aero Performance
Agrawal, Shreekant	Boeing-Long Beach	Aero Performance
Arslan, Alan	Boeing-Long Beach	Nonlinear Aeroelastic Loads
Barkey, Derek	Boeing-Long Beach	Structures
Becker, Brad	Boeing-Seattle	Weights
Bharadvaj, Bala	Boeing-Long Beach	ACE Team Leader/Coordinator
Bhatia, Kumar G.	Boeing-Seattle	Structures, Nonlinear Aeroelastic Loads
Biedron, Bob	NASA LaRC	Aero Performance
Borland, Chris	Boeing-Seattle	ACE Team Focal Point

Key Contributors to the Preliminary Aeroelastic Concept (Contd.)

Name	Organization	Area of Contribution
Carpenter, Jon	Boeing-Long Beach	Weights
Chaderjian, Neal	NASA ARC	Nonlinear Aeroelastic Loads
Coen, Peter	NASA LaRC	Structures
Giesing, Joe	Boeing-Long Beach	DOSS, Structures, Nonlinear Aeroelastic Loads
Giles, Gary L.	NASA LaRC	Structures
Goggin, Patrick	Boeing-Long Beach	Nonlinear Aeroelastic Loads
Green, Larry	NASA LaRC	ACE Team Focal Point
Guruswamy, Guru	NASA Ames	Nonlinear Aeroelastic Loads
Knoernschild, David	Boeing-Seattle	Design Optimization Synthesis System
Lavelle, Tom	NASA LeRC	Graphics for DOSS
Martin, Grant	Boeing-Long Beach	CFD Analyses
Magee, Todd	Boeing-Long Beach	CFD Analyses
McCullers, Arnie	Vigyan Associates	FLOPS sizing program support
Merritt, Fergus	AEA Technologies	Graphics for DOSS
Murman, Scott	MCAT	Nonlinear Aeroelastic Loads
Narducci, Bob	Boeing-Long Beach	Aero Performance
Nelson, Chet	Boeing-Seattle	Aero Performance
Okazaki, Alan	Boeing-Long Beach	Design Optimization Synthesis System
Pak, Chan-Gi	Boeing-Long Beach	Structures
Shih, Mike	Boeing-Long Beach	Structures
Tamigniaux, Thierry	Boeing-Seattle	Structures
Torres, Francisco	NASA Ames	Graphics for DOSS
Tu, Eugene	NASA ARC	ACE Team Focal Point
Tzong, George	Boeing-Long Beach	Structures
Vegter, Chris	Boeing-Seattle	Aero Performance
Wakayama, Sean	Boeing-Long Beach	Design Optimization Synthesis System
Yuan, Kuo-An	Boeing-Long Beach	Nonlinear Aeroelastic Loads

PRELIMINARY AEROELASTIC CONCEPT

Table of Contents

PRELIMINARY AEROELASTIC CONCEPT

List of Abbreviations

ACE - Aeroelastic Concept Engineering
ASAP - Aircraft Sizing And Performance
CFD - Computational Fluid Dynamics
DOSS - Design Optimization Synthesis System
DV - Design Variable
FLOPS - Flight Optimization Performance System
FPR - Fan Pressure Ratio
GENIE - GENeric Interface for Engineering
GUI - Graphical User Interface
GW - Gross Weight (same as TOGW)
HSR - High Speed Research
MDO - Multidisciplinary Design Optimization
MTOW - Maximum Take-Off Gross Weight
nm - Nautical Miles
OAC - Optimized Aeroelastic Concept
OEW - Operating Empty Weight
PAC - Preliminary Aeroelastic Concept
RS - Response Surface
RSVP - Response Surface View Program
SOCS - Sparse Optimal Control Software
TOGW - Take-Off Gross Weight (same as GW)

PRELIMINARY AEROELASTIC CONCEPT

Executive Summary

Milestone Objectives:

- Develop and implement a process to perform simultaneous optimization of several global configuration design variables to achieve a performance sized configuration that minimizes the MTOW.
- Demonstrate this process by introducing wing thickness perturbations as design variables for the TCA to support definition of the Preliminary Technology Configuration.

Accomplishments in Relation to Milestone:

Five wing thickness perturbation design variables were selected for implementation in the Preliminary Aeroelastic Concept (PAC). Each of the thickness perturbation design variables is a combination of spanwise and chordwise distributions of additional thickness to the baseline Technology Concept Airplane (TCA) defined at the end of 1995.

A process for estimating the sensitivity of the aerodynamic performance drag polars to wing thickness changes was developed. This process utilizes an intelligent combination of data from linearized aerodynamic analyses, nonlinear CFD analyses, and available wind tunnel test data. This process was applied to compute the change in drag due to the individual thickness and twist perturbations. Data from linear theory analyses supplemented with the nonlinear increments (using Response Surfaces) formed the total aero drag database for the studies.

Three approaches were initiated to reduce the cycle time to compute weight sensitivities based on structural analysis with FEMs. They represent different levels of simplifications in how the structure is represented in the model, and the type of approximations made during the structural sizing.

Since none of the three methods were completely validated in time to generate the data needed for PAC design studies, the demonstration of the optimization was done with three sets of assumed data for OEW sensitivity (since realistic input data was not ready). Set 1 assumed no change in OEW when thickness is changed representing one extreme case. Sets 2 and 3 assumed varying levels of structural weight reduction due to the thickness perturbations.

The drag polar sensitivity data and the assumed OEW sensitivity data were provided as inputs to the Design Optimization Synthesis System which does the performance sizing and simultaneous multivariable optimization of the airplane configuration. The optimization studies were done for the TCA airplane with a fixed propulsion system. The optimization problem was set up to vary the five thickness perturbation design variables between -1.0 and +1.0, and the configuration sized for -5db cutback for minimizing the Maximum Take-Off Weight (MTOW).

The thickness distribution recommended by the optimizer depends on the assumption made for the weight sensitivity. The MTOW was decreased in all three cases. However, the optimum thickness distribution was different. The results indicate that the optimization scheme is responsive to the input data. Also, depending upon the actual numbers for the OEW change due to the thickness perturbations, the potential for reduction in TOGW may be significant.

Conclusion:

The Aeroelastic Concept Engineering process for simultaneous optimization has been exercised to study a new set of design variables. Even though the data used for the OEW sensitivities are only assumptions, the demonstration exercise shows that the optimization mechanism is working in a manner consistent with engineering intuition.

As a continuation of this work, the sensitivity of OEW to thickness changes will be updated and the thickness optimization cases repeated with the new data.

PRELIMINARY AEROELASTIC CONCEPT

Section 1

Preliminary Aeroelastic Concept Design Study Summary

1.1 Introduction:

The overall charter of the HSR ACE Team is to develop processes and a computational system to incorporate Multidisciplinary Design Optimization (MDO) technology into airplane configuration design. The eventual goal of the work in WBS 2.1.3. (Aeroelastic Concept Engineering or ACE) is to develop the system and define the Optimized Aeroelastic Concept (OAC) configuration in June 1998. Defining the OAC is an HSR Level II milestone and requires the development of a configuration that incorporates simultaneous optimization of several configuration design variables utilizing high-fidelity input data. Defining the OAC requires the generation of significant amounts of input data, and the solution of a complex optimization problem. The Preliminary Aeroelastic Concept (PAC) was introduced by the ACE Team as an intermediate check point to check the validity of the overall approach being implemented for the OAC, and make adjustments if needed.

The Preliminary Aeroelastic Concept is an HSR Level III milestone. It is based on the outcome of work done during the past several quarters to develop integration procedures, and utilizing these processes and tools for thickness optimization of the Technology Concept Airplane (TCA). The following are ACE Level IV milestones associated with the activities that lead up to the PAC.

(1) Design Optimization Synthesis System (DOSS) developed and demonstrated (completed in December 1996)

(2) Extend DOSS to accept additional input data and to optimize thickness and twist distributions (completed in September 1997);

(3) Develop process for aero drag sensitivities incorporating nonlinear effects through the use of CFD methods (completed in June 1997); and

(4) Develop FEM-based process for estimating OEW sensitivities (originally scheduled for June 1997, partially completed in September 1997).

The original plan was to use the processes for drag sensitivity and the OEW sensitivity to generate data for thickness and twist perturbations around the TCA as the baseline, input them to DOSS, and generate optimum distributions of thickness and twist perturbations to minimize the MTOW. However, since completion of the FEM-based process for estimating OEW sensitivities has been delayed, the scope of the PAC has been reduced (with concurrence from the AMT) to that of demonstrating the capability of the system to incorporate thickness perturbations as design variables, and generate solutions based on best available input data.

Even though the scope of this milestone is reduced relative to the original plans, it is still consistent with the primary intent of this milestone, i.e., provide an early test run to evaluate the overall integration process in preparation for the OAC that involves a larger set of configuration design variables to be optimized.

1.2 Goals and Objectives:

Three primary goals for the Preliminary Aeroelastic Concept effort are as follows:

- Develop and implement a process to perform simultaneous optimization of several global configuration design variables to achieve a performance sized configuration that minimizes the MTOW.
- Develop processes and methods to improve the fidelity of sensitivity information being provided for the optimization studies by incorporating CFD analyses for aerodynamics and FEM-based methods for structural sizing.
- Demonstrate the ACE process by introducing wing thickness perturbations as design variables for the TCA, and conduct design studies to support definition of the Preliminary Technology Configuration.

1.3 PAC Design Variables:

The ACE process uses "global design variables" that are optimized to develop the best configuration. Global design variables are selected as those variables that have a significant impact on the definition of the airplane configuration, and usually have an impact on more than one discipline providing inputs to airplane performance sizing. [This is described further in the reports on DOSS.]

The main objective for the PAC was to exercise the processes on a relatively simple test problem that incorporates elements of the more complex multivariable design optimization corresponding to the OAC. Therefore the number and type of design variables was deliberately kept low. For this study, they are limited to the thickness perturbations and twist perturbations about the baseline geometry of the TCA. Some work was also done with engine size as another design variable which is a standard variable in traditional airplane performance sizing.

The thickness perturbations defined for this study are localized changes in thickness in the region of the main wing box. Five thickness perturbation design variables were selected. Each of the thickness perturbation design variables is a combination of spanwise and chordwise distributions of additional thickness to be added to the current loft line. A unit value of these variables represents a spanwise perturbation of thickness in the form of a "tent function" with a maximum value at a specified span location tapering off to zero at some distance from the peak (see Figure 1). The chordwise variation is shaped in the form of a smoothly varying Hicks-Henne function with the peak value at a specified chordwise location and blending into the baseline airfoil shape.

Two design variables were used to introduce twist perturbations. The first corresponds to a linear wing twist from the side of body to the wing tip. The second twist variable is active only over the outboard wing, and varies linearly from a value of zero at the break location to unit value at the wing tip.

In the traditional performance sizing methodology, engine size and wing area are the two quantities treated as design variables. In the MDO approach, DOSS treats the size of the engine as one of the design variables. Engine size was treated as a design variable to develop some of the processes for the PAC.

1.4 PAC Process Development:

Several process development activities were conducted as part of the work related to the PAC. These include work done on the Design Optimization Synthesis System, developing processes to compute higher fidelity sensitivity information based on CFD and FEM analyses, as well as developing processes to incorporate nonlinear aerodynamic effects into the aeroelastic loads that are used in structural sizing. Work done in these areas is summarized in the next few paragraphs.

1.4.1 Work on DOSS and its Extension:

Significant amount of work has been done in this area. The details of this work on DOSS are documented in two HSR reports published in February 1997 and November 1997.

- Basic working version of DOSS was demonstrated (Dec. 1996) and adequately documented (Feb. 1997).
- DOSS 1.0 was released with training to several HSR user groups, and applied to study various application problems within HSR.
- Several modifications and enhancements to increase the generality and user friendliness of the code have been included in DOSS 2.0 (completed in September 1997).
- Included the capability to read raw input data files in common HSR format agreed upon by the Sizing Code Calibration (SCC) team, and convert them into Response Surfaces for use in DOSS.
- Modified DOSS to include thickness and twist perturbations as design variables.
- Modified DOSS to read OEW changes due to thickness perturbations computed external to the parametric weights equation.

1.4.2 Aerodynamics Process:

A process to generate the change in aero performance drag polars due to modifications of the configuration has been developed. This information is needed to supplement the aero drag polar database for the baseline configuration during the sizing and optimization process. The goal for ACE is to include nonlinear aerodynamic effects in the sensitivity data used for the configuration optimization in DOSS. The aerodynamics process that has been developed utilizes a combination of linear theory analysis and selective CFD analyses to estimate the sensitivity data. Since CFD analyses tend to be resource intensive, the process depends on a correction factor technique to bring in the nonlinear effects through a limited use of CFD analyses combined with a response surface technique. Details of this process are documented in Sections 2.1 through 2.5.

1.4.3 FEM-based Weights Process:

Development of FEM-analysis based processes to estimate the change in Operating Empty Weight (OEW) due to changes in configuration has been pursued since early 1996. Three approaches based on different levels of simplifications in how the structure is represented in the model, and the type of approximations made during the structural sizing are being pursued. At the time of writing this report, the ELFINI based process has been validated against results for the TCA generated by the DITS ITD Team. A second process based on NASTRAN using plate element representation has been shown to match the full 3D model in several areas of comparison, however converged structural sizing has not been achieved. A third process based on the ELAPS plate formulation has been significantly enhanced for full configuration analysis, and is being validated against a full 3D model. Details of these approaches and validation data are documented in Sections 3.1 through 3.6.

1.4.4 Nonlinear Aeroelastic Loads Process:

Procedures have been developed to integrate data from CFD based nonlinear aerodynamic analyses into the aeroelastic loads process. A procedure using a correction factor technique has been developed and demonstrated by application to the MDC 2.4-7A configuration, and compared with other techniques to compute the nonlinear load distribution; this process is documented in Sections 4.4, 4.5 and 4.8. Efforts have also been made on developing an alternate approach that utilizes a direct coupling between CFD analysis and structural deflections using ENSAERO, and are documented in Section 4.6. Some work has also been done on issues related to the accuracy of CFD solutions at conditions corresponding to critical structural loading; this is documented in Section 4.7.

1.5 PAC Optimization Demo Studies:

Studies were done to demonstrate the simultaneous multivariable optimization capability of ACE by utilizing a combination of data for thickness perturbation design variables.

1.5.1. Input Aerodynamics Data:

The process for aero performance drag polar sensitivity was applied to compute the change in drag due to the individual thickness and twist perturbations. Since the aerodynamic effects are typically nonlinear, the process was also applied to the various combinations of these design variables resulting in a total of 48 combinations. The incremental drag was computed for all the combinations using linear potential flow analysis at Mach 2.4 and 1.1. At transonic cruise and lower Mach numbers, it was assumed that any increase in drag due to positive thickness perturbations can be fully compensated by adjusting the flap settings resulting in no net change in drag. A subset of 8 cases was identified for studies with nonlinear CFD Navier Stokes analysis. Results from these CFD studies were used to generate a response surface of nonlinear increments to the linear theory database. The data from linear theory analyses combined with the nonlinear increments (with appropriate interpolations) formed the total aero drag database for the studies.

1.5.2 Input Weights Data:

Since real data from structural analysis/design was not available, it was decided to use assumed dummy data for the weight changes as a way to demonstrate the overall optimization technique. Interestingly enough, we were able to do this because of the inherent feature of DOSS to use input data from different sources and of varying fidelity levels - back-of-the envelope, simple approximate analysis, or complex accurate analysis. These input data for changes in OEW will have to be replaced with other more credible data when they become available.

The demonstration of the optimization was done with three sets of assumed data as indicated in the table below. Set 1 assumes no change in OEW when thickness is changed - admittedly not realistic, but represents one extreme case. Sets 2 and 3 assumed some level of structural weight reduction due to the thickness perturbations. As an example, Set 2 assumes that there would be a reduction of 2000 lb. for a unit increase in thickness for Design Variables 1, 2 and 3.

Thickness Design Variable	Assumed ΔOEW - Set 1	Assumed ΔOEW - Set 2	Assumed ΔOEW - Set 3
#1 at 429-in peaks in-between spars	0	-2000 lb.	-3000 lb.
#2 at 525-in peaks in-between spars	0	-2000 lb.	-3000 lb.
#3 at 205-in peaks in-between spars	0	-2000 lb.	-3000 lb.
#4 at 275-in peaks at rear spar	0	-1000 lb.	-1500 lb.
#5 at 275-in peaks at front spar	0	-1000 lb.	-1500 lb.

No attempt was made even to guess any OEW sensitivity numbers for the effect of twist.

1.5.3 Optimization Demonstration:

The drag polar sensitivity data and the assumed OEW sensitivity data were provided as inputs to DOSS. The optimization studies were done for the TCA airplane with a fixed propulsion system. The optimization problem was set up to vary the five thickness perturbation design variables between -1.0 and +1.0, and the configuration sized for -5db cutback for minimizing the Take-Off Gross Weight (MTOW). Results obtained can be summarized as follows.

Case	Δt_1	Δt_2	Δt_3	Δt_4	Δt_5	MTOW	ΔMTOW
TCA - Base	0	0	0	0	0	789,439 lb.	0
Set 1 Data	-1.0	-1.0	-1.0	-1.0	-1.0	746,093 lb.	43,346 lb.
Set 2 Data	1.0	1.0	1.0	0	1.0	776,136 lb.	13,303 lb.
Set 3 Data	1.0	1.0	1.0	1.0	1.0	753,511 lb.	35,928 lb.

The baseline configuration was sized for -5db cutback at a MTOW of 789,439 lb.

When the ΔOEW due to thickness was set to zero (Set 1) corresponding to no OEW change associated with the thickness perturbations, the preferred solution was to decrease the thickness everywhere to the minimum permissible to take advantage of the benefits of drag reduction. This result is intuitively consistent with the input data. The TOGW for this configuration was lower by about 43000 lb.

When the data in Set 2 were used, the optimizer recommendation is to increase thickness everywhere except at perturbation #4. The resulting reduction in TOGW predicted is about 13,000 lb.

When the data in Set 3 were used (assuming larger OEW reduction for a unit thickness increase), the optimizer recommendation is to increase the thickness at all stations (including at #4). This combination reduces the TOGW by about 36,000 lb. relative to the baseline.

The results from Set 2 and 3 indicate that the optimization scheme is responsive to the input data. Also, depending upon the actual numbers for the OEW change due to the thickness perturbations, the potential for reduction in TOGW may be significant.

1.6 Lessons Learned and Conclusion:

The Aeroelastic Concept Engineering process for simultaneous optimization has been exercised to study a new set of design variables. Even though the data used for the OEW sensitivities are only assumptions, the demonstration exercise shows that the optimization mechanism is working in a manner consistent with engineering intuition. Also, this demonstration highlights the capability of the ACE process in general, and DOSS in particular, to accommodate variable fidelity input data.

As a continuation of this work, the sensitivity of OEW to thickness changes will be updated using a combination of data from simple strength analysis (within ACE) and the impact of thickness changes on flutter velocities (within DITS). The thickness optimization cases will be repeated with the new data. For the longer term, the impact of thickness perturbations on the OEW will be updated with the FEM-based analysis methods and additional design variables included in the optimization using appropriate sensitivity information. These studies are scheduled to culminate in the Optimized Aeroelastic Concept (June 1998).

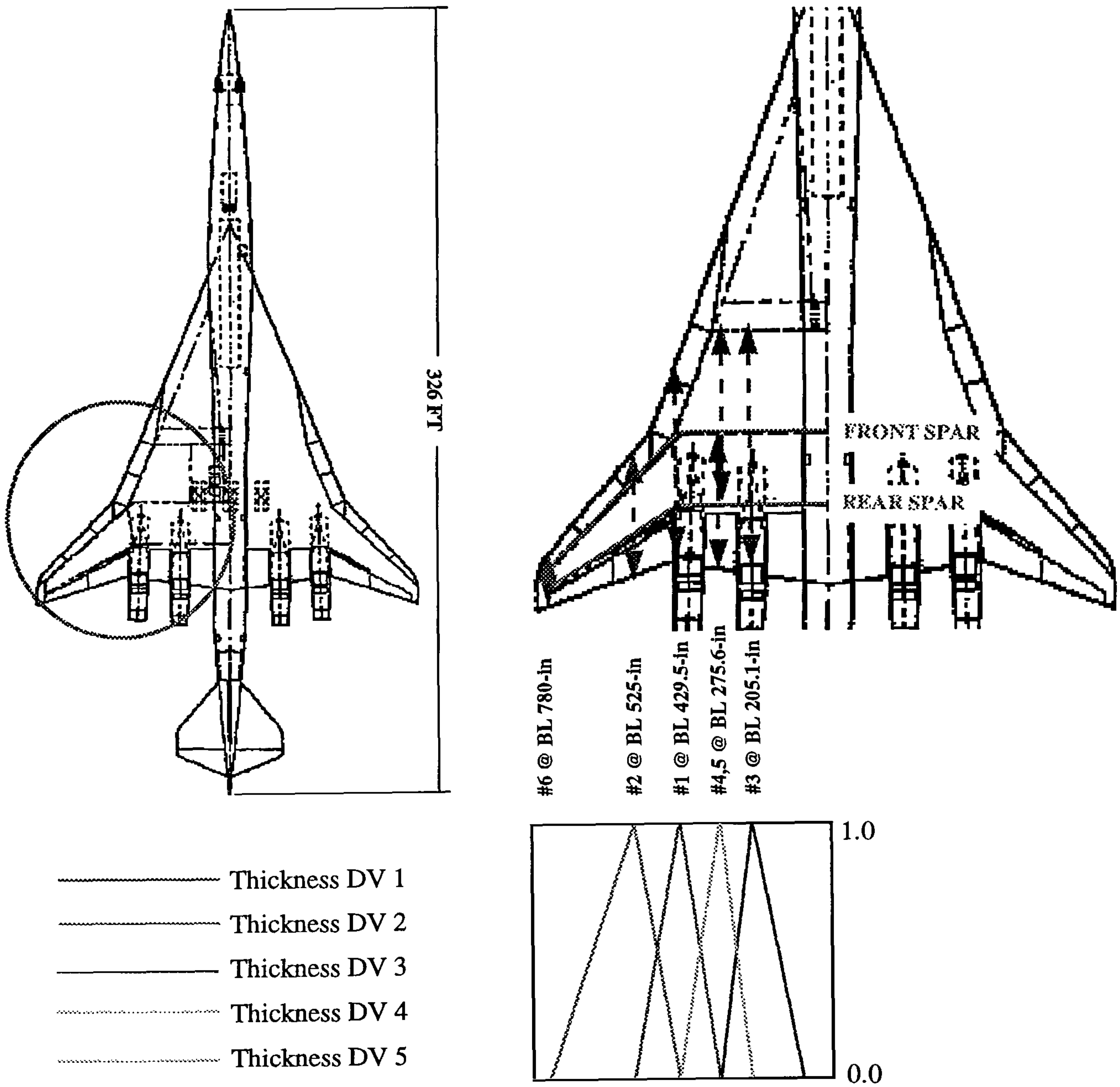

Figure 1. Thickness perturbation design variables for the Preliminary Aeroelastic Concept