JOURNAL OF AIRCRAFT
Vol. 37, No. 5, September–October 2000

Variable Stiffness Spar Approach for Aircraft Maneuver Enhancement Using ASTROS

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An innovative variable stiffness spar (VSS) approach is studied for improving aircraft roll performance. In this concept some of the existing wing spars are replaced by the adaptive-structure VSS to control the stiffness as a function of Mach number and altitude. The VSS stiffness scheduling is designed to maximize the roll rate while satisfying flutter, control surface hinge moment, and maximum deflection constraints. The VSS mechanism consists of a segmented spar having articulated joints at the connections with wing ribs and an electrical actuator capable of rotating the spar. The wing stiffness provided by the spar varies sinusoidally as a function of the rotation angle. The objective of the present study is to explore when and how to best apply this concept and assess its payoffs in terms of performance gains. The F/A-18 pre-roll-modification aircraft was selected as the baseline aircraft for its low torsional wing stiffness and available flight data. The multidisciplinary design optimization software ASTROS* was used for performing the analyses in the Mach number range of M = 0.8–1.2 at altitudes up to 35,000 ft (40,668 m). Results show that VSS can amplify the aeroelastic forces and significantly enhance roll performance of aircraft.

Introduction

MODERN fighter and military aircraft are required to achieve high maneuverability, agility, and stealth under wide ranges of critical flight conditions. The design goal tends to arrive at more flexible aircraft with optimum application of the control systems. This goal can be better achieved with multidisciplinary optimization (MDO) procedures, digital flight control systems, and adaptive-structure technologies. These technologies can aeroelastically manipulate aerodynamic loads and yield favorable static/dynamic responses of an aircraft to achieve the required maneuver performance, while improving the drag polar and reducing the structural weight.

During the 1980s, Rockwell (now Boeing/Rockwell) pioneered and advanced one such concept, the active flexible wing (AFW) concept.[1] This innovative concept exploited the aeroelastic effects, rather than fighting them, to provide weight savings and improved aerodynamics. The AFW concept, later supported by Wright Laboratory and NASA/Langley, was further used to exploit the wing flexibility with active leading and trailing-edge control surfaces, up to and beyond reversal, to provide high-performance roll rates without using the horizontal tails.[2,3] In so doing, the AFW control surfaces are used as tabs that trigger the wing twist into a wing lift reversal. In this way the airstream energy, measured in terms of dynamic pressure q, is diverted to twist the wing with lessened control surface motion.

Deadband and Postreversal

There is a certain q range between the prereversal and postreversal ranges, where the control surface becomes ineffective. This region is called the deadband region.[4] The significance of deadband and postreversal can be elucidated by a two-dimensional typical section study. Consider a NACA 0012 airfoil with a 10% flap, which is supported by a torsional spring at x_{EA} with stiffness K_θ (Fig. 1).

The aerodynamic lift CL and pitching moment CM vs the flap deflection δ_e are computed by a two-dimensional code.[5] The airfoil rotation angle θ can be related to δ_e by the linear aeroelastic equation

$$\left(\bar{K} - C_{m_\theta}\right)\theta = C_{m_{\delta_e}}\delta_e \tag{1}$$

where $\bar{K}$ is the nondimensional torsional stiffness parameter, defined as $\bar{K} = K_\theta / qc^2$. Clearly, $\bar{K}$ is a significant physical parameter that measures the reversal capability of an aeroelastic system. The total lift C_L is computed according to the following equation:

$$C_L = C_{L_\theta}\theta + C_{L_{\delta_e}}\delta_e \tag{2}$$

The deadband region shown in Fig. 2 is confined by the shaded area with the $\bar{K}_{\mathrm{rev}}$ line at the center. The lift changes sign at the $\bar{K}_{\mathrm{rev}}$ ($\bar{K}$ reversal) point, which divides the pre- and postreversal regions. The $\bar{K}$ region associated with negative C_L is the postreversal to the left of $\bar{K}_{\mathrm{rev}}$. Figure 2 also shows that the position of the deadband and the applicable postreversal region are very sensitive to the elastic axis location. Because the sectional torsional stiffness K_θ, the elastic axis x_{EA}, and the chord length c vary along the span of a tapered three-dimensional wing, the sectional deadband characteristics change

Received 31 January 1999; presented as Paper 99-1471 at the AIAA/ASME/ASCE/AHS/ASC 40th Structures, Structural Dynamics, and Materials Conference and Exhibit, St. Lois, MO, 12–15 April 1999; revision received 10 January 2000; accepted for publication 12 January 2000.

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accordingly. By manipulating the different sectional deadband characteristics, the AFW overcomes the deadband with multiple leading- and trailing-edge control surfaces through a digital flight control system.

Variable Stiffness Spar(s)

In this study an adaptive-structural concept called variable stiffness spar(s) (VSS) is used. The VSS controls wing torsional stiffness to enhance vehicle performance in the complete flight envelope. VSS can also provide time-varying stiffness for active dynamic load control. In essence, the VSS concept could be considered as the next logical evolution of AFW. In the AFW concept the control surfaces are varied, but the structural stiffness is fixed, whereas in the VSS concept the structural stiffness is varied, too. Thus, VSS has all of the benefits of AFW and further amplifies postreversal aerodynamic forces to enhance maneuver.

Inspired by the AFW concept of Miller,[1] Griffin and Hopkins proposed use of smart stiffness spars in a discretized (or bang-bang control) manner for stiffness control. Recently, their concept[4] has materialized into an ingenious VSS mechanism. Moreover, the discretized stiffness control concept has been improved to a continuous VSS mechanism (Griffin, K. E., private communication, Southwest Research Institute, San Antonio, TX, Aug. 1998). Figure 3a shows the actual mechanism built, whereas Fig. 3b presents its schematic diagram. The mechanism consists of a segmented spar having articulated joints at the connections with wing ribs and an electrical actuator capable of rotating the spar through the 90-deg angle. When the orientation of the joints are horizontal, the segments are essentially uncoupled, and the spar offers no bending resistance. As the spar is rotated, the segments join and provide a larger amount of stiffness. In the vertical orientation of the joints, the segments are completely continuous, and the spar attains its maximum stiffness. The VSS mechanism replaces the shear web of the existing spar, and it is completely contained within the wing. The spar caps of the original spar now only offer local stability to the wing box. Although this VSS mechanism is not yet formally released, the VSS concept can be readily adopted and analytically modeled for software design/analysis. Other than its low power and weight requirements, the continuous (or time-varying) VSS mechanism can dial in for a set stiffness. This then allows for the temporal adjustment of the stiffness according to the local q range during maneuver, unlike other approaches[6,7] wherein the basic wing stiffness remains unaltered. It suggests that the VSS concept can be potentially utilized for postreversal control.

To present the adaptive-structure strategy in employing the VSS concept, consider a baseline wing with low torsional stiffness represented by K_{Base}. A newly designed wing is one that modifies the baseline wing with some of its spars replaced by VSS. Thus, the torsional stiffness K_θ of the present newly designed wing can be expressed as

$$K_\theta = K_{\mathrm{fix}} + K_{\mathrm{VSS}}(M, q) \tag{3}$$

where K_{fix} is the stiffness of the newly designed wing with the modified VSS part nullified. Bounded by the maximum and minimum of K_{VSS} ($K_{\mathrm{VSS_{max}}}$ and $K_{\mathrm{VSS_{min}}}$), $K_{\mathrm{VSS}}(M, q)$ is the added VSS stiffness, which is generally a function of M and dynamic pressure q, or the (M, q) pair. The normalized torsion stiffness parameter $\bar{K}$ for the newly designed wing reads

$$\bar{K} = K_\theta/(qc^2) = (K_{\mathrm{fix}} + K_{\mathrm{VSS}})/(qc^2) \tag{4}$$

Now the adaptive-structure strategy is to vary the wing stiffness such that its aileron and trailing-edge flap (TEF) can operate in the postreversal region. Thus, $\bar{K} < \bar{K}_{\mathrm{rev}}$ during maneuver. The preceding analysis also suggests that the K_{fix} of the newly designed wing should be designed sufficiently low so that it will allow an ample range for VSS to apply postreversal control. The previous two-dimensional study in principle supports the achieveability of postreversal in q ranges, where $\bar{K} < \bar{K}_{\mathrm{rev}}$. But in practice this may not be possible as the wing structure can fail because of wing flutter or strength requirements. To search for the lowest possible $\bar{K}$ requires a MDO methodology to thoroughly explore the complete flight envelope.

F/A-18 VSS

To perform the feasibility study on the VSS concept, an earlier prototype version of the F/A-18 (called the F/A-18 pre-roll-modification or F/A-18 PRM) is selected for two reasons:

1) F/A-18 PRM has a relatively low torsional wing stiffness. Current production F/A-18 includes the modifications of wing stiffness by beefing up the wing structure with 150 lb (68 kg) each. The stiffness of F/A-18 PRM is represented by K_{Base}.

2) Flight-test data of F/A-18 PRM are available.

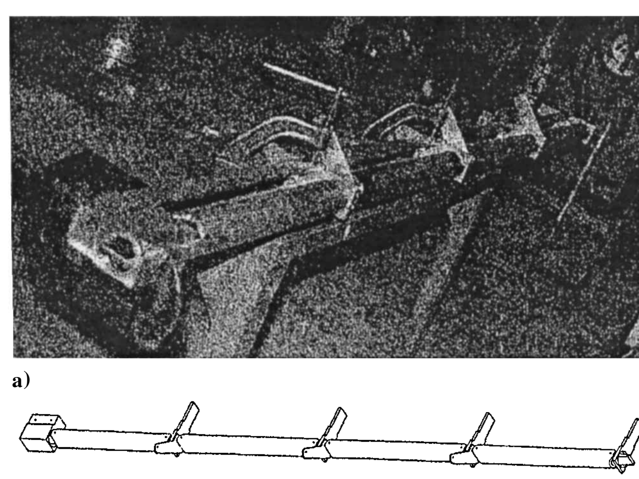
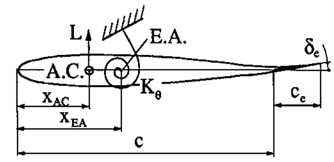


Fig. 3 VSS mechanism.

Fig. 1 Typical airfoil section.



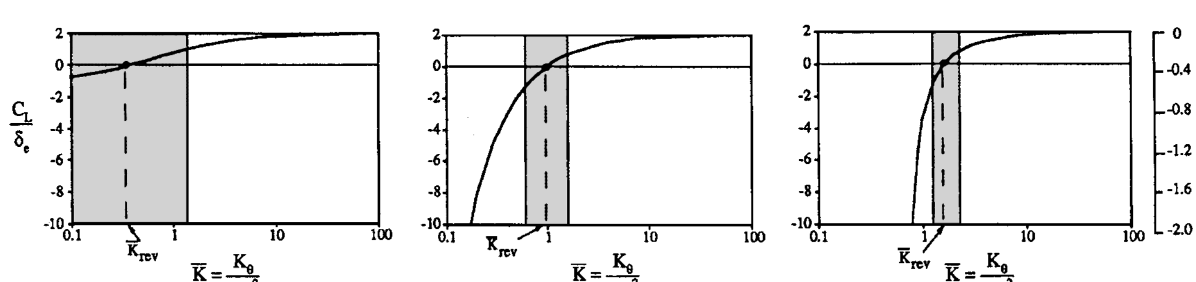


Fig. 2 Lift per flap deflection angle vs normalized torsional stiffness showing shaded deadband and applicable postreversal region [X_{EA} = a) 0.15c, b) 0.25c, and c) 0.35c].

The newly designed aircraft, the F/A-18 PRM with VSS modification, is now called F/A-18 VSS. The wing planform of F/A-18 VSS with leading-edge and trailing-edge control surfaces used for roll and the finite element model (FEM) with two darkened spars representing VSS is shown in Fig. 4.

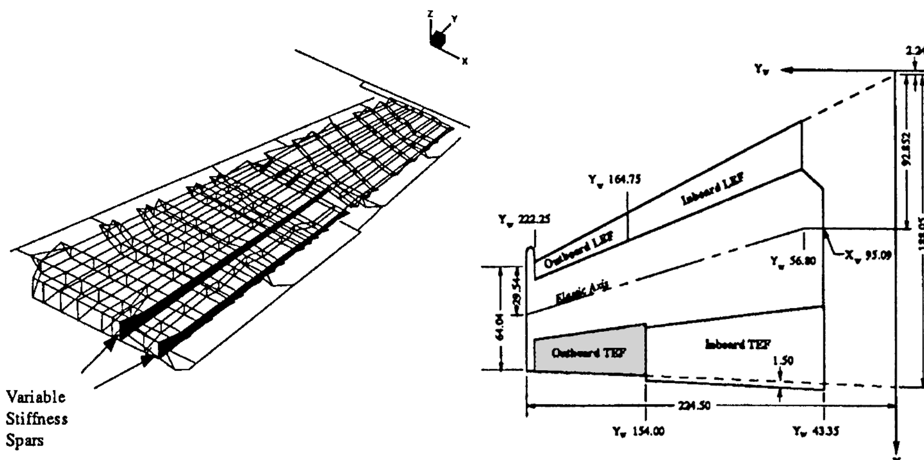
MDO Methodology ASTROS*

The success of the proposed adaptive strategy applied to the present F/A-18 VSS relies on its wing control surface system to achieve the following: optimal design of the VSS stiffness scheduling in terms of M, q for max roll rate; ensure no occurrence of dynamic instability or flutter (with adequate margins of safety); and satisfy the strength requirement at critical maneuver load conditions. Clearly, the preceding stringent requirements call for an MDO software with an embedded accurate aerodynamic module covering the required Mach-number range. In this regard ASTROS* appears to be the only such MDO software with the needed capability.[8–11]

ASTROS (Automated STRuctural Optimization System) is a proven engineering design/analysis software that includes most of the disciplines that impact a structural design. ASTROS* is the enhanced version of ASTROS that is seamlessly integrated with a Unified Aerodynamic Module (ZAERO).[12–15] The integration of a comprehensive aeroservoelastic module with ASTROS* was completed leading to ASTROServo*. With these enhancements ASTROS* can be considered as a unique tool to perform the feasibility study on the proposed adaptive-structure concept through F/A-18 VSS.

Overall Design Strategy

An overall design strategy is formulated for the F/A-18 VSS design. This strategy consists of three design loops (Fig. 5). The outer



FEM Model of the F-18/VSS Wing **F-18/VSS Planform with Dimensions**

Fig. 4 F/A-18 VSS wing planform and FEM model.

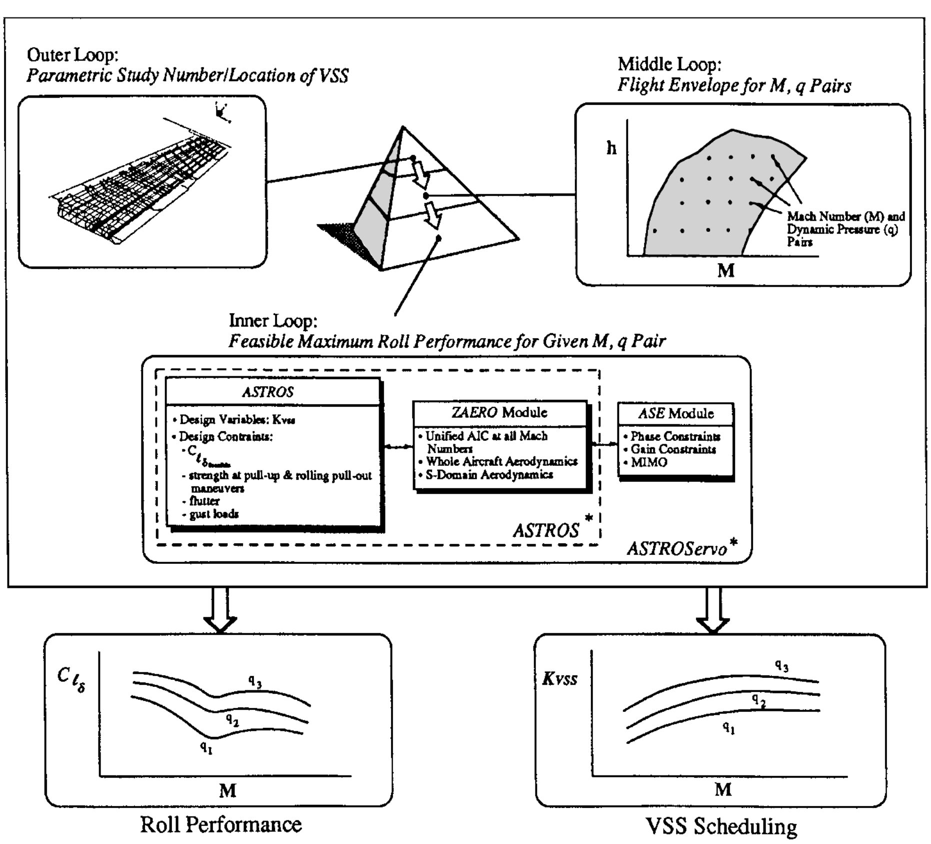


Fig. 5 Overall design strategy.

loop is created for a parametric study, where numbers and location of VSS are selected.

The middle loop defines the assigned (M, q) pairs throughout the flight envelope to establish the VSS scheduling. The inner loop searches for the so-called feasible maximum roll moment for maneuver at each (M, q) pair. The final goal of the overall strategy is aimed at achieving an optimized VSS scheduling for a viable F/A-18 VSS structural design.

Objectives

The objectives of this study were to develop an innovative adaptive structural concept that fully utilizes the wing flexibility by means of a VSS mechanism to enhance maneuverability (roll maneuver) of the existing F/A-18 PRM aircraft. We used ASTROS* (an MDO software comprised of ASTROS and the ZAERO module) as a design/analysis software tool. The essential objectives of the study were to 1) explore when/how to best apply F/A-18 VSS concept for roll maneuver enhancement; 2) develop VSS stiffness scheduling for postreversal control; 3) decide what must satisfy the strength, flutter, and control surface hinge moment constraints; and 4) assess VSS design payoffs.

Baseline Model (F/A-18 PRM)

The F/A-18 PRM was selected as the baseline aircraft, as discussed earlier. The NASTRAN model of this aircraft was obtained from the Airforce Flight Research Laboratory, which was used to define the ASTROS* model. Figure 6 presents a comparison of the natural frequency and mode shapes for two typical modes (4 and 6) obtained from NASTRAN and ASTROS* models. The two structural models produce nearly identical results, which validate the ASTROS* model.

The aerodynamic model for ZAERO computations is shown in Fig. 7. NASTRAN and ASTROS* computations of the (flexible) roll control power ($C_{l\delta_a}$) at $M = 0.7$–1.3 show excellent agreement (Fig. 7). Having validated the ASTROS* structural and aerodynamic models of F/A-18 PRM, the roll rate for the baseline aircraft was computed at $M = 0.8$–1.2 (altitude = 0–35,000 ft (0–10,668 m)). The F/A-18 aircraft is required to have the roll rate of 120 deg/s or more at the transonic Mach numbers (Yurkovich, R. N., private communication, The Boeing Company, St. Louis, MO, Dec. 1998). However, the control surface deflection is constrained by the actuator capacity for aileron and TEF (50,000 and 130,000 in lb (5,649 and 14,688 Nm), respectively). The leading-edge flap deflection is limited to 5 deg. Also, the horizontal tail is not used for roll in the current study, unlike the F/A-18 aircraft in service. Table 1 shows that the F/A-18/PRM does not meet the roll-rate requirement in transonic flight.

F/A-18 VSS Approaches

To demonstrate the potential of the VSS concept, it is applied to enhance the roll maneuver performance of F/A-18 PRM. The wing stiffness is controlled (increased or reduced within a certain range)

Table 1 ASTROS* results (roll rate, deg/s)

Altitude, kft	Mach number						
35	770	723	631	632	139	153	183
25	597	551	483	370	79	136	171
15	418	340	268	186	88	192	213
5	243	187	134	78	215	361	332
0	166	120	89	99	312	478	412
——	0.80	0.85	0.90	0.95	1.05	1.10	1.20

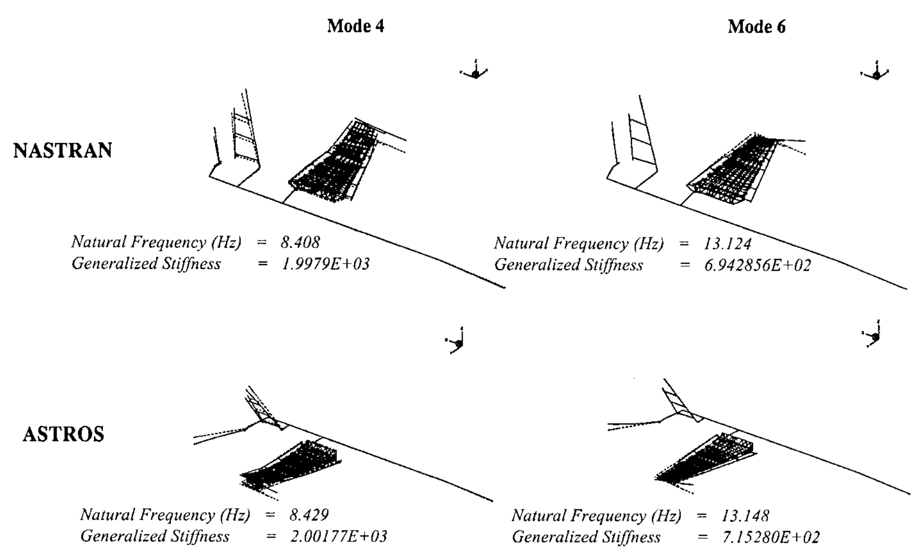


Fig. 6 Comparison of NASTRAN and ASTROS* structural models.

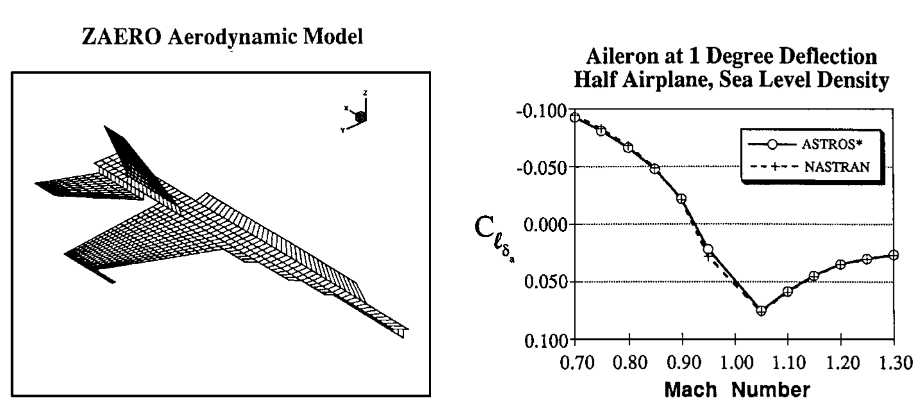


Fig. 7 Comparison of NASTRAN and ASTROS roll control powers.

as per the optimized schedule as a function of the flight condition (M, q). Two VSS designs are adopted for the reasons discussed next.

In the single VSS design the wing stiffness is controlled through a single spar with variable stiffness. As such, single VSS is a perturbation from the baseline F/A-18 PRM and hence can be retrofitted. In this case the F/A-18 PRM flight-test data can be used for validation with the VSS stiffness equal to the baseline value. Also, the future wind-tunnel test program can include tests of the F/A-18 PRM along with the VSS. To select the most suitable spar for the single VSS design, the sensitivity of each spar stiffness on roll rate was determined using the validated ASTROS* model. Figure 8 shows the roll-rate sensitivity (roll rate with minimum stiffness—roll rate of baseline aircraft) for each spar at $M = 0.90$ as a function of the dynamic pressure (altitude). The observation is made that the first and the sixth spars have much larger effect on the roll rate compared to other spars. The sixth spar, which shows the maximum roll-rate sensitivity, is selected as the variable stiffness spar, and other spars remain unaltered. The single VSS design is shown schematically in Fig. 9.

Any change in wing stiffness influences its flutter speed. Particular care has to be exercised to satisfy the flutter margin requirement (i.e., flutter speed should be at least 15% above the air speed) when reducing wing stiffness. The flutter speed was calculated at $M = 0.85$–1.20 using ASTROS* with the minimum stiffness (10% of baseline value) for the single VSS design. The calculated flutter speed was corrected based on the correlation established by Boeing, St. Louis, MO, between NASTRAN results and flight data of F/A-18 aircraft.[14] Even with the minimum wing stiffness, sufficient flutter margin is available throughout the Mach-number range, as shown by the difference between the flutter speed and the design speed in Fig. 10.

In another approach the torsion-free wing concept is used to exploit fully the benefits of the VSS design. In this approach, called VSS/torsion-free (VSS/TF), the wing bending moment is mostly carried by two very strong and stiff spars, which are closely spaced. The other spar stiffnesses are reduced to produce a wing with very low torsional stiffness. This design amplifies the aeroelastic effects (in the postreversal region) and thereby enhances roll performance. Also, additional lift generation by aeroelastic wing twist can be used to reduce the fuselage drag through decreased aircraft angle of attack. Because the first and the sixth spars have much larger roll-rate sensitivity compared to other spars (Fig. 8), these two are selected as VSS. To decide on the non-VSS spars with increased stiffness, flutter sensitivity was established for each of those spars using ASTROS*. Figure 11 presents the flutter speed at $M = 0.95$ with the increased stiffness for one of the spars (other spar stiffnesses remain at the baseline value). Largest flutter speeds are obtained with increased stiffnesses for spars 3 and 4, which are designated non-VSS. To complete the torsion-free wing concept, the remaining two spars, i.e., spars 2 and 5, are removed. Figure 12 shows the VSS/TF design schematically.

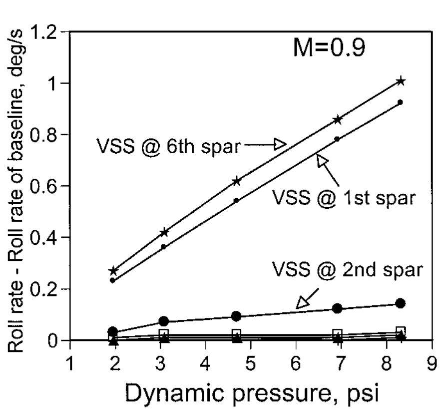


Fig. 8 Roll-rate sensitivity.

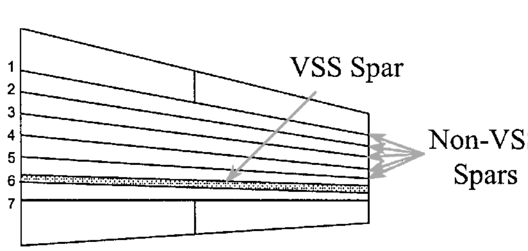


Fig. 9 Single VSS design.

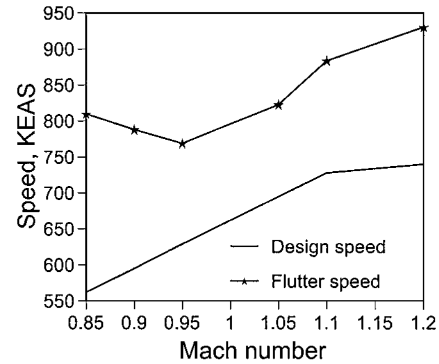


Fig. 10 Flutter speed for single VSS.

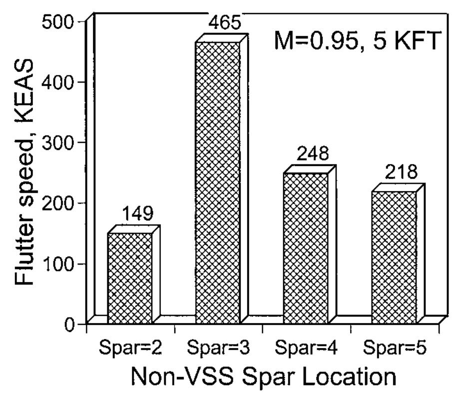


Fig. 11 Effect of non-VSS spar location on flutter speed.

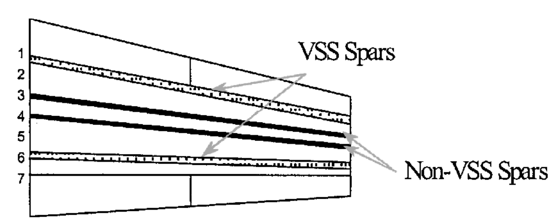


Fig. 12 VSS/torsion-free design.

F/A-18 VSS Optimization

The F/A-18 PRM does not meet the roll-rate requirements at transonic Mach numbers, as noted earlier (see Table 1). Two VSS approaches, already discussed, are proposed to enhance the roll performance. Further studies focus on those five flight conditions (M, q pairs) with roll-rate deficiency.

The F/A-18 roll-rate requirement and physical constraints of the four control surfaces can be formulated as a well-defined optimization problem. The requirement of 120 deg/s roll rate in the whole flight envelope leads to the following objective function formulation:

$$f = (120/\text{roll rate})^2 \qquad (5)$$

Minimization of f leads to the maximum possible roll rate, and squaring the ratio ensures positive sign of the objective function. There are five design variables for this optimization problem, namely, VSS stiffness and the deflection angles for aileron, TEF, inboard leading-edge flap (LEF(IB)), and outboard leading-edge flap

(LEF(OB)). VSS stiffness is treated as a single design variable even for the torsion-free approach (i.e., the variable stiffness is identical for the first and the sixth spars). The aileron and the TEF deflections are limited by the capacity of their actuators (50,000 and 130,000 in lb, respectively). Accordingly, the constraints are formulated as follows:

$$g_1 = \left(\frac{\text{Ail HM}}{50{,}000}\right)^2 - 1.0 \tag{6}$$

$$g_2 = \left(\frac{\text{TEF HM}}{130{,}000}\right)^2 - 1.0 \tag{7}$$

The flutter margin is always satisfied by the single VSS design (Fig. 10), but for the VSS/TF case it forms an important consideration. The third constraint function defines the flutter speed requirement as follows:

$$g_3 = \left(\frac{1.15^*\text{Air speed}}{\text{Flutter speed}}\right) - 1.0 \tag{8}$$

The leading-edge flaps are restricted to the maximum/minimum deflection of ±5 deg, which are expressed as side constraints:

$$-5\text{ deg} < \text{LEF(IB)} < 5\text{ deg} \tag{9}$$

$$-5\text{ deg} < \text{LEF(OB)} < 5\text{ deg} \tag{10}$$

To evaluate the objective function and the constraints for optimization, an extensive database was generated through ASTROS* analysis. The database includes roll rate for variable spar stiffness values ranging from nearly zero to five times the baseline stiffness, with the four control surfaces deflected separately by 1 deg each. Because the structural and the aerodynamic analyses use linear methods, roll rate for any control surface deflections can be obtained through a linear combination. Figures 13 and 14 present the roll-rate database at $M = 0.95$ (sea level) for single VSS and VSS/TF cases, respectively. As expected, VSS/TF generates much larger roll rate than single VSS at low stiffness values.

Similar to the roll-rate database, aileron and TEF hinge moment data were also generated to evaluate constraints during optimization. The hinge moments are insensitive to VSS stiffness (Fig. 15); therefore, the database is independent of the stiffness value. The hinge moment database (at sea level) is presented in Figs. 16 and 17 for aileron and TEF, respectively. Both aileron and TEF hinge moments increase by about 70% from $M = 0.9$ to 1.05. The TEF experiences much larger moments compared to the aileron because of its larger area and location (and, therefore, it has more powerful actuator). Because of aerodynamic interactions, the control surfaces induce hinge moments on each other. The observation is made that the induced hinge moment is up to 25% at certain flight conditions.

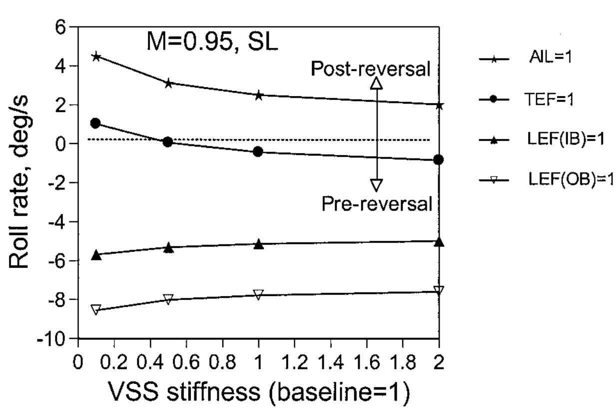


Fig. 13 Roll-rate database for single VSS (M = 0.95, sea level).

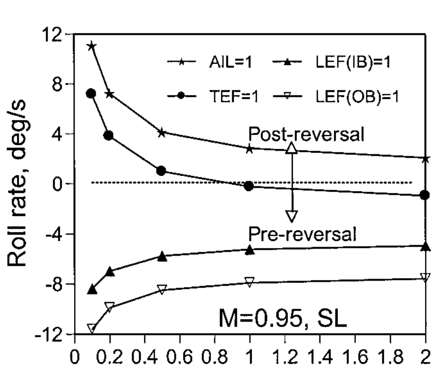


Fig. 14 Roll-rate database for VSS/TF (M = 0.95, sea level).

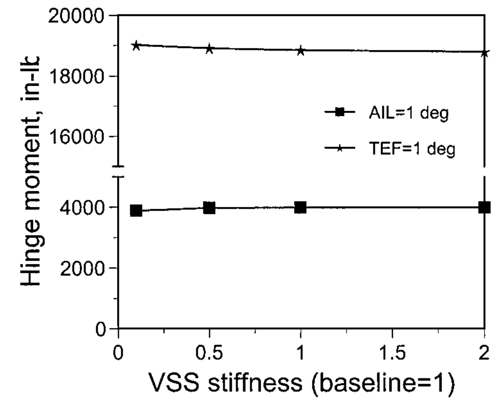


Fig. 15 Hinge moment variation with VSS stiffness (M = 0.90, sea level).

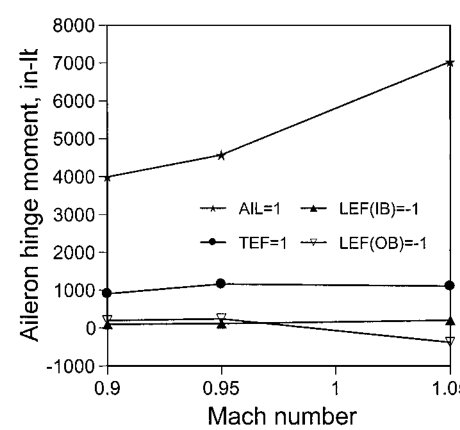


Fig. 16 Aileron hinge moment database.

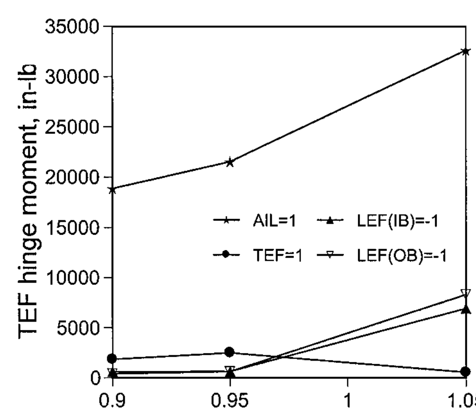


Fig. 17 TEF hinge moment database.

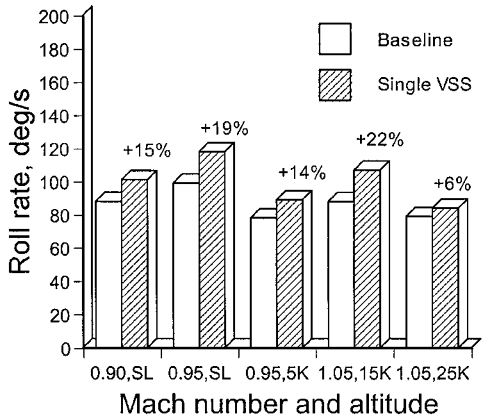


Fig. 18 Single VSS optimization results.

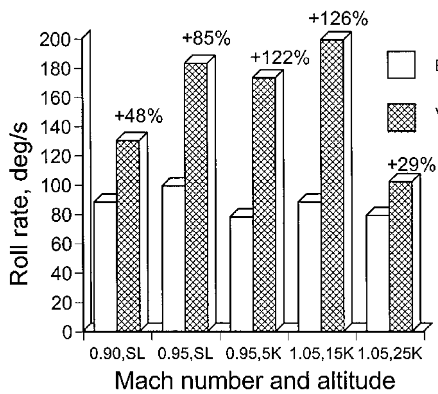


Fig. 19 VSS/TF optimization results.

The databases just mentioned (roll rates and hinge moments) were used to perform a constrained optimization[16] for single VSS and VSS/TF (Figs. 18 and 19). For the single VSS design the roll rates improve by 6–22% at the five critical flight conditions identified earlier. The hinge moment constraints for aileron and TEF are active, and the leading-edge flaps are fully deflected for the optimum roll rates. As mentioned earlier, flutter margin is always satisfied for the single VSS case, making the flutter constraint inactive. The optimum VSS stiffness is 10% of baseline value at $M = 0.95$, sea level and $M = 1.05$, 15,000 ft (4,572 m). At the other three flight conditions wing with stiffness equal to five times the baseline value yields the maximum roll rates.

With the VSS/TF design the increase in roll rates (29–126%) is much larger than the single VSS case. The roll-rate requirement of 120 deg/s is satisfied at all flight conditions, except $M = 1.05$, 25,000 ft (7,620 m) altitude where 102 deg/s is achieved. At several flight conditions the roll rate exceeds the requirement by a large margin. The optimum VSS stiffness ranges from 1 to 25% of the baseline value.

Conclusions

An innovative VSS approach for the enhancement of aircraft roll performance has been investigated. The F/A-18 PRM aircraft is used as the baseline aircraft for its low torsional wing stiffness and available flight data. The MDO software ASTROS* was used for performing the analyses in the range of $M = 0.8$–1.2 at sea level to 35,000 ft (10,668 m) altitude. The observation was made that the baseline aircraft does not meet the roll-rate requirement of 120 deg/s at certain critical transonic flight conditions. Two VSS wing design approaches, namely, single VSS and VSS/TF, have been investigated. The VSS stiffness scheduling is designed to maximize the roll rate while satisfying flutter, control surface hinge moment, and maximum deflection constraints. Based on the present study, the following important observations are made:

1) VSS can further amplify the aeroelastic forces and significantly enhance roll performance: a) 6–22% roll-rate improvement by single VSS approach and b) 29–126% roll-rate improvement by VSS/TF approach.

2) ASTROS* is an ideal tool for present study: rapid VSS sensitivity analysis by ZAERO aerodynamic database.

3) Multiple static aeroelastic and flutter constraints are at subsonic, transonic, and supersonic Mach numbers.

Acknowledgment

The authors acknowledge the support of this work by U.S. Air Force Research Laboratory through Contract No. F33615-98-C-3204 with technical monitors Ed Pendleton and Pete Flick.

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