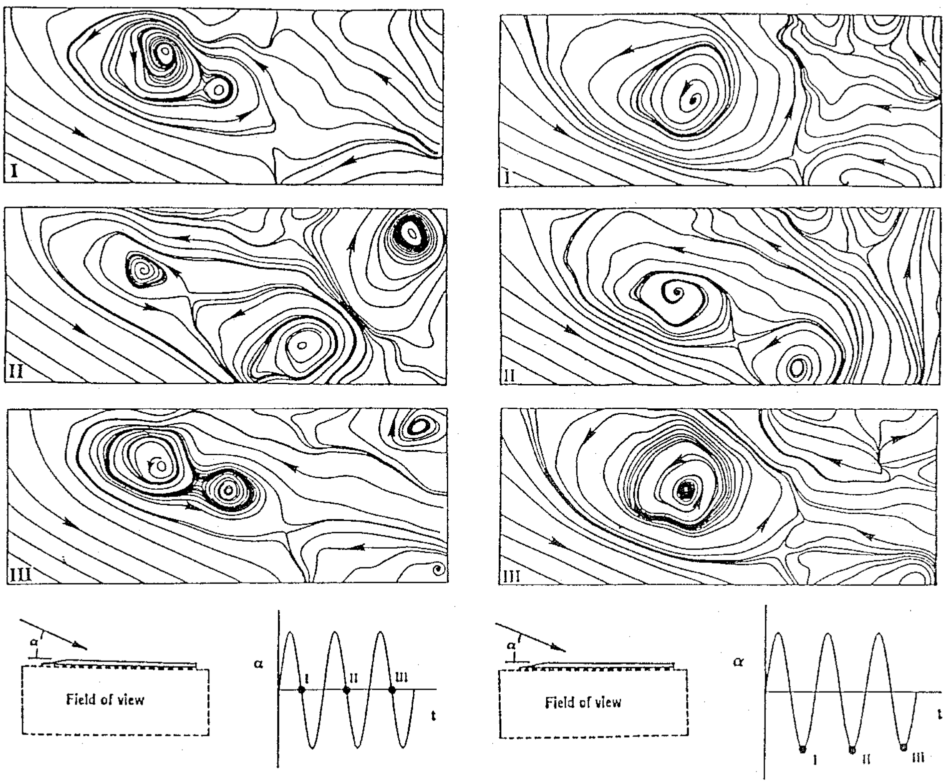


**Fig. 5 Instantaneous streamline patterns for phase-locked response of flow structure on a 45-deg delta wing at $\alpha = 30$ deg, $\Delta\alpha = 5$ deg, $\bar{\omega} = 2\pi$ (Ref. 1).**

$\bar{\omega}$, and for full realization of the dynamic camber effect $\bar{\omega} < \omega\Delta t_c < 2\bar{\omega}$. That is, for $\bar{\omega} = \pi$, $\omega\Delta t_c < 2\pi$, so that every cycle of the oscillation in Fig. 2 starts out fresh, whereas $\omega\Delta t_c > 2\pi$ for $\bar{\omega} = 2\pi$, causing remnants of the dynamic camber effect to be present from the previous cycle (Fig. 5). As a consequence, the vortex pattern repeats every other cycle, not every cycle as in Fig. 2 for $\bar{\omega} = \pi$.

## Conclusions

An analysis of recent high-rate pitch–oscillation tests with a 45-deg delta wing has shown that the use of an earlier developed time-lagged DES flow methodology is very helpful when trying to reach an understanding of the flow physics, even in cases where the pitch–oscillation frequency is extremely high, $\bar{\omega} > \pi/2$, where time–history effects cannot be approximated by the effect of a single, constant time lag.

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# Smart Stiffness for Improved Roll Control

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## I. Introduction

THE application of smart structures technology offers some intriguing possibilities for high-performance aircraft. For

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example, the ability to prescribe both static and dynamic shapes of lifting surfaces to enhance their lift production and drag reduction qualities has been recognized for years.[1] These opportunities must be balanced with concerns for how much weight must be added to mechanize the shape-changing techniques and how much added power, usually electrical, is required to manipulate significantly sized lifting surfaces. These concerns prompted this investigation to look for opportunities to employ objectives of the adaptive structures area in smart structures for the controlled improvement in lifting surface structures. These improvements show the potential for low-power requirements and little added mass.

The improvement chosen for investigation here is aircraft roll control. This focus was inspired by the Active Flexible Wing (AFW) work of Miller.[2] However, a fundamentally different approach in active flexible wings is employed here for aircraft roll. A new adaptive structures strategy is described in this Note, where the structural stiffness of the primary structure is changed or adapted as a function of flight dynamic pressure $q$. This stiffness change is effected to take advantage of post-reversal aileron control of a single outboard trailing-edge control surface for roll control. This is in contrast to the present AFW practice of using a fixed wing stiffness and multiple leading- and trailing-edge control surfaces to provide optimum roll throughout the aircraft flight envelope.

## II. Control Concept

The control effector concept chosen for this investigation is based on the observed characteristics of lifting surfaces and their aircraft. Significant control forces are required for attitude changes of aircraft. The primary method to create additional aerodynamic forces on lifting surfaces is to place those surfaces at an angle of attack (AOA) with respect to the freestream.[3] These attitude changes usually are brought about by deploying the leading- and/or trailing-edge flaps.

The desirable control effector traits sought in this adaptive structure investigation are low-power requirements of the controller and low weight. The concept chosen here for a low-power control effector exploits aileron use in a postreversal mode; that is, postreversal aileron aeroelasticity designed to produce large aircraft roll forces. The force amplification created by the aeroelasticity of a small trailing-edge control surface used at flight $q$ above its reversal dynamic pressure is appealing. This aeroelasticity provides the desired low-power controller.

The aircraft rolling moment about the aircraft centerline is the metric used to track and optimize this reversed aerodynamic control effector. $M_{\text{roll,flex}}$ is the rolling moment created by a unit aileron deflection of an aileron on a wing that is allowed to deform aeroelastically. Likewise, $M_{\text{roll,rigid}}$ is the rolling moment created by a unit aileron deflection of an aileron on a rigid wing. The flexible-to-rigid ratio of these moments

$$FR_{\text{roll}} = (M_{\text{roll,flex}})/(M_{\text{roll,rigid}})$$

can be used to represent the aeroelastic amplification available to roll control. From takeoff up to the aileron reversal flight dynamic pressure $q_{\text{rev}}$, $FR_{\text{roll}}$ has a positive value that decreases to zero. Above $q_{\text{rev}}$, it increases again in absolute value, but opposite in sign. Note that as $q$ continues to increase, the rolling power of the control effector comes primarily from the elastic shape of the wing, not the aileron.

## III. Adaptive Structure

An adaptive structure strategy is needed to make this single flap control effector useful over the entire flight envelope. While the utility of postreversal control has been well documented[4] once the aircraft is operated significantly above $q_{\text{rev}}$, there is an important $q$ range around $q_{\text{rev}}$ of the trailing-edge aileron where the aileron is nearly useless. This significant region of deadband dynamic pressures is seen in studies of Ref. 2. The adaptive structures challenge is to remove that loss of control authority.

The approach is to adapt the stiffness of the lifting surface structure to that needed to maintain control authority. This adaptive stiffness, identified here as smart stiffness, must maintain adequate strength and avoid instabilities such as flutter and divergence. The smart stiffness strategy is to provide adequate stiffness for the aileron to perform its control function in a normal prereversal manner until adequate flight $q$ is achieved by the aircraft for postreversal control. Once adequate flight $q$ is available, the stiffness is changed so that the lifting surface can now operate in a postreversal fashion. The pilot provides the aileron control input and the flight-control system applies the appropriate sign and amplitude to supply consistent roll control.

The value of this approach is lost if the stiffness change technique requires a large amount of control power and/or considerable additional structural weight to effect the stiffness change. Thus, the stiffness change must not require a large additional force to the wing structure, which when combined with the existing forces makes the stiffness appear less. Rather the stiffness change must be a change in the structural spring of the lifting surface structure. This change needs to be made using a small additional force in such a way that some of the stiffness is uncoupled when low stiffness is selected.

## IV. Fighter Wing Example Case

To illustrate the concept of smart stiffness for lifting surfaces, a contemporary fighter wing is used to examine a conventional aircraft planform in which high $q$ roll performance is desired. The adaptive structures strategy is to change or adapt the stiffness of the wing box to allow the aileron to switch to its more desirable postreversal operational mode once sufficient flight $q$ is available, typically before transonic maneuvering.

The planform view of the aircraft depicting the steady aerodynamic idealization is shown in Fig. 1. To roll the aircraft, for this study, a very small outboard trailing-edge flap is assumed and only the most outboard trailing-edge box of the static aerodynamics is allowed to act as an aileron. This is an overly restrictive example since the actual aileron would be sized up to provide adequate roll for low-speed maneuvering. However, this small aileron allows investigations in the flexible-to-rigid ratios of rolling moments.

The structural idealization used by TSO, the wing aeroelastic synthesis procedure,[5] is a Rayleigh–Ritz trapezoidal composite wing box as shown in Fig. 2. Graphite/epoxy composite upper and lower covers form the structural box. Included in this structural box are two added spars explicitly included as finite element beams to address stiffness changes of the smart stiffness concept. One spar augments the trailing edge of the wing box and the other runs from the leading-edge root to the trailing-edge tip of the wing box. These beams are called smart spars. The root attachment of the wing box uses finite element

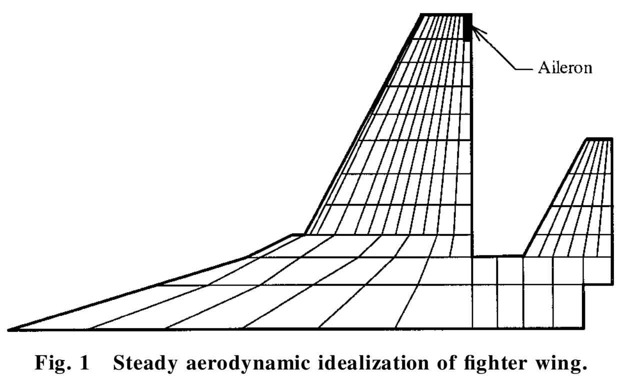


**Fig. 1 Steady aerodynamic idealization of fighter wing.**

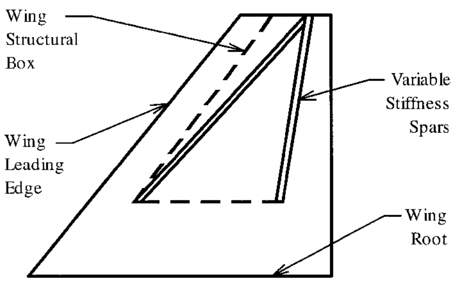


**Fig. 2 Fighter wing structural box idealization.**

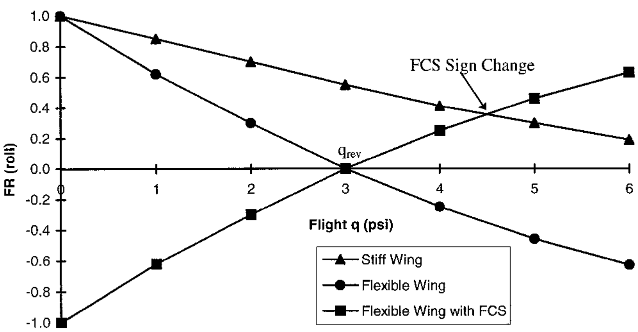


**Fig. 3 Flexible-to-rigid aircraft rolling moment vs flight *q*.**

beams to represent the stiffness of the fuselage attachment lugs typically used for composite wing designs. The smart stiffness approach for this wing really involves these smart spars. A smart spar has a web that can either transmit shear between its upper and lower cap or disable the shear transmission between the upper and lower cap.

The trimmed aeroelastic loads analysis specified for static strength uses a trimmed symmetric pull-up condition of 7.33 *g* at 10,000 ft and 0.9 Mach airspeed. This is the altitude at which $FR_{roll}$ values are examined in this study. For the purposes of maintaining a flutter-free wing, the flutter constraint used 0.95 Mach at sea level as the constraint value.

To illustrate how these effects could be integrated into an adaptive structure application, consider $FR_{roll}$ as a function of flight $q$ for 1) the stiffer wing box and 2) the more flexible wing box, shown plotted together in Fig. 3. The curve labeled flexible wing with FCS (flight-control system) is the optimum use of either the stiff or flexible wing using a flight-control computer to apply the appropriate signal signs. The desirability of adaptive stiffness can be seen in this figure and is defined in the following text. Note the drop in $FR_{roll}$ as $q$ increases for both the stiff and flexible wings, just as expected. For the flexible wing, $FR_{roll}$ transitions from positive to negative at $q_{rev}$ then continues to grow more negatively as $q$ increases. If, at a flight $q$ of 4.5 psi, the control system for the aircraft roll function would reverse the sign of the output signal to the aileron and turn off the smart spar stiffness in the wing, then roll effectiveness would never drop below about 40% and would grow progressively stronger again as flight moves into high $q$ for air-to-air maneuvering. All of this is accomplished using a single outboard trailing-edge flap.

In developing these tailored stiffness designs, the active constraints that shape the resulting design can be very interesting. For this study, the strongest constraint to higher values of $FR_{roll}$ was clean wing flutter. For the TSO procedure, flutter constraints are created by restricting crossings from positive damping to negative damping of vibrations modes. This is accomplished using $k$ based $v$-$g$ eigenvalue tracking. In this study, the aeroelastic tailoring design process tried to lower $q_{rev}$, the change in the wing box design variables tended to drop the first torsional vibration frequency into close proximity to the first bending mode of the wing. This continually confounded the flutter constraints as the classic wing bending/torsion flutter mode critical velocity would drop in parallel to $q_{rev}$. Only when the first torsion mode frequency was forced below that of first bending could progress be made. Generally, a higher torsional mode would quickly become a problem as well, but this forced drop in the first torsional wing vibration mode approach allowed usable drops in $q_{rev}$.

During the early stages of this research effort, the manipulation of the wing root conditions was thought to be a convenient way to manipulate the wing stiffness. This could be made possible using simple mechanical approaches that would not require exotic materials or significant power. The three most streamwise wing attachment lugs were sites of interest. Considerable changes in the aeroelastic response of the wing were expected from a pinned connection that could be clamped when desired. The aft lugs were investigated with the hope that the maximum effect on torsional wing stiffness could be made with minimum effect on the primary loads paths of the upstream lugs needed for bending strength. However, flutter constraints continually prevented any exploitation of this for the wing.

## V. Conclusions

In the search for minimizing the power and weight requirements to make smart structures more attractive, the concept of adapting a structure through the use of smart or adaptive stiffness shows considerable promise. By using the aeroelastic characteristics of lifting surfaces to their maximum advantage, a force amplification is available to convert small control forces into useful levels for aircraft control.

Smart stiffness offers an intriguing method to create adaptive structures. The actual mechanization of the concept offers the greatest challenge. To keep the power and weight requirements low, concepts such as a smart spar may be useful. This is a spar that can modify its capability to carry shear in its shear web, either mechanically or using a smart material. Other techniques such as variable stiffness wing root attachment hardware also may be useful.

Some consistent themes of limitations are present when creating lifting surface structural boxes with adaptive stiffness that also meet strength and stability requirements. Flutter seems to limit to what degree aileron reversal can be exploited as a force amplifier for wings. However, even with this limitation, considerable improvements are available at affordable weights and power levels for aircraft control using adaptive stiffness techniques.

Interesting areas for future work are suggested by the variable stiffness concept. This is especially true of dynamic stiffness changes coupled with aeroelasticity. Flutter suppression may be possible through selected phasing of variable stiffness changes. Stall flutter may be controlled by dynamic wing torsion control. Wing boundary-layer flows may be improved by energy introduction using very small wing AOA oscillations. These oscillations made possible through aeroelastic responses form dynamic stiffness perturbations.

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