ADAPTIVE STIFFNESS SYSTEMS FOR AN ACTIVE ALL-MOVING VERTICAL TAIL

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Abstract

An investigation is described into the design, manufacture and testing of several adaptive stiffness attachments for an all-moving vertical tail wind tunnel model as part of the 3AS project. Following a brief description of all-moving vertical tails and the specification for adaptive torsional stiffness attachments, the design and manufacture of a range of adaptive attachments is illustrated. Findings from component bench and wind tunnel tests are described.

Introduction

Conventional aircraft design treats aeroelastic effects as being undesirable and these have traditionally been eliminated through the use of heavy, stiff structures. Such an approach has also applied to aircraft vertical tail, leading to large high aspect ratio fins that are prone to high loads and give further weight and drag penalties. Recent work has aimed towards using aeroelasticity in a positive manner, for instance the Active Aeroelastic Wing[1], the Morphing Program[2] and the 3AS (Active Aeroelastic Aircraft Structures[3]) research programmes. These projects aim to develop more efficient, lighter aircraft structures through the use of various passive and active aeroelastic concepts.

The work described in this paper is part of the 3AS project which has the aim of developing and demonstrating Active Aeroelastic All-Moving Vertical Tails (AAAMVT). Such fin designs should lead to decreased tail size and structural weight whilst meeting all tail performance goals. All-movable vertical tails are attached via a single attachment, initial studies have shown that the use of a single attachment enables a greater influence on the aeroelastic behaviour than for a fin with multiple attachments[4]. Once the attachment is moved far enough aft, it is possible to get an effectiveness greater than unity.

However, as the torsional stiffness is reduced, the flutter and divergence speeds will also reduce. Consequently, there has to be a trade-off between the gains in the aeroelastic efficiency and aeroelastic stability considerations in any design. Initial work [4] concluded that an adaptive variable stiffness attachment is required in order to cope with the different requirements at low and high speeds.

This paper describes the development of several adaptive stiffness attachments employing different concepts for use with an all-moving vertical tail component designed for the EuRAM wind tunnel demonstrator. The design, construction and testing of the attachments is described, along with the findings from experimental tests.

➢ EuRAM Model

The EuRAM wind tunnel model is one of four demonstrators that have been developed as part of the 3AS project. It has been used to demonstrate the use of novel active control devices and also the Active Aeroelastic All-Moving Vertical Tail component. A number of adaptive attachments for the AAAMVT, based upon conventional and smart technologies, have been developed at the University of Manchester, CIRA and INTA, with the aim of producing a maximum effectiveness of 1.5 and the ability to control the stiffness (and hence the effectiveness). A maximum requirement of 70Nm/rad was specified. It should also be noted that there were restrictions on the size of the attachments so that they could be fitted on the EuRAM model.

Figure 1 shows the vertical tail designed especially for the 3AS project and Figure 2 the vertical tail on the EuRAM wind tunnel demonstrator. Both the EuRAM model and vertical tail component were designed and manufactured by TsAGI in Russia. One feature of the vertical tail component is that the attachment position could be adjusted to be at 30%, 40% or 50% of the mean aerodynamic chord.

University of Manchester Device

The philosophy behind the adaptive stiffness attachment used in this work was to use of pneumatic cylinders whose effective stiffness can be altered via changes in the compressed air supply.

Fig. 1. Vertical Tail Component

Fig. 2. EuRAM Demonstrator

Figure 3 shows the configuration employed. A pair of cylinders, attached in series to the air supply so they both experience the same pressure, were used to resist the torsional motion. The greater the pressure, the greater the resulting torsional stiffness. The device that was manufactured was designed to operate up to a pressure of 10 bar, however, due to limitations in the available air supply, the maximum possible air pressure was 6 bar.

Initial tests focused upon bench-tests of the adaptive device, in particular the torsional stiffnesses that could be achieved and also the practicalities of changing and controlling the stiffness. The torsional stiffness was calculated for static loads (fig 4) for various pressures, thus enabling a calibration factor to be developed relating air pressure to stiffness.

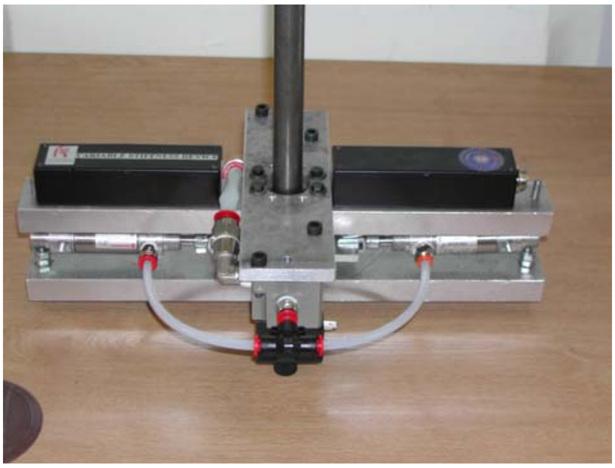


Fig. 3. Pneumatic Adaptive Stiffness Device

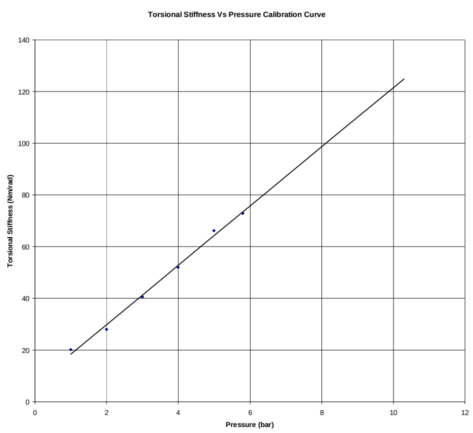


Fig. 4. Calibrated Stiffness vs. Pressure

As well as achieving the required torsional stiffness, it was of great interest to investigate the practicality of changing the air pressure and hence the stiffness. This turned out to be relatively straightforward, with changes in the stiffness being almost instantaneous. A controller device was designed and manufactured that enabled the air pressure to be changed to meet the required torsional stiffness. Again, the effectiveness of this device was very successful and was very easy to use.

The AAAMVT was bench-tested for a range of different torsional stiffness settings and also attachment positions. Hammer testing was used to measure Frequency Response Functions (FRFs) relative to a reference station and these were then curve-fitted in order to determine natural frequencies, damping ratios and mode shapes. Reasonably good agreement was achieved between these experimental results and the FE model. As was to be expected, the flexible modes of the AAAMVT remained more or less the same for different attachment stiffnesses, however, the underlying low frequency rigid body torsion mode was directly related to the stiffness of the attachment.

A series of static and dynamic tests were performed using laser displacement devices to measure the response. A range of different torsional stiffnesses were implemented for several different attachment positions. Static testing consisted of setting the AAAMVT at several initial angles of attack and measuring the static twist angle for differing speeds. The effectiveness was defined at the ratio of the resulting total twist angle (including the initial angle) to the initial angle. Figure 5 shows some of the effectiveness measurements which agreed well with analysis.

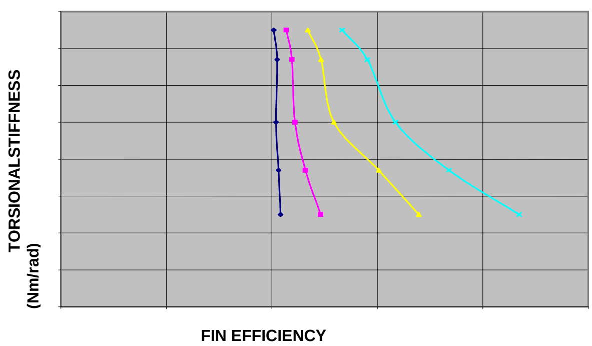


Fig. 5 Typical Fin Efficiency Results

Dynamic tests were then performed to determine how the vibration characteristics for different parameter settings (torsional stiffness, attachment position) varied with speed.

A final test was used to investigate the possible freeplay characteristics of the adaptive stiffness attachment. At a particular stiffness setting, the rotating turntable of the environmental tunnel was rotated from around +15 degrees through to -15 degrees. Such a procedure meant that the AAAMVT changed the side to which it was twisted. By examining the resulting angle of twist, it is possible to see whether any free play is present as there would be a sudden change in angle of twist should that be the case. Figure 6 shows that freeplay in the system was negligible.

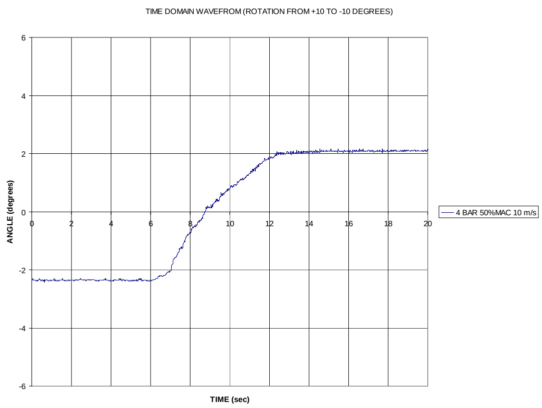


Fig. 6 Twisting Angle for Rotating Turntable Tests

The controller that was developed to control the torsional was very effective. It was possible to go from zero stiffness to maximum stiffness (or maximum to zero) in less than half a second. Due to the inertial effects of the rotating vertical tail component there was a certain amount of overswing, but this was damped out in a few cycles.

CIRA Devices

CIRA efforts inside '3AS' Project have been focused on the design and manufacturing of devices able to control torque stiffness of the all-movable vertical tail of the EuRAM model. The two devices that proved to fit WT requirements are: the classic spring plate device and the MRF based on variable stiffness device. The *classic device* produces stiffness variations by changing, through step motors, the length of two plate springs connected to the tail shaft. The working scheme of the device is illustrated in fig.7: clamps moved by step motors constrain the plates by affecting their effective length and thus their stiffness.

The plate length has been defined by means of theoretical and numerical non linear investigations. According to the numerical predictions, a prototype has been manufactured as illustrated in fig.7. An experimental campaign has been carried out on the device to validate numerical predictions and to point out eventual deviations. As a result, a calibration curve of the device torque stiffness vs. the clamp position along the plates could be plotted (see fig.8). An electronic apparatus has been designed and manufactured to allow the device control (clamps' location and moving speed) during WT tests.

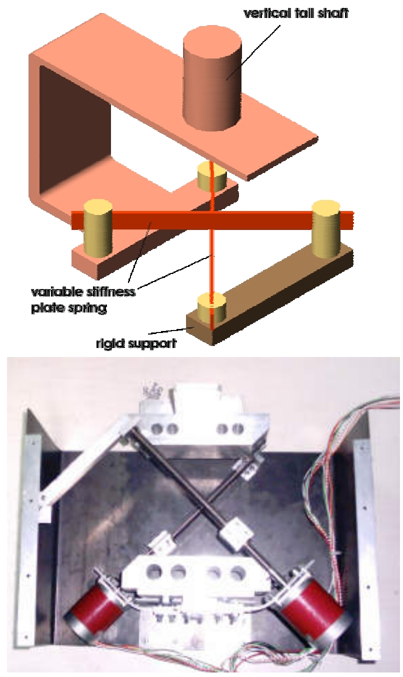


Fig. 7. Classical Device Model and Prototype

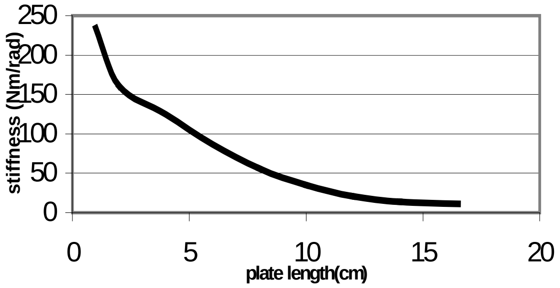


Fig. 8. Experimental Stiffness vs. Length

The *MRF variable stiffness device* is constituted by 5 linear elastic elements connected in serial way and linked to the tail shaft, as shown in fig.9. The global rigidity of the system is minimum if all the springs may expand or contract; on the other hand, stiffness increases may be achieved if one or more springs are locked. Many practical solutions may be adopted to produce locking: mechanic, hydraulic, and so on; a block system, an MRF hydraulic circuit has been considered a valid solution, because of the absence of mechanical movable parts (with a consequent reduction of failure problems and redundancy architectures).

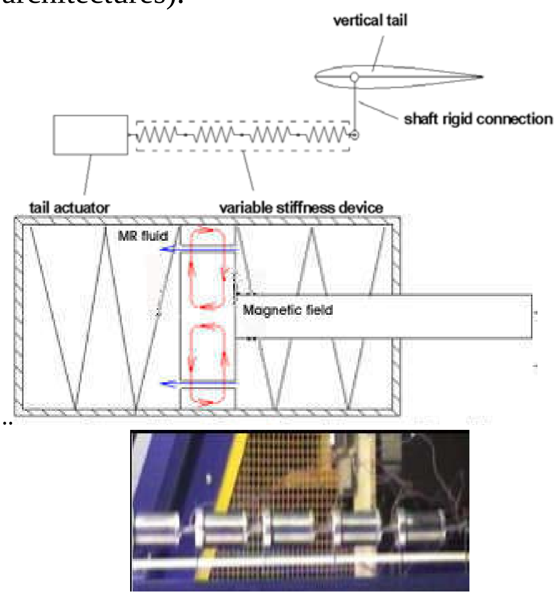


Fig. 9. MR Device Principle and Device

The hydraulic system is represented by a cylinder-piston; each spring of the device is ideally split into two elastic elements located on the two sides of the piston, whose base presents an annular valve to let the MR fluid pass through. If no magnetic field is applied close the valve zone, the fluid may run and piston stroke may occur: as a result, both the springs may expand and contract, respectively. If magnetic field is applied, the fluid is slowed down up to the valve choking: in this condition, no piston stroke is allowed and related springs do not give their elastic contribution to the global spring system, with a consequent over-all stiffness variation. Annular valve dimensions (internal and external radii and depth) by applying the momentum eq. to the corresponding control volume, for an assigned internal pressure. Lastly, the magnetic circuit features have been defined (i.e. the current intensity I and the coils number N), by means of a FE investigation. According to the numerical prediction an experimental prototype constituted by 5 cylinder-pistons has been manufactured (see fig. 9). Both static and dynamic tests have been performed to characterise the system. Static tests have proved the ability of the MRF lock system of balancing a static force of 200N, as from requirements. Dynamic tests were aimed at measuring system stiffness and damping under sinusoidal excitation with amplitude and frequency ranges of 40-100N and 1-20 Hz, respectively. Stiffness values with and without activation of all the cylinder-pistons for a frequency of 4Hz were plotted; the max stiffness increase (280%) has been measured for a force of 70N. Lastly, in fig. 10, the rigidity excursion of the system vs. activated cylinder-piston combination is plotted for an external

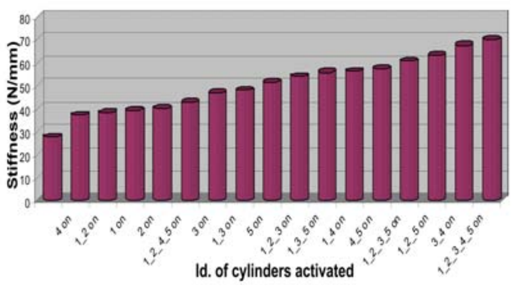


Figure 10. Experimental Stiffness for Cylinder Combinations

INTA Devices

The working principle of the *Rotating Beam Attachment* (RB) is shown in fig.11. It consists in supporting the command actuator of the aerodynamic surface onto a cantilever beam. This beam is of rectangular section and

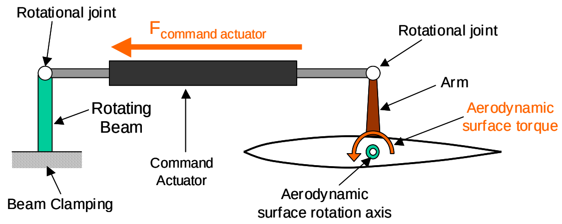


Fig. 11: RB Attachment working principle

can be rotated along its axis, therefore the stiffness provided can be modified as required by flight conditions. The stiffness variation corresponds to the inertia moment of the RB cross section (see fig 12).

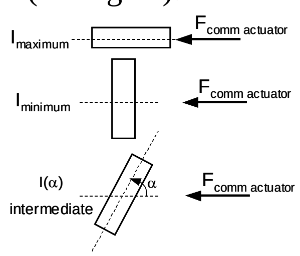


Fig. 12. Rotating Beam Positions

Because of the complexity and variety of requirements imposed to the Adaptive Attachment, two adaptive attachments [5] were produced. The RB Prototype (see fig 13), to verify the design adequacy, and prove the mechanical solution of stiffness variation. This was followed by a version for the EuRAM with an improved design, taking advantage of lessons learned from RB Prototype, and whose performances (max. and minimum Stiffness), and geometry are defined by the Aeroelastic experiments on EuRAM demonstrator (divergence, flutter, efficiency, etc.)

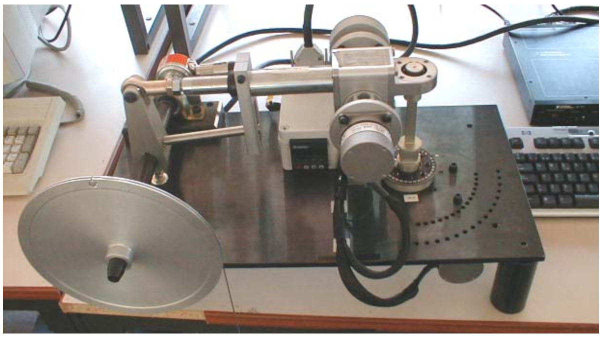
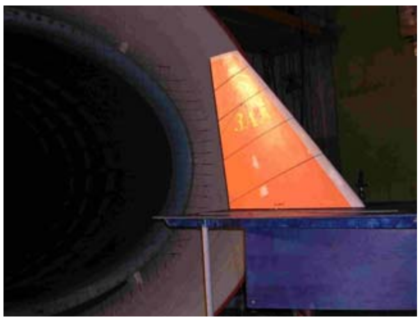


Fig.13. RB Prototype

RB clamping is achieved by a couple of preloaded angular contact bearings. The RB Prototype use only one RB, while RB - EuRAM uses a double RB system with inverted Beams position, because of the limited space.

The RB angular position is controlled by a stepper motor. A Command Actuator used is Electro-mechanical, moved by a stepper motor. Aerodynamic surface axis is joined to an arm, that transmits only axial loads to the Command actuators. A spherical joint is used in RB Prototype, while two Cardan are used at RB - EuRAM. The FEM technique was used for the Attachments theoretical models.

Functional tests to validate numerical predictions and Wind Tunnel Aeroelastic tests were performed. The rig was controlled via a Power Unit for Command actuator and RB stepper Motors, and the Control computer (includes an acquisition card). Control application is programmed in Labview, allowing independent control of Command and RB Stepper motors: speeds, ranges, etc.



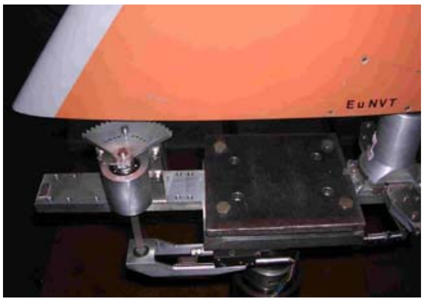


Fig. 14. RB Component Test at TsAGI

High stiffness ratios (K_{max}/K_{min}) were produced by the attachments, the solution used was demonstrated to be adequate. For RB Protoype, some stiffness loss was found (20% for K_{max}), because of a parasitic flexibility of RB support bearings. This was solved for the RB - EuRAM, and no deviation was found at tests. For the RB Prototype a kind of non-linear hysteresis effect was found, the stiffness produced in a given RB position was dependent on the previous RB position. The reason was the friction at spherical joints of the Command Actuator. For RB - EuRAM attachment, joints with lower friction were used, and the effect was solved. Fine Stiffness resolution (ΔK of 10 % of K_{min} are possible) with almost no freeplay (less than 0.1º).

WT tests were made for RB - EuRAM supporting an All Movable Vertical Tail (AVMT), at TsAGI (Russia), Wind Tunnel T-103 (see fig 14). Different tests are performed and no problems were found with integration and the RB attachment allowed independent motion of Vertical Tail actuators.

The whole range of RB Attachment stiffness were tested. The systems shows a good behaviour in terms of stiffness, stiffness resolution, and very small freeplay. Good correlation with aeroelastic calculations was found.

Conclusions

Several adaptive torsional stiffness device based a range of concepts have been designed, manufactured and tested as an attachment for an active aeroelastic all-moving vertical tail. The devices have been shown to be very effective and enable the all-moving vertical tail to be controlled with a predetermined static effectiveness.

Acknowledgments

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