TORNADO , AN ADVANCED STOL FIGHTER-BOMBER DESIGN

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Abstract

After a short introduction to the TORNADO which outlines the design philosophy to meet the operational requirements for this STOL aircraft weapon system for the three participating nations UK, Italy and FRG, the paper will deal with primary advanced design features of this aircraft.
Thus, Tornado represents an aircraft incorporating design features such as variable wing sweep , variable supersonic inlet, sophisticated primary and secondary flying controls, advanced structural design with modern materials and a high technology afterburning by-pass engine specifically designed for Tornado.

Flight testing of Tornado has started in 1974 and 8 aircraft are flying at the three industry flight test centres at this time. The paper will give highlights of the design philosophy with emphasis on the overall integrated function and performance of the airframe achieved by synthesis of all systems.

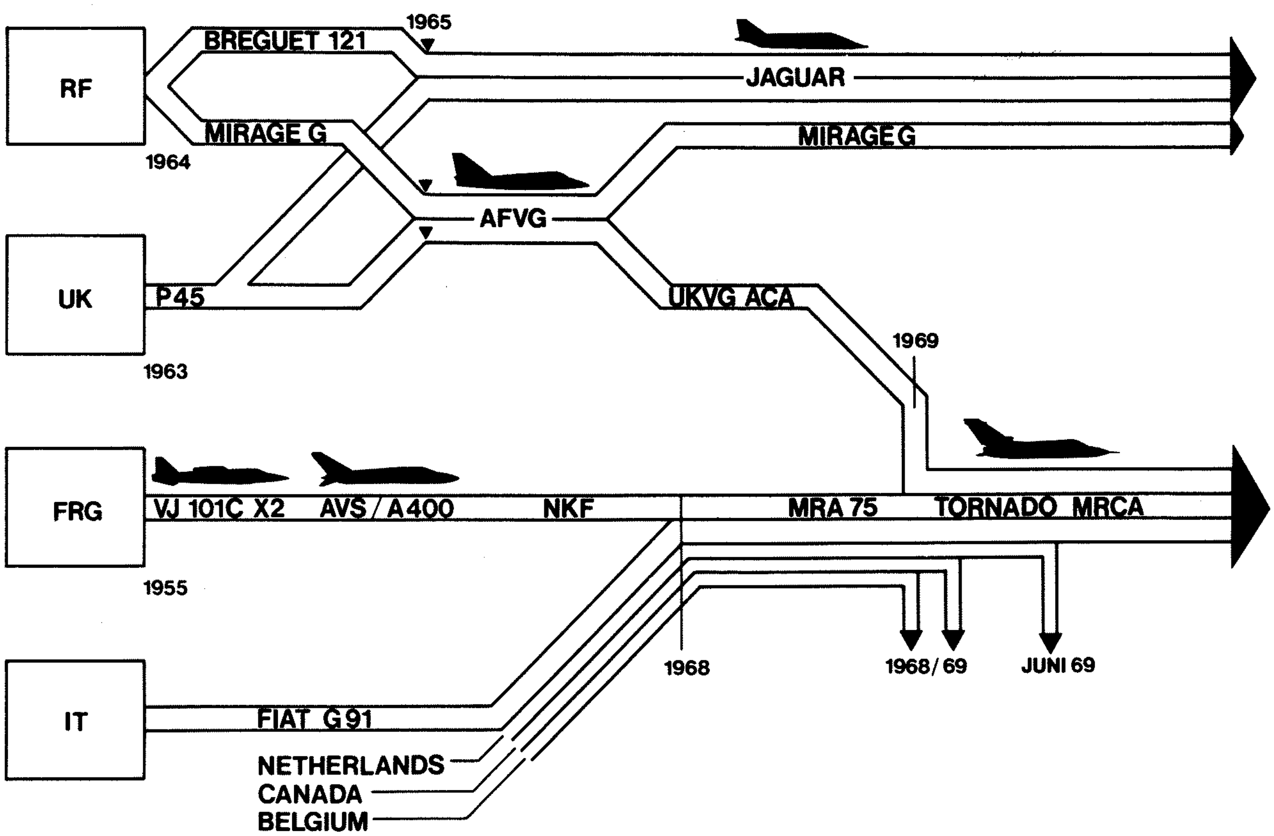
A short film summarizes and highlights major flight test milestones.

1. The Programme

Although the main emphasis of this presentation is to discuss engineering and technical matters of Tornado, I think it is appropriate to introduce you into the Tornado programme with a short programme summary.
The idea to fulfil the requirements of more NATO air forces with one weapon system concept and a virtually identical aircraft took shape when in 1968 the staffs of six NATO countries joined together to study the possibility of combined operational objectives for an advanced fighter/attack aircraft. Besides the United Kingdom, Italy and the Federal Republic of Germany the other three interested nations were Canada, Holland and Belgium. All air staffs were interested in a low level interdiction mission, good manoeuvrability up to medium altitudes, and to a varying degree in high altitude manoeuvre performance and acceleration capability. The desirability of superior STOL performance was an agreed design objective, in particular for those who considered dispersed operation or operation from partially damaged runways as an important goal. Before the actual project formulation phase was finished in 1969, Belgium, Canada and finally Holland had discontinued their participation in the MRCA programme for various reasons ranging from cost considerations to differing opinions of the primary operational role for this weapon system. In parallel to the activities of the air staffs, discussions started on industry side in autumn 1968 on the available technology to verify the project and on principles for a collaborative venture. The technical and technological background in particular at BAC and MBB formed the basis for the agreement to form a joint project team with the task of proposing an aircraft solution which fulfilled the major operational objectives still retaining a very high degree of commonality in configuration, airframe, structure and systems design. The result of the integrated project study was presented to the governments after five weeks of intensive project work first at Warton and then at Munich by March 1969 and was accepted as a basis for further project definitions including the selection of an engine which would meet the specific requirements of Tornado.
This was possible because before both, MBB and BAC, had already invested intensive project and technology work in advanced fighter aircraft concepts including variable wing sweep, V/STOL propulsion and control, advanced flight control using fly-by-wire techniques and advanced avionic systems.

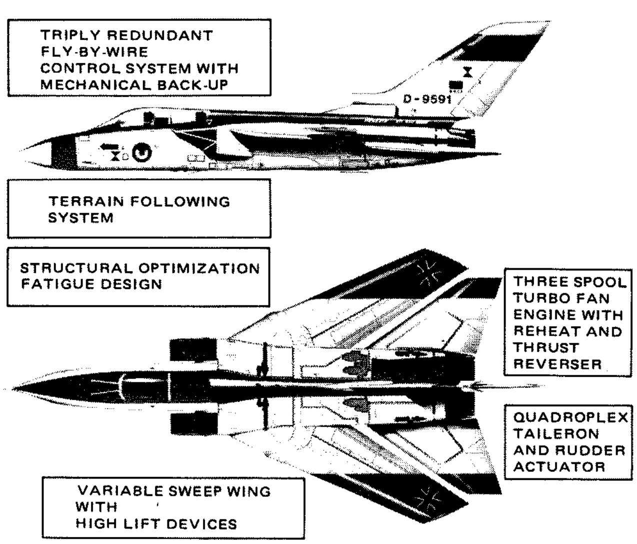
Fig. 1 illustrates this background:

Fig.1 Historical Background



Before I revert to some more programme aspects, I think it is appropriate to briefly introduce the Tornado MRCA to you.
Fig. 2 shows a two-view picture giving an overall impression of the aircraft configuration.

Fig. 2 The Aircraft



The MRCA has a two-seater tandem cockpit, two RB 199-34 R three spool bypass engines; the aircraft is designed to fulfil the LC-LO-LO interdiction/strike missions at subsonic and transonic speeds. A variable supersonic inlet provides optimum cruise and high supersonic performance without undesired compromises; the undercarriage is designed for semiprepared field operation and maximum flexibility in weapon loading. It is also worthwhile to have a closer look at the wing which incorporates full span high lift devices, slats and double slotted trailing edge flaps, a Krueger flap on the fixed nib and a total of four sweepable external store stations for the carriage of a variety of loads. Three additional long underfuselage pylons are provided for the carriage of major loads. The relatively large vertical tail is a result of an optimization in order to arrive at the minimum wetted area or drag to fulfil the design missions. The horizontal tail provides adequate power for aircraft rotation at comparatively low lift-off speeds plus roll control. At low speeds and below medium wing sweep angles additional roll power is provided by two pairs of spoilers on each wing. The sweep angle of the wing which varies from 25° to 68° provides very good ride qualities at transonic speeds and the required manoeuvrability and high lift performance at intermediate and forward sweep angles using partially and fully extended high lift devices. Short deployment times provide very

fast lift augmentation for manoeuvres.
An indication of the internal arrangement of the aircraft highlights major features of Tornado which in combination have contributed to the technical and technological advancement of this aircraft. It can be seen that RB 199-34 R reheated bypass engines with their high thrust volume ratio and their short length including the integrated target type thrust reverser is a powerful factor in the integration of this compact aircraft. It may also be worthwhile to mention again that one of the main objectives during the project study was to minimize wetted area for subsonic/transonic drag without compromising on internal fuel volume and volume for the comprehensive avionics package. This has been achieved and Tornado is probably one of the densest aircraft ever built. A comparison with the F-15 shows that the density ratio Tornado/F-15 is approx. 1.5 at take-off weight and Tornado having the wings swept to 45^{o}, a comparable leading edge sweep. The main dimensions of Tornado are:

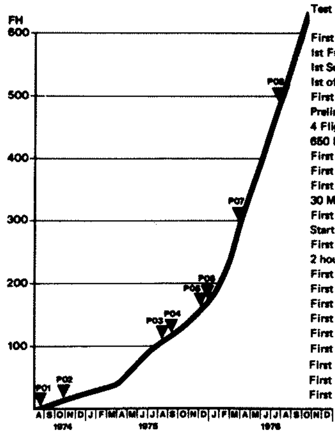
fuselage length	14,5 m
wings span 25^{o}	13,9 m
wing span 68^{o}	8,6 m

The Grumman F-14, which happens to have a similar overall configuration, is bigger in geometry by a factor of 1.4, the F-104 has the same fuselage length as Tornado.
The Tornado is an example for a programme concept in which right from the beginning the prime objective was to develop and produce an aircraft weapon system in an overlapping schedule which, of course, requires a production decision to be taken before the completion of the test programme of more than 3000 hrs testing. This programme philosophy certainly has the big advantage that the overall programme can be conducted in the shortest time span and since the operational prototype provides at the earliest possible date not only information on basic aircraft performance but also important weapon system test results, an early and programme compatible production decision can be taken. This is fundamentally different if an experimental programme approach is chosen, where the primary programme goal would be to demonstrate the feasibility of a technical/technological concept first and only if positive experimental proof is available to make the decision to begin with a weapon system development.
Such a programme requires more time and it is advisable, if such time is available, and in particular if experimental demonstration of new state of the art is essential before making a further step in a programme.

Major MRCA Tornado milestones which I should pinpoint here are start of development at the beginning of 1970 and the first flight of the first prototype in summer 1974 followed by the first avionic system prototype one year later. 8 out of 9 prototype aircraft have resumed their part of the flight test programme. The 9 prototypes will be followed by 6 preseries aircraft which will undergo operational flight trials at the official test centres. The delivery of the first series aircraft will take place end of 70ies. 809 aircraft are planned for production for the three participating nations.

Before I come to the two selected topics, structural design aspects and afterbody integration I have summarized for you the status of the flight test programme on Fig. 3. More than 600 flight hours have been achieved, but more important, of course, are the completed technical milestones which are listed on the right hand side of this slide.

Fig.3 Status of TORNADO Flight Test



Test Result	Prototype	Date
First Flight	P 01	14. Aug. 74
Ist Full Wing Sweep	P 01	Aug. 74
Ist Supersonic Flight	P 01	Aug. 74
Ist official Demonstration	P 01	Sept. 74
First Flight	P 02	30. Oct. 74
Preliminary Performance	P 01	April 75
4 Flights on one day	P 01	April 75
650 Kts sea level	P 02	June 75
First In-Flight-Refuelling	P 02	July 75
First Flight	P 03	5. Aug. 75
First Piloting from the rear seat	P 03	Aug. 75
30 Minutes turn around	P 02	Aug. 75
First Flight	P 04	2. Sept. 75
Start Avionic Test	P 04	Sept. 75
First Flight with external stores	P 02	Oct. 75
2 hours flight time without refuelling	P 04	Oct. 75
First Radar and AFDS flight	P 04	Nov. 75
First OTC Flight	P 01	Nov. 75
First Flight	P 05	5. Dec. 75
First Flight	P 06	20. Dec. 75
First Flight with Gun	P 06	Dec. 75
First TF-Flight	P 04	Feb. 76
First Stores Release	P 06	March 76
First Flight	P 07	March 76
First Flight	P 08	July 76

2. Structural Design and Aeroelastic Stability

Structural Design

The structural design concept was developed under the consideration of the following aspects:
- structural integrity up to 4000 flight hours
- high accessibility and maintainability
- low production cost

In order to achieve a structural integrity up to 4000 flight hours and 20 years in service life under fatigue loads and a corrosive environment (Navy a/c), an intensive material selection and evaluation was performed. During the evaluation not only the common parameters as tension-, compression- and fatigue properties were considered but also the fracture mechanic properties fracture toughness K_{IC}, stress corrosion and crack propagation. This led to the use of the new high strength Zinc Alloy for sheet material.
It is known that plates thicker than 90 mm of such special material have not as good properties as the thinner plates. Therefore a modified alloy was evaluated and chosen for all machined parts with stock material size thicker than 90 mm. For one of the most important parts of the primary structure the carry through box (CTB) a comparison between high strength steel and titanium was performed. Titanium was selected as material for the CTB considering the higher relative critical crack length, the excellent electron beam weldiability and the mass advantage. To overcome the corrosion problems the structure is wet assemblied.

For all bolts in corrosion suspect areas corrosion resistant steel (CRP) was selected and all bearings in those areas are built by corrosion resistant steel. In order to demonstrate an adequate fatigue life, a lot of component tests and a full scale hinge fatigue test, a complete taileron and a wing fatigue test was conducted. In that way the weak points of the most fatigue critical structural parts could be found and a light mass high performance structure was developed.
Another important aim of the design concept was to develop a structure with high accessibility and low maintenance requirements. This excluded a fuselage design concept as a stiffened semi-monocoque body like civil aircraft structures. A design was developed with many relative closely spaced frames and only a few longerons. The main frames are NC machined. This design concept correlates with the requirement for modularity very well.
In the region of the highest bending moments the intake duct is designed to carry an important part of those. The duct in conjunction with the longerons is a highly redundant structure which is desirable for fail safe and low vulnerability. The access holes, a high percentage of the outer surface of the Tornado, is covered by bolted panels or doors with quick connecting fasteners. The engine installation is a "drop out" design with high accessibility and low maintenance effort involved. The large engine doors are fully load carrying and locked with shoot bolts.
By those means a closed cell structure was achieved which also carries the torsional loads with an adequate stiffness but is good accessible and maintainable.
The overall costs for a modern weapon system are growing and therefore big effort must be spent to keep the cost for the structure and the individual subsystems to a minimum. It has been shown that one important parameter being correlated with production cost is the amount of parts per mass. Therefore it was an aim for the Tornado designers to reduce the number of parts. Many of the bulkheads are designed as integral stiffened frames.
In addition, however, during the productionizing phase each individual frame was checked whether NC machining or conventional build up is more cost effective. As an example I would like to mention the wing box. The sidewall of the prototypes was welded from 6 parts, the production one from 2. The amount of parts went down from prototype wing box to production box by approx. 30 % . Fig. 4 shows the prototype wing box and gives you an impression of this structure.
Due to this extensive design work it was not only possible to reduce the cost for the structure but as well the mass. During the productionizing phase it was e.g. possible to achieve a mass saving for the centre fuselage of 8 % (Fig. 5).

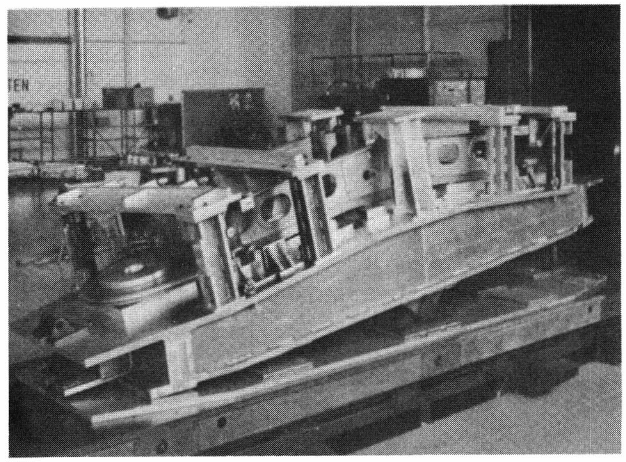


Fig. 4 PROTOTYPE WING BOX

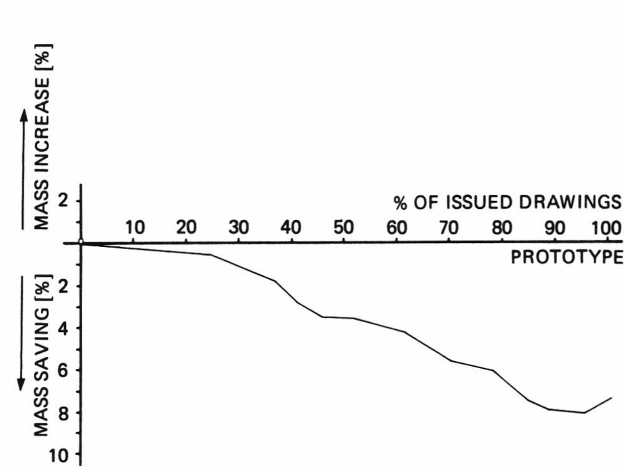


Fig. 5 MASS HISTORY – CENTRE FUSELAGE PROTOTYPE PRODUCTION A/C

Aeroelastic Stability

For the thin, minimum weight designed control surfaces of the Tornado the probability of penetration of the flight envelope by flutter speeds is high. To avoid weight penalties design flutter margins will be low. This philosophy requires a careful aeroelastic analysis supplemented by model and full scale test results. Such an investigation was conducted here and will be described shortly.
The first consideration in the design of the aircraft was to avoid flutter caused by aerodynamic interference between wing and tail by providing sufficient vertical offset between these two surfaces (1).

Fig. 6 shows how the vertical offset z increases the aerodynamic damping forces.

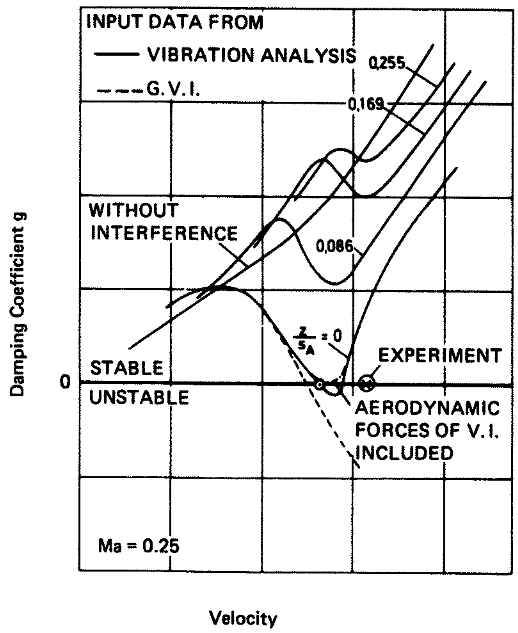


FIG. 6 DAMPING COEFFICIENT VS. VELOCITY FOR DIFFERENT VERTICAL POSITIONS OF THE HORIZONTAL TAIL (S_A = WING SEMI SPAN)

It was also necessary to provide an analytical tool for calculation of unsteady aerodynamic interference airforces in the subsonic and supersonic flight regime. Unsteady pressure distributions were measured on a rigid model to validate the theory.

The tailplane was laid out with the provision of apex mass since this was the most efficient way to increase flutter speed. A dynamically scaled model was built and tested to check the influence of the transonic aerodynamic forces. Since the effect of transonic aerodynamics was unknown on the fin rudder an elastic model was also built and tested. There was good correlation between test and calculation (2). In case of rudder actuator failure Fig. 7 shows that the flutter of the model was predictable analytically.

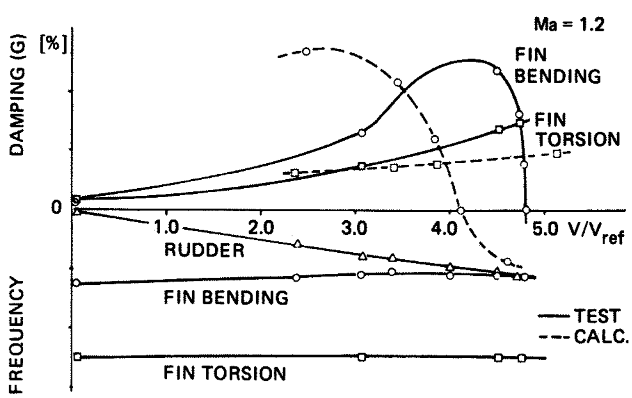


FIG. 7 FLUTTERSPEED VERSUS DAMPING AND FREQUENCY OF A FIN WITH ZERO RUDDER ACTUATOR STIFFNESS

Unsteady pressure distribution measurements were also performed on the fin and rudder in subsonic and transonic range. It was also necessary to predict the flutter speeds for the airplane with wing mounted external stores in an early design stage in order to find the optimum two sweepable pylon stations for each wing. Rather than concentrating on single stores a philosophy was adopted whereby all possible stores varying in mass and radius of gyration could be cleared for flutter (3), (4). In Fig. 8 the lines of constant flutter speed as a function of store mass and radius of gyration are presented.

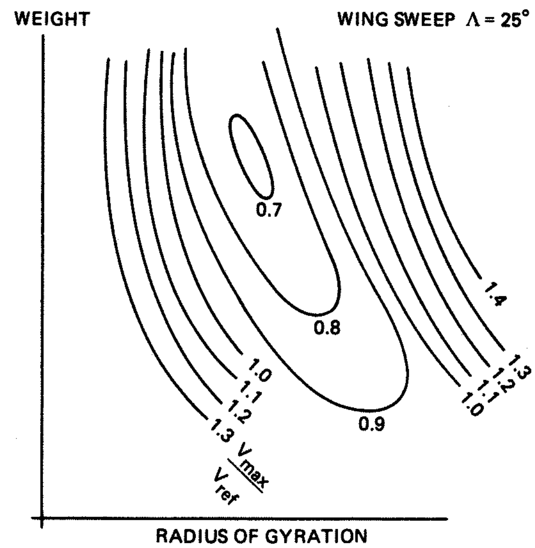


FIG. 8 TYPICAL CONTOUR PLOT CONSTANT FLUTTER SPEEDS AS FUNCTION OF STORE WEIGHT AND RADIUS OF GYRATION

With the aid of a total aircraft subsonic model it was possible to clear the flutter mechanism for symmetrical and asymmetrical store carriage (3), (4).

Fig. 9 shows that the flutter speed of the symmetrical and asymmetrical store configuration is a function of tuning of the various vibration modes.

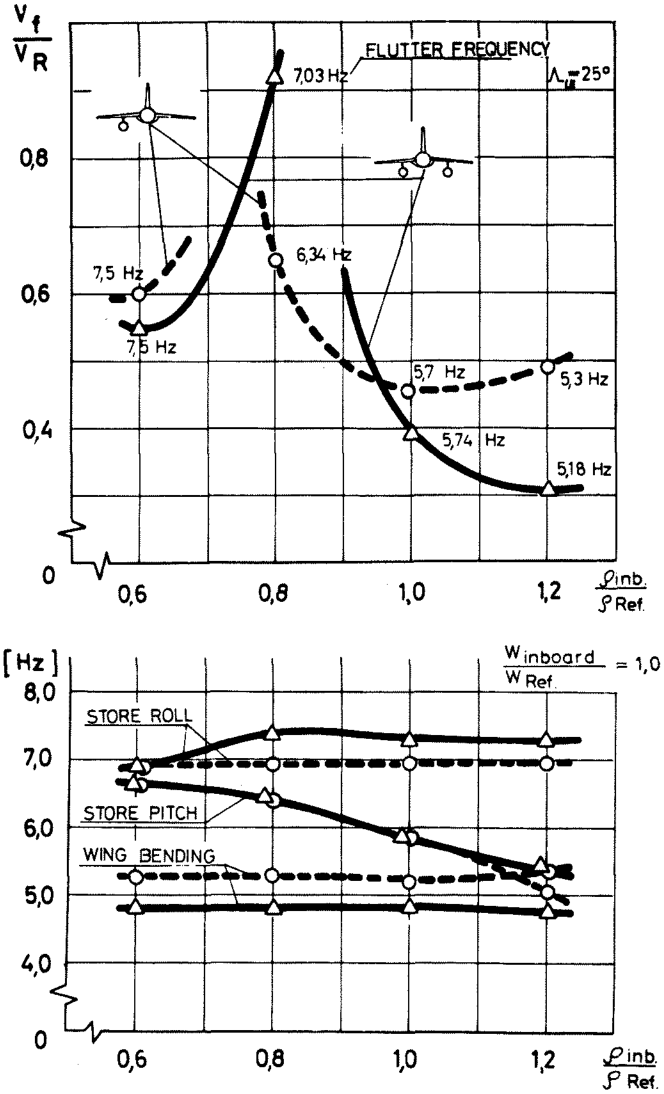


FIG. 9 FLUTTER SPEED AND MODAL FREQUENCIES VERSUS RADIUS OF GYRATION

Most recent evaluation techniques were used in flight flutter testing. Frequency sweep excitation was applied by small inertia exciters located in the surfaces and evaluated with non deterministic analysis procedures. (5)
Good correlation between flight flutter test and analysis could be established (5). In Fig. 10 the damping g as a function of air speed is plotted.

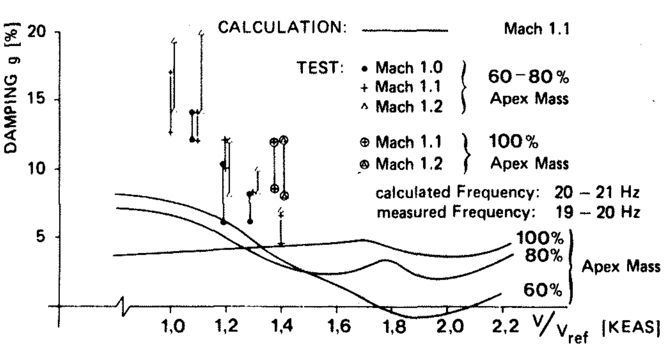


FIG. 10 COMPARISON BETWEEN MEASURED AND CALCULATED FLUTTER DAMPING FOR P 02

A great deal of work was also dedicated to avoid detrimental coupling of the Command Stabilization and Augmentation System (CSAS) with the elastic structure. For that purpose a notch filter was defined which covers the possible range of frequencies.

3. Afterbody Integration

General Aerodynamic Concept

The aerodynamic concept of Tornado is of course dominated by the variable sweep wing. Although the aircraft is naturally stable in all flight conditions and configurations, a full authority fly-by-wire Control and Stability Augmentation System (CSAS) has been introduced to meet the most demanding handling criteria for the aircraft as a weapon system platform. The gust response of the aircraft is basically low due to the relatively high wing loading, in particular at full wing sweep where $\Delta C_L / \Delta \alpha$ is low. With full CSAS the ride qualities are further improved with the autostabilization characteristics of the CSAS. Pilots reports about flights under gale winds and landing approaches under very gusty conditions are enthusiastic with regard to this characteristic. The design of the wing with its flexibility is a further positive feature for gust alleviation.
A large amount of literature is now available on the variable geometry-concept (VG) and aerodynamic criteria and methods to define the best configuration for a set of given requirements. I will therefore not go into detail here. In summary, the Tornado VG-wing has its pivot at relatively small wing span just outside the fuselage as the best compromise for the structure and neutral point shift. This has the advantage that the fixed portion of the wing can be kept small and full use can be made of the movable wing at forward sweep for the high lift devices at the leading and trailing edges. A further more indirect advantage is the relatively small nib and fairing area which can cause severe design problems if it is too large. Even so, the 60° nib is small, the double delta aerodynamic characteristic of the wing is fully developed at forward sweeps.
The transition from the movable wing to the fixed wing and the fuselage has been solved using a combination of "floating" elements like the nib and the fairing in front of the pivot and elastic fingers at the rear, constructed with glassfibre-epoxy, as we believe , a very good design which has proved to be free of fundamental problems. Minor problems have been encountered in the front discus area at one spot. Improved sealing and stronger local material have solved this problem. During the development and flight test so far the aerodynamic behaviour of the aircraft was in good agreement with the predictions.

Directional Stability at Transonic Speeds

One area which has given reason for some concern, a certain degradation in directional stability at transonic speeds, which could not be expected from wind tunnel data, will now be presented and the present status explained.

Wind tunnel tests confirmed the predicted stability. The experimental investigations were performed using a transonic model with a rear sting arrangement. To accommodate the rear sting and to provide realistic mass flow conditions it was necessary to modify the afterbody as shown in Fig. 11 , Model MC 3 with distorted afterbody. Because of the more gentle curvature of the slopes of the rear end, an improvement of the flow conditions was expected. To investigate these effects, a z-sting model suspension was developed. The wind tunnel testing of the prototype configuration as shown on Fig. 11 was concentrated mainly on longitudinals. Interference effects with the vertical fin were expected to be small.

When prototype flight test results became available, a reduction of directional stability, especially in the transonic speed range was detected. Fig. 11 .The rudder effectiveness was reduced proportionally.

Flow investigations were performed using Model MC 3 in its z -sting configuration with the basic prototype afterbody shape.

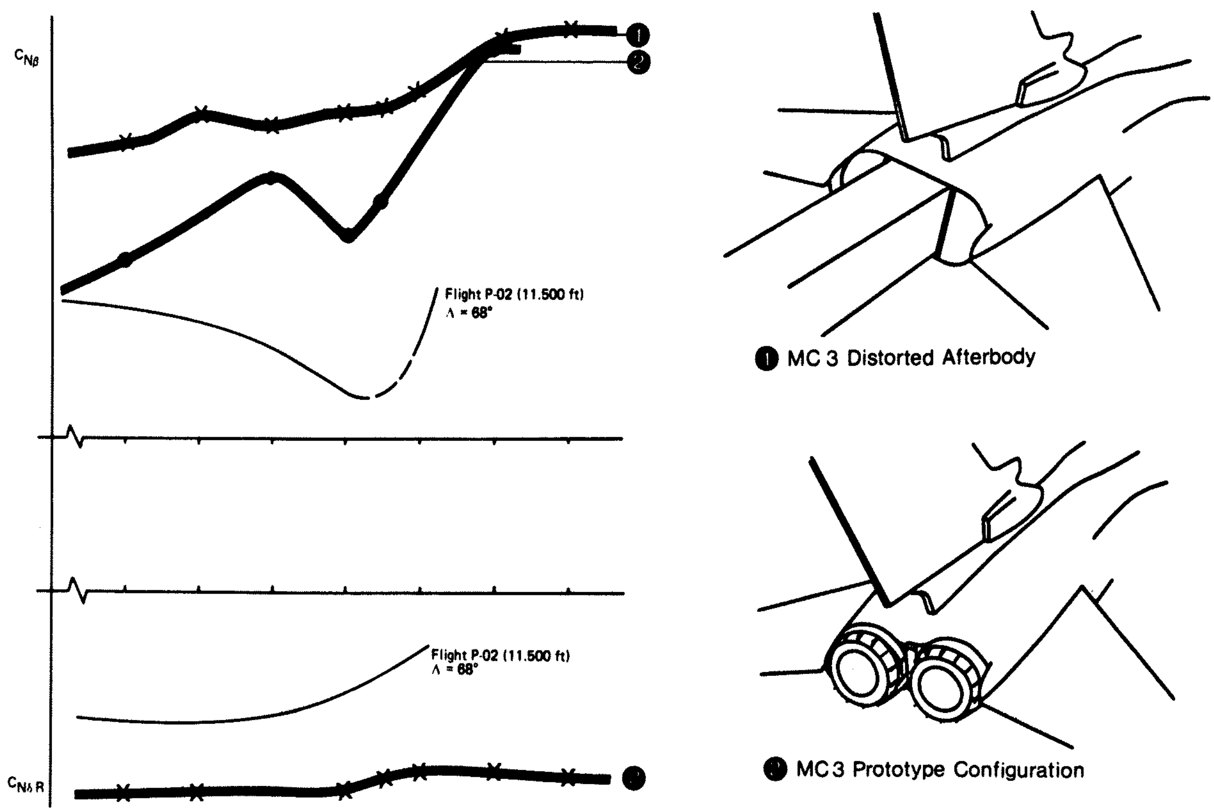


Fig. 11 MODEL MC3 DIRECTIONAL STABILITY AND RUDDER POWER

A relatively large separated flow field was found at high transonic speeds. The origin of the separation is located in the area, where the spine lines and the fuselage gully have the largest curvature.

In addition to these oil flow studies on the model, the rear end of the prototype a/c 01 was tufted. In principle, the same behaviour as on model MC 3 could be stated, though it seems to be fairly difficult to interpret flow separations on the basis of the intensity of swirling tufts.

Summarising the results of these flow investigations it became evident that the modifications recommended for testing on wind tunnel models should reduce the area of afterbody separation, affecting the fin and thus increase fin effectiveness. A lot of modifications have been evaluated on model MC 3 and the stage II modification was found as the optimum configuration for the prototype aircraft showing the best level of $C_{n\beta}$ of all modifications tested in the 1st test phase and allowing a reasonably quick fitting on the aircraft. The large benefit in level of directional stability due to the stage II modification can partly be explained by studying the corresponding oil flows made on model MC 3. The flow separation on the spine side, which could significantly influence the fin effectiveness, has disappeared and the separated regions on the lower fin and on the gully are reduced.

Flight test confirmed the good level of directional stability and the increased rudder effectiveness with the stage II modifications (Fig. 12).

But further development was necessary to obtain even higher levels of directional stability with good drag levels for the production aircraft. Additional wind tunnel measurements on both transonic models, MC 3 and MC 4, showed the necessity of an upper fuselage fairing, to fill the rear fuselage gully between the engine nozzles, and of a spine extension, in order to obtain the desired levels of $C_{n\beta}$ and acceptable drags. The stage III modification with a wide base spine extension was found as one of the most successful modifications. Flight tests with the prototype a/c 02 could confirm the improved directional stability due to the stage III modification compared to the aircraft with the stage II configuration, but a significant reduction in $C_{n\beta}$ in the transonic speed range required further investigations on the prototype aircraft (Fig. 12). The installation of vortex generators on the upper fuselage, the spine and on the lower fin effected a nearly constant high level of directional stability with Mach number combined with good rudder effectiveness (Fig. 12). The rear fuselage lines of the prototype a/c 06 differ slightly from the geometry of the other prototypes. The lines have been changed in an

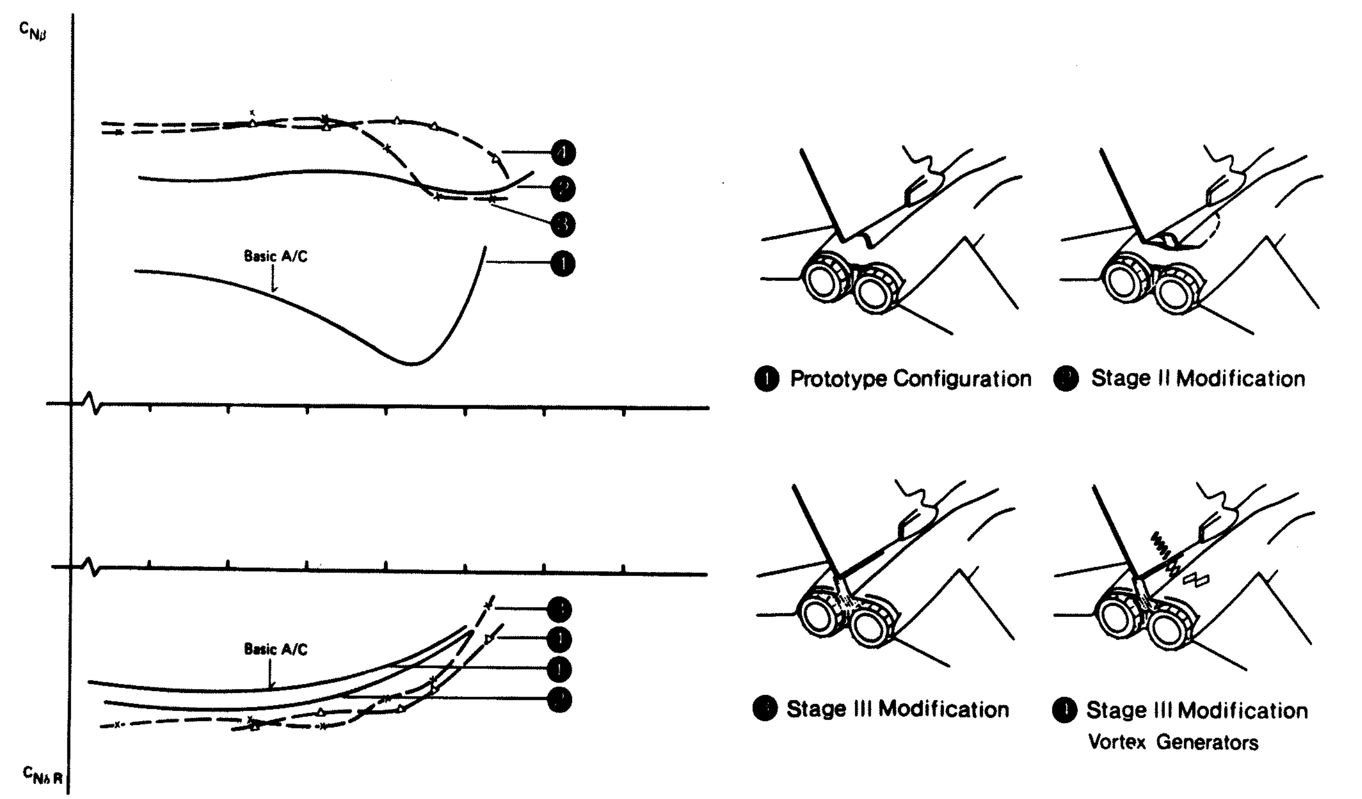


Fig. 12 TORNADO A/C 02 DIRECTIONAL STABILITY AND RUDDER POWER

early state of the development phase in order to prevent flow separation and to reduce the after-body drag. Flight tests with the a/c 06 prototype showed that the directional stability of the unmodified aircraft was excellent, but the decrease of rudder effectiveness with Mach number was not fully acceptable (Fig. 13).

Additionally a moderate level of vertical buffet was reported for the unmodified a/c 06. The attachment of vortex generators as investigated on a/c 02 could solve the problems in a satisfactory way (Fig. 13).

The aim was to come up with a final solution which not only satisfies directional stability and drag but also eliminates aircraft vibration to the maximum extent possible. This has been achieved by the addition of very small conical bodies in the spine fuselage transition at the rear end. By optimization of the size of these cones, the buffet was reduced to a level which stays below the limits set by acceleration criteria at the crew station. Pilots have flown the aircraft with this modification and have accepted it as the solution for production.

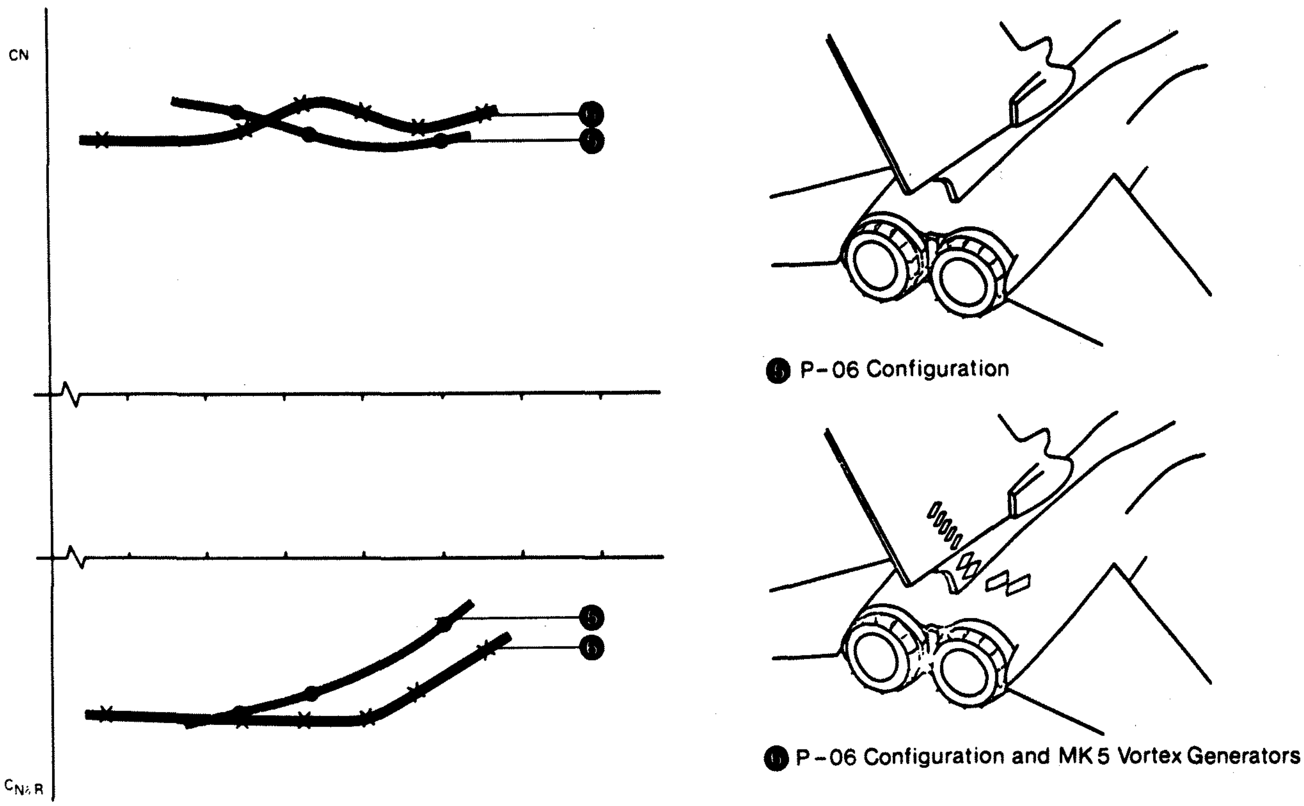


Fig. 13 TORNADO A/C 06 DIRECTIONAL STABILITY AND RUDDER POWER

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