# DESIGN STUDY OF A SUPERSONIC BUSINESS JET WITH VARIABLE SWEEP WINGS

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## Abstract

*A design study for a supersonic business jet with variable sweep wings is presented. A comparison with a fixed wing design with the same technology level shows the fundamental differences. It is concluded that a variable sweep design will show worthwhile advantages over fixed wing solutions.*

## 1 General Introduction

In the EU 6th framework project HISAC (High Speed AirCraft) technologies have been studied to enable the design and development of an environmentally acceptable Small Supersonic Business Jet (SSBJ). In this context a conceptual design with a variable sweep wing has been developed by ADSE, with support from Sukhoi, Dassault Aviation, TsAGI, NLR and DLR. The objective of this was to assess the value of such a configuration for a possible future SSBJ programme, and to identify critical design and certification areas should such a configuration prove to be advantageous.

This paper presents the resulting design including the relevant considerations which determined the selected configuration. This includes a design study of the hinge and the wing drive system. Mission and environmental performance of the design are presented. A short discussion concerning certification issues is included.

Fig.1 shows an artist impression of the design

Fig. 1 Artist impression variable sweep design AD1104

## 2 The HISAC project

The HISAC project is a 6th framework project for the European Union to investigate the technical feasibility of an environmentally acceptable small size supersonic transport aircraft. With a budget of 27.5 M€ and 37 partners in 13 countries this 4 year effort combined much of the European industry and knowledge centres.

To provide a framework for the different studies and investigations foreseen in the HISAC project a number of aircraft concept designs were defined, which would all meet at least the following requirements:

- Cabin dimensions Falcon 50 with standard 8 passenger seating
- Design range 4000 nm (supersonic mission)
- Cruise Mach number 1.6 to 1.8
- Initial cruise altitude at least 39000 ft
- Ops from 6500 ft runways (SL, ISA)
- Max approach speed 140 kts
- Certification noise levels ICAO ch IV, preferably ch. IV -10dB.

One research area was the possible application of variable sweep wings, or “swing wings”. This was covered by a separate task, led by ADSE with partners SCA (Sukhoi Commercial Aircraft), TsAGI, and Dassault Aviation.

This task aimed to provide the following:

- The effect of the application of swing wings on the efficiency of the design
- To provide a baseline geometry to investigate problems and certification issues typical for variable sweep wings

Based on data provided by the partners ADSE created a conceptual design of a swing wing aircraft architecture, as well a s a reference “conventional” supersonic business jet. This was based on the same design philosophy and data were calculated with the same design tools, in order to be able to draw meaningful conclusions from the emerging differences.

After this the swing wing conceptual design was further developed. Trade off studies were incorporated, the drag estimation was upgraded and the design tools were calibrated on the results of the designs of other HISAC partners. This resulted in a new concept design: AD1107.

## 3 Fundamentals of variable sweep wings for supersonic transport aircraft

There are basic differences in wings of transport aircraft designed for subsonic or supersonic flight, as a comparison of Concord with the current generation of high subsonic transport aircraft shows. Subsonic transport aircraft have high aspect ratio moderately swept wings, equipped with high lift devices over most of the span. The objective being to minimise the lift dependent drag both in cruise and the low speed regime, and provide high lift at low speed.

To achieve a reasonably low drag in supersonic flight the wings should be highly swept back, and as a consequence have a small wing span. This assumes a “subsonic leading edge”, where the wing leading edges stay well within the Mach cone. Alternatively the wings may be supersonic: the wing leading edges are swept less than the Mach cone and have very sharp wing leading edges. Such wings will have a drag penalty as the leading edge suction is eliminated this way, but the wing span may be increased for improved low speed performance. At its extreme this philosophy may result in a laminar flow supersonic wing, which was subject of a separate HISAC study project. Area ruling dictates a low cross sectional area, smoothly varying from nose to tail, and this favours slender wings like those of Concorde.

In all cases the maximum lift coefficient of supersonic wing planforms is quite low. Increasing the maximum lift coefficient by means of high lift devices is possible, but the potential is limited, and it will increase the lift dependent drag rapidly due to the high span loading usual for supersonic wings.

As a result the maximum lift will be lower and the drag at low speed will be much higher compared to conventional transport aircraft. For the same field performance a fixed geometry wing will therefore be larger and the installed takeoff thrust will be higher for a given takeoff mass. Concorde used afterburners in takeoff, leading to very high noise levels.

With a relatively large wing and large engines the opimum cruise altitude is much higher than for subsonic transport aircraft. Concorde cruises roughly 15000 ft higher than conventional transport aircraft.

With a variable sweep wing the configuration is essentially conventional when the wings are swept forward. This means that wing loading and thrust loading may be comparable for the same field performance. For supersonic flight the wing sweepback can be set for the required Mach number, typically 60° at the leading edge for M 1.6, without being compromised for low speed conditions.

Compared to fixed supersonic wing designs this leads to much less wing area and much less thrust required for a given takeoff mass. For cruise flight this leads to a lower optimum cruise altitude; in supersonic flight both the lift of the wings and the thrust of the engines are basically proportional to the air density, and as the air density at the altitudes of interest reduces by about 15% for every km higher cruise altitude, large reductions in engine size and wing area can be compensated by relatively modest reductions in cruise altitude.

This is illustrated by fig.2.

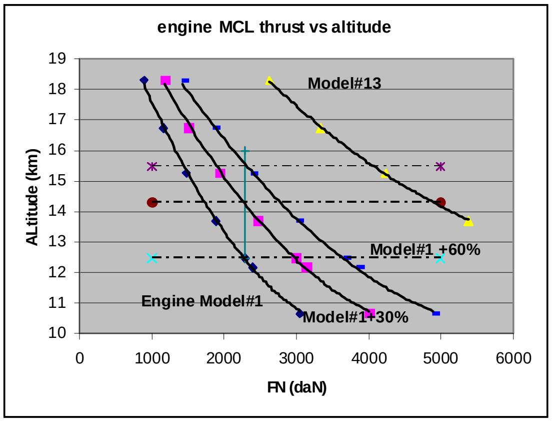


Fig. 2 HISAC engine models thrust level at M 1.6

In fig 2 the max climb thrust of HISAC engine models at M 1.6 is plotted against altitude. These engine models are scaled versions of a reference model, engine model #1 and a larger engine, model #13. This example shows that if the engine could be scaled down by a factor of 1.6 due to the improved performance of a variable sweep wing in takeoff, a reduction of cruise altitude by about 3 km would recover the climb/cruise thrust loss.

On the other hand, the installation of the wing hinge, a heavier high lift system and a high effective aspect ratio will lead to a wing which will be much heavier per unit area. Mechanical complexity is increased and the area of the wing around the hinge will have a drag penalty.

In order to bring these effects in mutual perspective a swing wing design and a fixed wing design have been developed to meet the same requirements using the same design tools. This will be discussed in the next paragraphs.

## 4 Design Study Variable Sweep wing

### 4.1 Design tools

For the development of the design concept ADSE in-house tools have been used, supplemented by open literature tools. In the early phase, intended only to identify characteristic differences between variable sweep and fixed wing configurations relatively basic design tools were used. They are discussed in [1] and are briefly described here.

The friction drag is calculated based on the wetted area of the different components, including shape factors and interference factors, taking account of the Reynolds number at the actual cruise altitude. The zero lift wave drag is calculated using the classical linear method of Jones [2], with the Jumper area rule method [3]. The lift dependent drag was calculated as a part vortex drag and a part lift dependent wave drag. The vortex drag is calculated with an ADSE in-house method (parameters aspect ratio and $CL^2$), the lift dependent wave drag was calculated with the method of RT Jones [2].

The maximum lift has been estimated with an ADSE in-house model. The method has been calibrated a.o. on a windtunnel test of a NASA variable sweep wing design as reported in NASA TN-D8380 [4]. A simplified vortex lattice model provides induced drag characteristics.

The structural mass is estimated with ADSE in-house analytical methods. The method has been calibrated on modern conventional transport aircraft and on a design concept of a Mach 2 airliner. For determination of the mass of the hinge and surrounding structure a simple structural model has been set up, based on estimated loads. This showed that the hinge fits within the room available.

For determination of the shift of the aerodynamic centre and for a first sizing of the horizontal tail surfaces a vortex lattice program was used [5].

The subsonic parts of the mission have been calculated with an ADSE in-house mission analysis program. For the supersonic parts of the mission a method was developed to calculate the flight path of the different mission elements (transonic acceleration, climbing cruise and supersonic descent), connecting to the subsonic climb and descent modules.

## 4.2 General layout

The reasoning behind the aircraft configuration has been described in [1]. It is summarised as follows:

The wing sweep concept is based on a proposal from SCA: see fig. 3

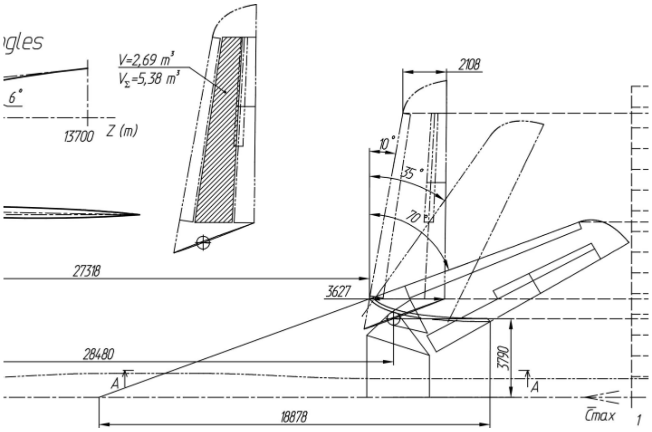


Fig. 3 Swing wing geometry provided by SCA

This was modified to have only 2 wing positions: a single subsonic position, both for transonic flight and takeoff/landing, and a supersonic position optimised for the M1.6 design cruise speed. This eliminates most of the aerodynamic centre shift due to wing movement –which is largest in the range of 10 to 35° sweep- and reduces the space required for the wing movement system and to stow the inner wing in swept aft position. This will reduce the benefit in low speed performance, but at this stage this is judged to be acceptable.

In the subsonic/low speed position the movable wing panels now have 35°leading edge sweepback and in the supersonic position 60° sweepback. This results in fully subsonic leading edges during M 1.6 cruise.

The inner, fixed part of the wing has a leading edge sweepback of 70°. This allows a relatively thick inner wing with a useful height at the hinge location, a useful fuel volume and helps the forward sweep of the isobars in the wing/fuselage interaction region.

The wing spanwise hinge position determines the achievable difference between high speed and low speed characteristics to a large extent, and also determines the shift of the aerodynamic centre due to wing panel movement. In the design presented here the hinge position and the landing gear mounting have been integrated such that the hinge position could be positioned as far inboard as possible. This allows the largest practical span increase and locates the hinge in a relatively thick part of the wing, albeit with higher bending moments. Later analysis showed that the shift of the aerodynamic centre was limited to about 5% Mean Aerodynamic Chord (MAC)

The outer wings have slats and fowler flaps with a large area extension. The inner wing has no high lift devices. Based on the predicted low speed performance the wing has been sized to the approach speed requirement, the engine was subsequently sized to the required takeoff performance. This allows an initial cruise altitude of 43000 ft, which satisfies the requirements (par. 2.1).

Due to the relatively large weight of the fuel the Centre of Gravity (CG) of the fuel should be close to the CG of the empty aircraft, and close to the aircraft aerodynamic centre, to minimise the CG travel. This allows the smallest practical horizontal stabilizer. This determines the relative location of wings, fuselage and engines.

The engines are relatively conventional turbofan engines with bypass ratio 3.7 as defined by CIAM and SNECMA for the HISAC project. They were placed at the rear of the inner wing, as a compromise between area ruling, structural considerations and aircraft balancing. Due to the proximity of the movable wing panels, the engines cannot easily be mounted on the wings themselves; the most direct load paths being crossed by the wing in fully swept position. Therefore the engines are supported from the fuselage behind the landing gear bay, with the engine pylons integrated in the wing trailing edge. This leads to a relatively long wing root chord with a low thickness/chord ratio (t/c). The engine inlets have been positioned underneath the wing surface, where the low local Mach number and high relative pressures lead to a higher intake pressure recovery. With a low set wing there will be no appreciable interference between the engines and the fuselage. A disadvantage is higher sonic boom overpressures with underwing mounted engines.

The distance between both engines gives a good possibility that a non-contained failure of one engine may be certifiable without special protective measures on the other engine, as the ratio of fan diameter to the distance between the engines is comparable to contemporary rear engined transport aircraft. This engine position may be susceptible to FOD and water thrown up from the nose wheel however, leading to the requirement for rimmed nosewheel tires.

A conventional empennage layout has been selected as this leads to a better overall arrangement in terms of area ruling. The tailplane was sized for a CG range of 8% MAC and neutral static stability at the aft CG limit with the wings swept forward. The tailplane was mounted high enough to avoid interference with the engine exhaust flow.

In the rear fuselage a trim tank will be installed to counter the shift of the aircraft neutral point caused by the transition from subsonic to supersonic flight and vice versa.

Fig.4 shows the resulting design, AD1104

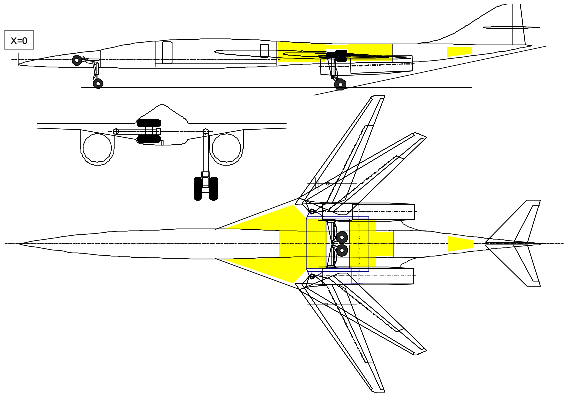


Fig. 4 General Arrangement design AD1104

The location of the fuel is given in yellow. Both wing hinges are connected via a structural box across the fuselage. The engines are supported by a structural box across the fuselage. A structural member connects the wing and the engine structural box on both sides of the aircraft, this forms a supporting structure for the main landing gear. The enclosed space forms the main undercarriage bay.

The cross sectional area distribution is determined by the required fuselage diameter at the front of the cabin and by the space required for the landing gear. The resulting area distribution is close to the ideal Sears-Haack distribution, which is to a large extent caused by the relatively small wing cross section. The next pictures shows the design with wings swept forward and aft:

## 5 Parallel Design with fixed wing geometry

To identify the basic effects of variable sweep wings the study included the definition of a parallel design with a fixed sweepback design. This was designed to the same performance specification, using the same design tools and assuming comparable technology levels. This approach eliminates possible systematic errors in the weight and drag prediction methodology to a large extent. The wing comes out much larger due to the lower CLmax, which also drives the empennage area. The large angle of attack associated with highly swept wings at low speed leads to a much higher landing gear. It was described in [1]. See fig. 5:

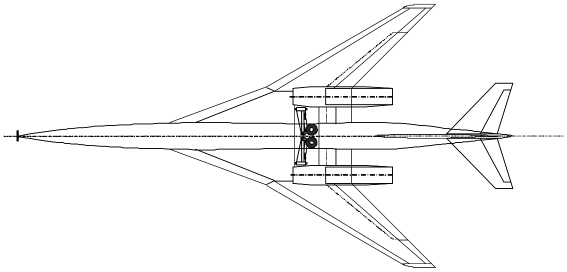


Fig. 5 Plan View Design AD1201

The maximum lift coefficient of the fixed wing design was calculated to be 1.1, vs 1.7 for the variable sweep wing design. Lift drag ratio in takeoff was calculated to be 7.7, which is probably optimistic as no leading edge vortex drag was taken into account. This compares to an L/D of 10.3 for the swing wing design. This results in the following comparison (fig 6), when both designs are sized for the same mission performance and the same field performance:

| | AD1104 | AD1201 Resized |
|---|---|---|
| | Variable Sweep wing | Conventional |
| MTOW (kg) | 43000 | 55000 |
| OEW (kg) | 23600 | 31233 |
| Wing area (sqm) | 92.5 | 176 |
| Installed TO thrust (daN/engine) | 7000 | 12300 |
| Initial Cruise Altitude | 43000 ft | 49000 ft |
| Range with 800 kg payload (nm) | 4025 | 4027 |
| Block fuel max range (kg) | 16840 | 20236 |
| Subsonic range (nm, M0.95) | 5061 | 3800 |
| TOFL (MTOW, SL, ISA+15C) | 6290 ft | 6400 |
| Approach speed @ MLW | 140 | 139 |

Fig. 6 Comparison variable sweep design vs. fixed geometry

Although due to the high cruise altitude the L/D of the fixed wing design is somewhat better than that of the swing wing the benefits in empty weight caused by the smaller wings and engines, and the fuel savings in the subsonic elements of the mission strongly override this effect. As a result the maximum takeoff weight of the fixed wing design is almost 30% higher. This means that the “snowball effect” is very large, being responsible for a significant part of the sizing of the wing and the engines. This is typical for supersonic designs operating at relatively long ranges, and differences between the two designs tend to be magnified by this effect. The results are therefore very sensitive to inaccuracies.

Some of the major weight differences are given in fig. 7:

| | AD1104 | AD1201 | |
|---|---|---|---|
| Wings, ex hinge | 4204 kg | 7673 kg | Including connecting structure in fuselage |
| Hinge plus drive system | 1023 kg | | |
| Engines inc. nacelles | 5682 kg | 7768 kg | |
| Reserve fuel | 1863 kg | 2834 kg | Difference 970 kg |

Fig. 7 Some characteristic weight differences

Note that the weight penalty of the hinge plus drive system is comparable to the weight saved in reserve fuel alone; as this fuel is carried around in all flights from takeoff to landing the designs are just as sensitive to this as to an equivalent empty weight difference.

## 6 Design refinement

In the second phase of the design the aircraft conceptual design was refined, and the design tools were calibrated on other designs developed in the HISAC programme. This involved the following elements [6]:

- The drag of the AD1104 design was analysed by NLR and DLR using advanced CFD tools. This showed about 10% higher drag compared to the used methods.
- The engine spillage drag was estimated based on [7] and [8].
- The weight prediction was calibrated on the results of other HISAC design teams

- The approach speed requirement had been relaxed for all designs during this phase, reducing the required wing area
- Based on optimisation studies a triple engine configuration was adopted. This also improved margins to the ICAO stage IV noise regulations
- Wing sweep actuation loads were determined and the system was sized to this. The actuators were located in front of the hinge connecting box as this area is relatively free of other systems. The fuel tank layout was adapted to this.
- The mission model was refined to be more representative for the performance requirements of the design.

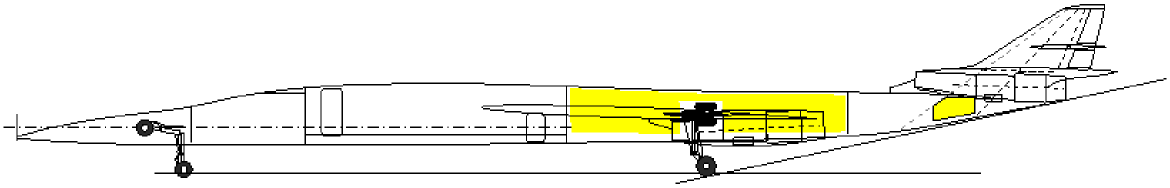
Fig. 8 shows the most important data of the revised design. Although the fuel over the mission has increased considerably, due to the reduced empty weight the maximum Takeoff Weight has reduced somewhat. The next picture gives the general arrangement of the resulting design AD1107:

| | **AD1107** |
|---|---|
| **MTOW (kg)** | **42500** |
| **Wing area (sqm)** | **75** |
| **Start of Cruise altitude (ft)** | **43000** |
| **L/D Start / end of cruise** | **7.88/7.54** |
| **Block fuel 4000 nm (kg)** | **18560** |
| **Subsonic range (nm, M0.95)** | **6000+** |
| **TOFL (MTOW, SL, ISA+15C)** | **1971/6466** |
| **Approach speed @ MLW** | **136 kts** |

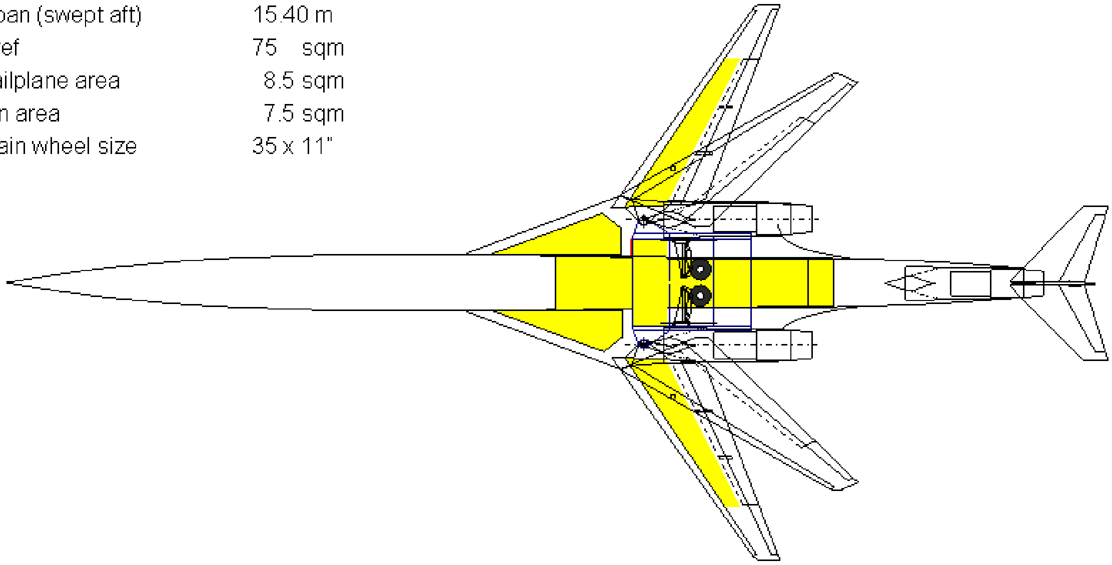
Fig. 8 Summary of data AD1107

The difference in lift drag ratio (L/D) between the start and the end of the cruise flight is mostly attributable to the difference in Reynolds number.

The refined mission model is defined to allow the lowest loads on the airframe and minimise the thrust requirements for transonic flight, as follows:



| | |
|---|---|
| Length o.a. | 40.8 m |
| Span (swept fw ) | 20.6 m |
| Span (swept aft) | 15.40 m |
| Sref | 75 sqm |
| Tailplane area | 8.5 sqm |
| Fin area | 7.5 sqm |
| Main wheel size | 35 x 11" |



With the engine sized for takeoff acceleration to supersonic speeds is executed at a relatively low altitude, where the aircraft accelerates to a speed where the dynamic pressure is equal to that at the beginning of the cruise. This translates to a speed just beyond M 1. With the thrust increase due to the higher airspeed acceleration and climb rate are balanced to keep the dynamic pressure constant in the climb phase. Top of climb is reached when the aircraft with the engine throttled back to max cruise rating just achieves M 1.6. This is depicted in fig.9:

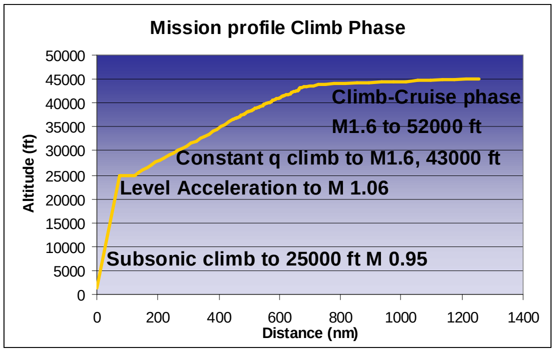


Fig. 9 Mission profile (first part)

## 7 Community noise

The airport noise has been calculated with a simplified method from Stanford University [10] calibrated on the certified noise levels of the Fokker 70 in high gross weight condition. The Fokker 70 is quite close to design AD1107 in weight and general dimensions, and the Rolls Royce Tay engines of the Fokker 70 are comparable in overall thrust level and bypass ratio to the engines used for AD1107.

In the calibration it is assumed that the Fokker 70 configuration, with its rear engines virtually over the wing trailing edge, has a benefit of 2dB due to noise shielding, which would not be available for the AD1107 design as 2 of the 3 engines are below the wings.

This may be somewhat conservative as no credit has been taken for the application of extensive acoustic lining in the long engine intakes of AD1107. Also the bypass ratio of the AD1107 engines is higher than that of the Rolls Royce Tay 620 engine (3.72 vs 3.1).

The flight paths of the Fokker 70 and the AD1107 have been calculated with the same performance program, where the cutback altitude of AD1107 has been taken at the minimum certifiable value. The Fokker 70 cutback altitude is optimised for minimum fly over noise. See fig. 10.

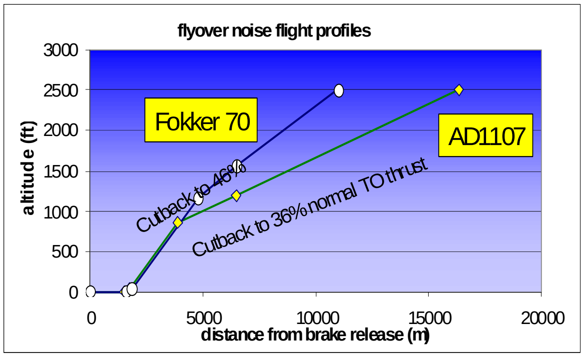


Fig. 10 Flyover noise profiles F70 and AD1107

It proves that the 3 engine configuration of AD1107 allows a deeper cutback, and that a higher cutback altitude would probably be beneficial for the AD1107.

Fig.11 shows the certification noise levels of the Fokker 70 and the calculated noise levels of the AD1107 resulting from this approach.

| Certification noise levels (EPNdB) | Fokker 70 | ICAO ch.3 | AD1107 | ICAO ch.3 |
|---|---|---|---|---|
| MTOW (kg) | 41730 | | 42000 | |
| MLW (kg) | 36740 | | 28000 | |
| Sideline | **89.5** | 94.6 | **90.2** | 94.7 |
| Flyover | **80.1** | 89.0 | **82.5** | 91.2 |
| Approach | **88.3** | 98.6 | **86.2** | 98.6 |
| **Cumulative** | **257.9** | **282.2** | **258.8** | **284.5** |

Fig. 11 Certification Noise levels AD1107 and Fokker 70

The Fokker 70 has a very large margin to ch.4, and this can be expected for design AD1107 as well. In additional with 3 engines the noise limit is 2.2 dB higher in the Flyover condition.

Although this prediction method is still relatively crude, the calibration with the Fokker 70 gives confidence that the AD1107 design may be certified against Chapter IV requirements with good margins. This is caused by the fact that the aircraft in low speed configuration is essentially a subsonic shape, with associated relatively low drag in takeoff and landing, and the engines have a relatively high bypass ratio.

## 8 Sonic boom

The design has not yet been analysed on its sonic boom characteristics. As no special measures have been taken to reduce the sonic boom the resulting boom characteristics will not meet the HISAC requirements for overland flight, a.o. because the engines are located under the wing, and because the cross sectional area distribution is optimised for minimum wave drag, and not for minimum sonic boom intensity.

If a variable sweep wing would be married to a minimum sonic boom architecture the following basic effects would occur:

- The lifting length of the wing for a given weight would probably be less, as the wing would be smaller. This tends to increase the sonic boom
- Basic boom mitigation methods remain possible and effective
- The lower aircraft weight would reduce the sonic boom somewhat.

It is expected therefore that most of the benefits as projected for the variable sweep wing architecture will also occur on a design optimised for low sonic boom.

## 9 Emissions

Compared to fixed wing designs considerably less fuel will be used. This leads to a proportionally reduced amount of Global heating Gases (GHG's).

In [11] the emissions have been calculated for the beginning and the end of the cruise segment of the mission, using the method provided in [12], weighing the resulting effect with the fuel flow in both conditions. The resulting temperature effect is considerably less than that of other HISAC designs. This is mostly caused by the reduced climate effect of water vapour at lower stratospheric altitudes.

Of course this only qualifies the environmental performance relative to other supersonic aircraft; although no direct comparisons have been made it seems obvious that emissions and climate effects will still be considerably larger than of subsonic designs with comparable payload range performance.

## 10 Certification issues

Based on discussions with EASA in the context of the HISAC projects [9], the wing hinge and drive system can probably be certified according to known experience with other flight critical moving parts, such as all-moving tailplanes.

The most critical condition would probably be a requirement to be able to execute a safe landing with the wings jammed in the most aft position. This is possible with the lifting capabilities of the wings as now defined at a low landing weight: most of the fuel may be assumed to be used or dumped. It is not required to demonstrate proper stalling characteristics in this flight condition.

## 11 Conclusions

Using relatively simple tools two designs for a supersonic business jet have been set up, both meeting the same performance requirements. This showed that with a variable sweep wing such an aircraft will have a much smaller wing and much smaller engines to meet the specified field performance requirements. The resulting cruise altitude is much lower than for a fixed wing design, but still exceeds the required 41000 ft Start of Cruise altitude.

A small penalty in lift drag ratio in cruise results, but the weight reduction of wings and engines, as well as the reduction of the amout of fuel carried for the subsonic parts of the mission, translates into a large reduction in the MTOW and the trip fuel consumption.

Further development of the variable sweep design showed that the mechanical design of the hinge seems technically feasible.

Community noise levels should be comparable to conventional modern transport aircraft, and meet ICAO ch.IV requirements with a large margin.

Sonic boom levels are not materially influenced by the variable sweep design.

Due to the relatively low cruise altitude and the low fuel consumption the effect on global temperatures will be lower than for the other HISAC projects, but will remain much higher than comparable subsonic business jets.

Although there is no history of certification for variable sweep commercial aircraft no obvious show stoppers have been identified.

Remaining uncertainties and risk areas of the variable sweep wing design are as follows:

- Hinge weight and hinge drag, including sealing of the hinge area at low and high speed
- Structure and systems integration in the hinge area
- Aeroelastic effects, including a possible effect of hinge wear

Compared to fixed geometry solutions the following aspects of the variable sweep wing design have lower risks:

- The cruise altitude is considerably less. This may reduce decompression and cosmic ray protection risks
- The low speed configuration is essentially subsonic; lift and drag are better predictable, no certification issues concerning stall definition and low speed drag divergence are expected.

The results prove to be very sensitive to small changes in weight and drag. Considering the identified uncertainties these conclusions are therefore still tentative therefore.

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