Dynamic hammershock effects on the air intake design of supersonic aircraft
J. Becker, H. Bergmann & W. Luber
Deutsche Aerospace AG, Military Aircraft,
LME273, 81663 Ottobrunn, Germany

1 Introduction

The design of an intake structure for supersonic aircraft is highly dependent on assumptions to be defined in the early design phase and in the subsequent check stress and structural clearance phases. The assumptions to be made are related mainly to the dynamic hammershock pressure wave and its dynamic behaviour in terms of magnitude depending on the pressure at the engine face, the shape of the intake / duct, the flight condition, the change of magnitude during its travel from the air intake to the engine along the duct to the forward intake and the effect of surge interaction in case of two engine intake / ducts. The assumptions have to be based on the extrapolation of known data from other existing projects and a statistical approach has to be chosen with respect to the probability of occurrence of the hammershock for flight hour and aircraft missions. Secondly the effect of dynamic response of the intake duct structure has to be carefully estimated during design.

The design philosophy can be based on the concept that the structure is able to carry for the limit load case a static loading consisting of flight manoeuvre loads, steady-state pressure and a maximum positive and negative hammershock pressure factorised by a dynamic factor and that the structure withstands ultimate loading resulting from steady-state pressure and manoeuvre loads with the allowance for plastic deformation due to ultimate hammershock pressure. For both concepts it is essential during the different design and clearance phases to verify the assumptions made from the beginning using comparisons of different methods, experimental results from model tests, on aircraft ground surge interaction tests and flight test results. The careful consideration of all dynamic aspects allows for a design without bigger weight penalties.
The paper presents a description of the hammershock loading, different calculation tools for dynamic response due to hammershock, results from calculation and validation of calculated results.

2 Hammershock loading

Aircrafts with supersonic flight capability require an intake / duct in front of the engine because the engine cannot operate in supersonic flow conditions. Therefore the intake / duct has to be designed for subsonic flow conditions at the engine face (fig. 1).

Origin of hammershock (H/S)

From the compressor region up to the combustion chamber a strong steady pressure increase occurs (fig. 2). Near limit engine performance conditions a short-time pressure wave, called hammershock, can occur which advances in opposite direction of the airflow with high velocity \( v_{HS} \approx 300 \text{ to } 400 \text{ m/s} \). Under normal distortion free conditions there is a steady pressure increase of the air until the combustion chamber of the engine. If a high unsteady pressure difference occurs which is caused by distortion of the air flow at limit engine performance conditions, an engine surge will occur, fig. 2. This surge causes a very short pressure wave, which travels in opposite direction of the flow direction. The shock like wave - called hammershock (H/S) - produces a pressure up to 3 times of the steady state pressure.

Effect of engine bypass ratio and compressor overall static pressure ratio on H/S peak pressure

Increasing the compressor overall pressure ratio in general increases the ratio peak H/S pressure to steady-state pressure at engine face and a decrease in engine bypass ratio leads to an increase in hammershock peak pressure.

Assumption of design H/S pressure

The extrapolation of air intake H/S peak pressures from existing engines has to be based upon the evaluation of the root mean square value added to the mean pressure as function of the overall static compressor pressure ratio. The peak H/S pressure is then chosen as 3 times or 2 times of the root mean square value added to the mean value pending design assumptions.

Description of dynamic hammershock wave

The definition of the design hammershock wave is in general derived from experimental on ground surge - and flight test surge tests. Measurements performed on different aircraft at the engine face show typical time histories of the pressure at A.I.P. (air intake pressure), see for example fig. 4. The general evaluation of a set of time histories will allow a definition of the H/S pressure time history for subsonic and supersonic flight condition as demonstrated in fig. 5. Important for dynamic response is, besides the magnitude of the peak value,
the rise time to the positive peak value (values from 5 msecs down to 0.6
msecs have been measured) and the rise time to the negative peak value. It has
to be noted that the negative H/S pressure wave resulted from the reflected H/S
at the forward intake.

Effect of duct cross section on design
Different duct cross section shapes lead to different design conditions (fig. 3)

- supersonic intake duct case in the square shaped duct membrane stresses are
  critical for the more flat panels. In the tank region additional tank
  hydrostatic and tank system pressures ($p_{TH}$ and $p_{TV}$) cause an attenuation of
  the total differential pressure on duct skin.
- subsonic intake duct case in the round shaped duct stability requirements
design the panels. In the tank region additional tank hydrostatic and tank
  system pressures ($p_{TH}$ and $p_{TV}$) cause an increase of the total differential
  pressure on duct skin.

3 Analytical procedure

The intake / duct structure has to be analysed in the different design steps in
order to calculate the resulting stresses on the intake / duct panels and frames
due to a total loading from manoeuvre 'g' loads, steady-state pressure,
hydrostatic pressure from fuel and dynamic hammershock pressure.
In order to perform dynamic calculations a finite element model (FEM) has to
be established which is able to describe local structural responses up to 5 kHz,
i.e. to cover essential panel vibration modes and which has the capability to
introduce the static loads or displacements from manoeuvres and steady-state
pressures.
In general for dynamic calculations an existing static FEM is modified by
subdividing each of the original elements according to the frequency resolution
requirement, see fig. 8.
A full structural idealisation of the total intake / duct structure which would
fulfill this requirement is not feasible at the moment due to the enormous
complexity of the model leading to computer capacity and computer time
problems which would hinder a practicable approach. Therefore different
structural sections of the duct have to be treated.

Calculation tools for limit load and ultimate load case
Different tools are applied in the dynamic investigations. In the first step, the
natural frequencies and elastic mode shapes are calculated using NASTRAN
SOLUTION 63 for model vibration analysis. In the second step for the
investigation of the stresses and dynamic displacements in the limit load case
NASTRAN SOLUTION 109 is applied for transient response analysis, with and
without static preload using a dynamic hammershock load as described in para.
2, fig. 5. The properties of the geometry and of the elastic materials are linear.
During the dynamic calculation local concentrations of high displacements and corresponding stress nests occur, see fig. 6, which change in magnitude and position with the travel of the hammershock wave. The maximum stresses may remain for limit load case within the stress limit $\sigma_{0.2}$ with the effect of the dynamic response covered by a dynamic factor on hammershock pressure in static design required by design philosophy. For this case the verification of the static design can be performed with NASTRAN SOLUTION 109, assuming that geometrical nonlinearities are not significant. For the ultimate load case the design philosophy might be based on the assumption that the duct structure is designed to ultimate loads from flight manoeuvres including steady state duct and hydrostatic pressures only, where the stress pulse from the ultimate hammershock pressure increment is covered by the plastic deformation capability of the duct material, see fig. 7 right side. For this approach, a nonlinear dynamic calculation with DYNA3D including nonlinear plastic material description and nonlinear geometrical properties is necessary for verification.

4 Results - Validation of Tools

4.1 Comparison of different methods

Dynamic hammershock calculations have been performed on supersonic squared shaped and subsonic circular shaped duct sections using NASTRAN SOL 109 and DYNA3D software in order to verify analytical tools and to verify dynamic factors used in the static design. Fig. 8 demonstrates that the original FEM for static calculations has to be refined for dynamic calculations from the frequency resolution point of view. A typical example of a dynamic model was a FEM consisting of 2348 grids, 12164 degree of freedom, 2073 QUAD elements, 785 triangular elements, 631 bar elements and 608 rod elements. Fig. 9 demonstrates that the local response of the stress on outer and inner side of the duct skin varies from element to element, i.e. the dynamic factors are different. The verification of an assumed dynamic factor in static design is demonstrated in the comparison of a static calculation with increased hammershock load and a dynamic calculation using SOLUTION 109 with a hammershock acting from 0 to 10 msecs on the structure in fig. 10a and 10b.

The comparison of static and dynamic calculation results resulted in an almost equivalent ratio of maximum stress to allowable stress $(\sigma/\sigma_A)_{\text{static}} = 0.57$, $(\sigma/\sigma_A)_{\text{dyn}} = 0.58$. Fig. 10b shows in addition that large structural portions have smaller stress levels than seen from the static calculation, fig. 10a. The comparison of the different methods SOLUTION 109 with DYNA3D resulted in excellent agreement for limit load case investigations.
4.2 Comparison with experimental results

The dynamic response was measured in terms of strains on a duct test section. A finite element model of the test section was used for calculation of strains with the DYNA3D model using an input the experimental pressure pulse. The comparison of measured and calculated strain was reasonable good to validate the calculation.

5 Conclusions

- There is sufficient evidence for the application of software tools from the performed comparisons of calculated results using NASTRAN SOLUTION 109 and DYNA3D and from the comparison from calculated and measured dynamic strains for dynamic hammershock response and stress calculation in the process of the verification of air intake - duct structure.
- Comparison of local dynamic stress calculations to static stress calculations with assumed constant dynamic load factors (based on identical FEM) indicate that the dynamic tools could be applied not only for verification but also for the design to minimise structural weight. The dynamic design approach is relatively more complex and time consuming. The profits of local dynamic design might be reduced by manufacturing constraints.
- The verification of the assumed magnitude of the hammershock pressure and its risetime for a given shape of duct is the most important step for structural clearance.
Fig. 1: SCHEME OF INTAKE / DUCT OF SUPERSONIC AIRCRAFT

Fig. 2: ORIGIN OF HAMMERSHOCK

Fig. 3: INFLUENCE OF INTAKE / DUCT SHAPE ON TOTAL PRESSURE INCLUDING HAMMERSHOCK
Fig. 4: TIME HISTORY OF MEASURED INFLIGHT HAMMERSHOCK AT ENGINE FACE, SUBSONIC CASE

Fig. 5: HAMMERSHOCK WAVE SHAPES FOR SUPersonic AND SUBsonic CASES AT ENGINE FACE DERIVED FROM EXPERIENCE

Fig. 6: STRESS DISTRIBUTION AT TIMESTEP T ACCORDING TO A DYNAMIC LOAD CASE

Fig. 7: AIR INTAKE / DUCT DESIGN, STRESS / STRAIN RELATION FOR LIMIT / ULTIMATE LOAD CASE
426 Structures under Shock and Impact

Fig. 8: **FINITE ELEMENT MODELS OF INTAKE / DUCT STRUCTURES**

![Finite Element Models](image)

Fig. 9: **TYPICAL RESPONSE OF DIFFERENT DUCT SKIN ELEMENTS ON HAMMERSHOCK EXCITATION**

![Typical Response](image)

Fig. 10: **COMPARISON OF STATIC AND DYNAMIC HAMMERSHOCK CALCULATION RESULT**

![Comparison](image)