Towards a Tool for the Noise Assessment of Aircraft Configurations

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This lecture deals with the first steps of the development of a ray tracing code for the assessment of acoustic shielding effects of engine installations at new aircraft configurations.

The work has been performed at DLR in the project 'Configurations 2020' within the framework of the national German aeronautical research program III.

Outline

- Introduction
- Ray equations
- Algorithm
  - Geometry description
  - Shooting algorithm
  - Source Description
- First tests
  - No diffraction, no mean flow
  - Boeing 747 and LNA-configuration
- Summary and Outlook

After an introduction the basic acoustic ray equations with and without taking a mean flow field into account will be given.

The emphasis of the lecture is laid on the details of the numerical algorithm.
So far, only the reflection of rays at the geometry is implemented in the code.
Future work will take into account diffraction effects and a mean flow field.

Finally, first shielding calculations at a Boeing 747 geometry and a new Low-Noise-Aircraft (LNA) configuration will be given.

Acoustic Shielding

- **Task**
  - Calculation of the interaction of the airframe geometry with sound waves.
  - Goal is to assess the influence of different engine positions on the sound signature of the aircraft.

- **Approach**
  - Since it requested to develop a tool suitable for use in the design phase of an aircraft, the usual CAA methods, e.g. based on the solution of the linearized Euler equations, seem to bee much too expensive.
  - Therefore, it is suggested to use a ray tracing algorithm to tackle the problem.

The basic motivation for using a ray tracing approach for the solution of the governing equations are the prohibitive numerical costs of classical CAA methods, which usually solve the discretized equations in the whole space.

Efficiency is especially important, since during the design phase of an aircraft a lot of different configurations have to be assessed acoustically.

Ray Tracing

- The basic idea of ray tracing is to consider the high frequency limit of the governing linearized Euler equations. Then one can calculate an approximation of the solution along curves in space, so called rays, by the solution of ordinary differential equations.
- The principal approach is to calculate all rays between a source point $\boldsymbol{x}_0$, and an observer point $\boldsymbol{x}_1$, and to sum up the amplitude contributions of all these rays.
- The high frequency limit assumes that the geometric length scale L of objects in the sound field is considerably larger then the wave length λ of the components of the solution.

$$L \gg \lambda$$

In the high frequency limit the solution of the governing (linearized Euler) equations can be calculated along curves in space which are solutions of ordinary differential equations.

Usually, one is only interested in the solution at relatively few points in space (observer points) which can be quite efficiently reached by a shooting procedure.

Restrictions of Ray Tracing

- The most important restrictions of the high frequency limit are
  - No diffraction of rays on bodys (Remember light rays!)
    - Try to taken into account e.g. by geometrical theory of diffraction.
  - Caustics possible in case of inhomogeneous flow fields.
    - Caustics are envelopes of intersecting rays.
    - Can be complicated surfaces in 3d.
    - Special approximation necessary.

The most important drawbacks of the straightforward ray tracing approach are the neglection of diffraction and the possible existence of caustics in case of inhomogeneous mean flow fields.

A possibility to take diffraction effects into account is the application of the geometrical theory of diffraction.
The treatment of caustics, which can have a complicated structure in the general 3d-case, needs special local approximations of the underlying differential equations.

Ray Tracing without Mean Flow

Helmholtz equation for pressure

$$p_{,kk} - (\ln \rho_0)_{,k}\, p_{,k} + \frac{\omega^2}{c_0^2} p = 0$$

Density $\rho_0(\boldsymbol{x})$
Sound speed $c_0(\boldsymbol{x})$

Debye series: asymptotic expansion for frequency $\omega \to \infty$

$$p(\boldsymbol{x}, \omega) = e^{i\omega\psi(\boldsymbol{x})} \sum_{m=0}^{\infty} \frac{A_m(\boldsymbol{x})}{(i\omega)^m}$$

Phase function $\psi(\boldsymbol{x})$
Amplitude factors $A_m(\boldsymbol{x})$

Gradient of phase function and its length

$$\nu_k \equiv \psi_{,k}(\boldsymbol{x}), \qquad \nu \equiv \sqrt{\nu_k \nu_k}$$

As first example for the ray tracing approach, the acoustic wave equation in case of an inhomogeneous field of density and sound speed is considered.

The ansatz for the high frequency limit is a socalled Debye series which introduces a phase function $\psi(\boldsymbol{x})$ and amplitude factors $A_m(\boldsymbol{x})$.

An important quantitiy in the calculations is the gradient $\nu_k = \psi_{,k}(\boldsymbol{x})$ of the phase function and its length $\nu = \sqrt{\nu_k \nu_k}$.

Ray Tracing without Mean Flow

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Substitution gives at 0th -order the eikonal equation $(\nu_i \equiv \psi_{,i})$

$$H(x_k, \nu_k) = \frac{1}{2}\left(\nu_i \nu_i - \frac{1}{c_0^2}\right) = 0$$

The ray $\boldsymbol{x}(\tau)$ is a solution of the ODE's

$$\frac{dx_k}{d\tau} = H_{,\nu_k} = \nu_k \qquad \frac{d\psi}{d\tau} = \nu_k \frac{dx_k}{d\tau} = \nu_k \nu_k$$

$$\frac{d\nu_k}{d\tau} = -H_{,x_k} = (c_0^{-2})_{,k}$$

The amplitudes $A_m(\tau)$ can be calculated from the hierarchy (D is the Jacobian of ray)

$$\frac{d}{d\tau} \ln \frac{A_0^2 D}{\rho_0} = 0 \qquad D = \left|\frac{\partial(x,y,z)}{\partial(\tau,\theta,\phi)}\right| = \frac{\partial \boldsymbol{x}}{\partial \tau} \cdot \left(\frac{\partial \boldsymbol{x}}{\partial \theta} \times \frac{\partial \boldsymbol{x}}{\partial \phi}\right)$$

$$A_m \frac{d}{d\tau} \ln \frac{A_m^2 D}{\rho_0} = -\frac{\partial^2 A_{m-1}}{\partial x_k^2} + \frac{\partial A_{m-1}}{\partial x_k} \frac{\partial \ln \rho_0}{\partial x_k}$$

Substitution of the Debye series into the wave equation and collection of terms with the same power of the frequency yields at 0th- order the socalled eikonal equation.
This is a partial differential equation of first order for the phase function and thus can be solved along characteristic curves.

The higher order terms result in a hierarchy of ordinary differential equations for the amplitude factors. Especially simple is the equation for the first coefficient A_0 : Its square times the Jacobian D of the ray divided by the density is constant along the ray. Its initial value has to be determined from the source model.

The differential equation for A_0 becomes singular for $D=0$. This indicates the intersection of neighboring rays and thus the development of a caustic.

The determination of the higher order amplitude factors requests the calculation of partial derivatives of increasingly higher order with respect to x, i.e. one has to calculate an increasingly higher number of nearby rays.

It is expected that for frequencies high enough it is not necessary to take into account more than the first few terms of the Debye series.

Ray Equations without Mean Flow

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Density and sound speed constant!

$$\frac{dx_k}{d\tau} = \nu_k \qquad \frac{d\nu_k}{d\tau} = 0$$

$$\frac{d\psi}{d\tau} = \nu_k \nu_k$$

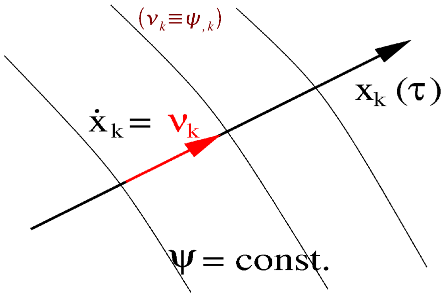
High frequency limit of

$$p_{,kk} + \frac{\omega^2}{c_0^2} p = 0$$

Amplitudes along the ray

$$\frac{d}{d\tau} \ln \frac{A_0^2 D}{\rho_0} = 0$$

$$\frac{d}{d\tau} \ln \frac{A_m^2 D}{\rho_0} = -\frac{A_{m-1,kk}}{A_m}$$



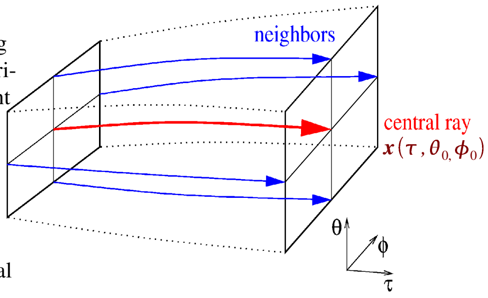
Rays are perpendicular to wave fronts

$$\frac{A_0^2 D}{\rho_0} = const.\ along\ the\ ray$$

In case of constant density and sound speed, the rays are straight lines which are perpendicular to the wave fronts, i.e. surfaces with a constant phase value.

Calculation of the Jacobian

Parametrization of rays emanating from a (point) source by parametrization of the initial phase gradient

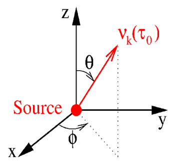


$$v_k(\tau=0)=v^0\begin{pmatrix}\sin\theta\cos\phi\\ \sin\theta\sin\phi\\ \cos\theta\end{pmatrix}$$

The Jacobian D is the infinitesimal volume of a ray tube:

$$D=\left|\frac{\partial(x,y,z)}{\partial(\tau,\theta,\phi)}\right|=\frac{\partial\boldsymbol{x}}{\partial\tau}\cdot\left(\frac{\partial\boldsymbol{x}}{\partial\theta}\times\frac{\partial\boldsymbol{x}}{\partial\phi}\right)$$

$$\frac{\partial\boldsymbol{x}}{\partial\theta}\approx\frac{\boldsymbol{x}(\tau,\theta_0+\Delta\theta,\phi_0)-\boldsymbol{x}(\tau,\theta_0-\Delta\theta,\phi_0)}{2\Delta\theta}$$



In order to calculate the Jacobian D, a parametrization of the rays is necessary. Here, a point source is assumed and two parameters are introduced by the spherical coordinates of the direction of the initial gradient of the phase function.

Ray Tracing with Mean Flow

Substitution of the vectorial Debye ansatz

$$\begin{pmatrix} p' \\ v_k' \\ \rho' \end{pmatrix} = e^{i\omega(\psi(\boldsymbol{x})-t)} \sum_{m=0}^{\infty} \begin{pmatrix} A_m(\boldsymbol{x}) \\ B_{km}(\boldsymbol{x}) \\ D_m(\boldsymbol{x}) \end{pmatrix} \frac{1}{(i\omega)^m}$$

into the linearized Euler equations yields the eikonal equation $(\nu_k \equiv \psi_{,k})$

$$H(x_k, \nu_k) = \frac{1}{2}\left(\nu_k \nu_k - \frac{1}{c_0^2}\left(1 - v_k^0 \nu_k\right)^2\right) = 0$$

$v_k^0 = v_k^0(\boldsymbol{x})$ is the mean flow velocity

If a mean flow field is present, the governing equations are the linearized Euler equations and one has to choose a vectorial Debye ansatz. The whole algebra is significantly more complicated but the 0^{th}-order eikonal equations is only a little bit more complicated than in case of no mean flow.

Ray Tracing with Mean Flow

The ray equations are

$$\frac{dx_k}{d\tau} = H_{\nu_k} = \nu_k + \frac{\nu}{c_0} v_k^0 \qquad \frac{d\psi}{d\tau} = \nu\left(\nu + \frac{\nu_k v_k^0}{c_0}\right)$$

$$\frac{d\nu_k}{d\tau} = -H_{x_k} = -\frac{\nu}{c_0}\left(\nu c_{0,k} + \nu_j v_{j,k}^0\right)$$

The pressure amplitudes $A_m(\tau)$ can be calculated from the hierarchy of equations (D is Jacobian of ray)

$$\frac{d}{d\tau}\ln\frac{A_0^2 D}{\rho_0 c_0^2 \nu^2} = 0$$

$$\frac{d}{d\tau}\ln\frac{A_m^2 D}{\rho_0 c_0^2 \nu^2} = r.h.s.$$

The ray equations follow by the same partial derivatives from the eikonal equation like in case of no mean flow.

The form of the differential equations for the pressure amplitudes is also very similar. Especially the equation for the 0th-order coefficient can again be integrated immediately. However, the right hand side of the higher order equations is considerably more complicated and cannot be given here.

Ray Equations with Mean Flow

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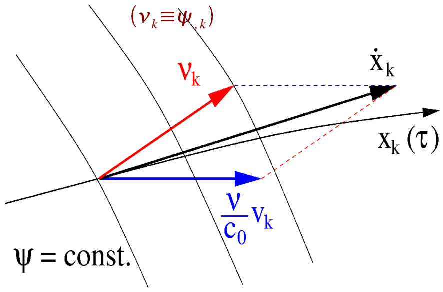
$$\frac{dx_k}{d\tau} = \nu_k + \frac{\nu}{c_0} v_k^0$$

$$\frac{d\nu_k}{d\tau} = -\frac{\nu}{c_0}\left(\nu c_{0,k} + \nu_j v^0_{j,k}\right)$$

$$\frac{d\psi}{d\tau} = \nu \left| \nu + \frac{\nu_k v_k^0}{c_0} \right|$$

High frequency limit of the LEE.



Amplitudes along the ray:

$$\frac{d}{d\tau} \ln \frac{A_0^2 D}{\rho_0 c_0^2 \nu^2} = 0$$

Rays no longer perpendicular to wave fronts!

$$\frac{d}{d\tau} \ln \frac{A_m^2 D}{\rho_0 c_0^2 \nu^2} = r.h.s.$$

$$\frac{A_0^2 D}{\rho_0 c_0^2 \nu^2} = \text{const. along the ray}$$

Only 0^{th} order coefficient implemented so far!

In case of a mean flow field, the rays are no longer perpendicular to the wave fronts. So far, only the equation for the first amplitude factor $A_0(\boldsymbol{x})$ is implemented in the ray tracing code.

Shooting Algorithm

- The ray equations are an initial value problem.
- The rays start at the source position.
- The solution is searched on selected points in space (target points).
- A shooting algorithm is appropriate ('ballistic' problem).
- A problem is the provision of suitable initial conditions for the phase gradient which determine the initial direction of the ray:
  - different rays can hit the same target point
  - several reflections on ray path possible
- A multi step algorithm is advisable.

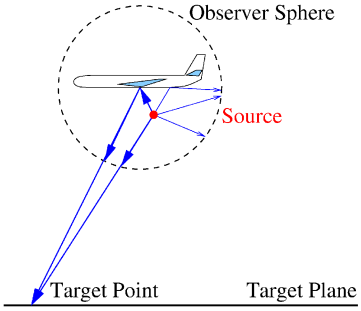
As mentioned above, generally the solution is sought only at selected points in space (target/observer points), which have to be hitten by the rays.
The required shooting algorithm for the ray equations requests the determination of suitable initial conditions for the phase gradient.

A special problem is that due to reflections at the geometry, a target point can be hitten by different rays whose initial conditions are not known in advance.

Therefore, the search for appropriate initial conditions has been split in several steps.

Shooting Algorithm

- Calculate rays in all space directions from source to an observer-sphere. Outside the observer-sphere the mean flow is assumed to be homogeneous and the rays are straight lines.
- Find those rays on observer-sphere that hit the target-plane.
- Select a point of the target-plane and determine initial conditions for the shooting procedure from rays hitting nearby.
- Determine all rays that hit the target point.



Here, we give a general overview over the shooting algorithm.
We wish to determine all rays starting at the source position that hit a target plane.

Starting at the source position, rays are launched in all space directions. The integration is stopped if an observer-sphere is reached, i.e. a sphere that encloses the whole geometry and outside of which the mean flow is assumed to be homogeneous.

Then, outside of the sphere the rays are straight lines and it is easily possible to calculate those rays that hit the target plane.

For a given target point on the plane, one can calculate initial conditions from rays that hit the neighborhood of the point.

Shooting Procedure

- Given
  - initial point x_k^0
  - initial length of gradient ν^0
  - target point x_k^{Target}
- Solve nonlinear equations with a Newton procedure to obtain (τ_1, θ, ϕ)

  $x_k(\tau_1, \theta, \phi) = x_k^{Target}$

- Problem: Appropriate initial values for (τ_1, θ, ϕ)

Differential equations

$$\frac{d x_k}{d\tau} = f_k(x_i, \nu_i, \tau)$$

$$\frac{d \nu_k}{d\tau} = g_k(x_i, \nu_i, \tau)$$

Initial conditions of ODE's

$$x_k(\tau=0) = x_k^0$$

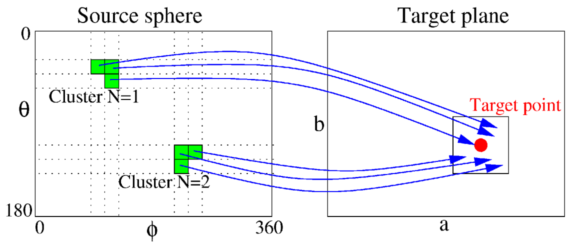
$$\nu_k(\tau=0) = \nu^0 \begin{pmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{pmatrix}$$

Once appropriate initial conditions have been calculated, the ray equations to the target point are solved by a Newton procedure. The unknowns are the initial angles (ϕ, θ) of the ray and the value τ_1 of the parameter along the ray in the target point.

Now some details of the determination of the initial values follow.

Initial Values for Shooting

Due to reflections, the same target-point can be reached from different positions on the source sphere.



Target point can obviously be reached by 2 different rays from the source.

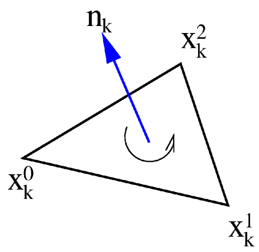
The mean values $(\overline{\tau}_1, \overline{\theta}, \overline{\phi})$ of cluster N will be used as initial value for the shooting procedure of ray N to the target point.

Due to reflections a target point can be reached from different positions on the source sphere (i.e. directions from the source position). After shooting from the source to the target plane, one can generally identify the several groups of rays that can hit the same target point.
Technically this is done by introduction of a rectangular grid on the source sphere and combination of neighboring cells (called here 'cluster') that contain rays to the neighborhood of the target point. From the rays of the cluster, one can determine mean values of the ray parameters that are used as initial values for the shooting procedure to the target point.

Geometry – STL Files

Triangulation of surface:
Sequence of triangles (facets) stored in stereolithography (STL) format file:

```
solid OBJECT
    facet normal n1 n2 n3
    outer loop
    vertex x01 x02 x03
    vertex x11 x12 x13
    vertex x21 x22 x23
    endloop
    endfacet
    ...
endsolid OBJECT
```



More flexible representation is necessary:
E.g.: properties of facets, etc.

Now, a short description of the geometry approximation will be given.
One has to use a discretization of the aircraft geometry. The most simple representation of a general geometry in the 3d-space is a surface triangulation.
Every triangle consists of its 3 corners and a face normal pointing outside of the body.

A quite general file format for surface triangulations is the stereolithography (STL) format. It can be written by many CAD-programs.

A drawback is that the STL-representation is not flexible enough, e.g. if it will be necessary to take into account special properties of the facets, like wall impedances etc., these informations cannot be stored in the STL-format.
Thus, the STL-representation will be supplemented by other formats in the future.

R-tree Search

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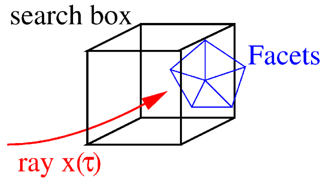
- An R-tree are is tree-structure of (n-dimensional) bounding boxes.
- It is easy to extract the bounding boxes that overlap a given one.
- Bounding boxes for all facets of the geometry are calculated and sorted into the R-tree.
- The R-tree is used whenever facets have to be searched, e.g.:
  - Impact search
  - Calculation of the optical boundary of the geometry

During the calculation of the rays, one has to check continuously for collisions of the rays with the triangles which form the aircraft geometry. In order to reduce the number of triangles which have to be checked for collisions, it is convenient to sort the triangles (more precisely their bounding boxes) into an R-tree.
Triangles which overlap with a given box in space can then be easily extracted from the R-tree.

Searching Impact Points

- The tip of the ray is surrounded by a search box.
- Facets overlapping with the search box are extracted from the R-tree.
- Only these facets must be tested for impact.



In order to perform the collision test of a ray with the geometry, the tip of the ray is surrounded by a box of appropriate size. Then, all triangles which overlap with this box are extracted from the R-tree and checked for collision with the ray.

Reflection Conditions

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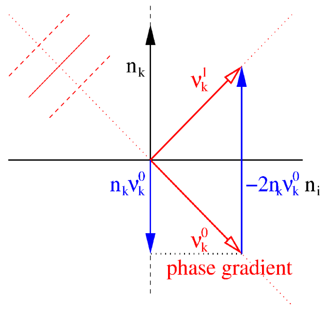
- Reflections at solid surfaces are considered
- The component of the phase gradient normal to surface is flipped
- The phase gradient after reflection is

$$\nu_k^1 = \nu_k^0 - 2(\nu_l^0 n_l) n_k$$

- In case of no mean flow the optical reflection condition for rays results



At the moment, only reflections of the rays at solid (acoustically hard) surfaces are implemented in the code.
The reflected ray starts at the wall with a phase gradient ν_k^1 which is calculated from the phase gradient ν_k^0 before the impact by retaining the components tangent to the surface and by flipping the component normal to the surface. This is consistent with the zero normal velocity boundary condition at the surface.

Source Description

- Sound source is high-bypass aero-engine.
- Approximation of measured/calculated directivity of engine by point source (sources?) - To be done!
  - monopole sound source with artificial directivity ?
  - multipole approximation of engine ?
- Test source so far is simple monopole in uniform flow

In order to use a ray tracing approach for acoustic shielding calculations, the sound field of a high-bypass aero-engine has to be modeled in an appropriate way. Most of the source modeling has still to be done.

In a first step, it seems to be suitable to approximate the sound field by a multipole expansion of the free field Green's function. This would have the advantage to approximate the engine sound field by a point source, which would fit well into the ray tracing concept.

At the moment, the sound source implemented in the code is a simple monopole in a uniform flow field.

Monopole in Uniform Mean Flow

Pressure

$$p(\boldsymbol{x},t)=A(\boldsymbol{x})e^{i\omega(\psi(x)-t)}$$

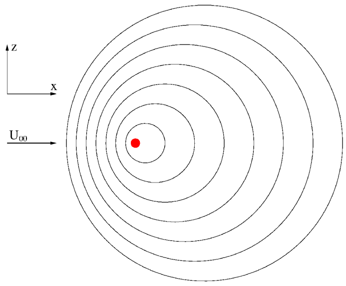
Amplitude

$$A(\boldsymbol{x})=\frac{B}{\sqrt{x^2+(1-M^2)(y^2+z^2)}}$$

Phase

$$\psi(\boldsymbol{x})=\frac{\sqrt{x^2+(1-M^2)(y^2+z^2)}-Mx}{c_0(1-M^2)}, \quad \nu_k\equiv\psi_{,k}$$

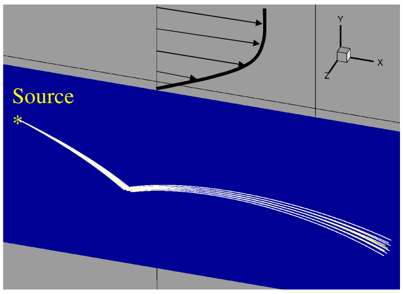
$$\nu=\sqrt{\nu_k\nu_k}=\frac{1}{c_0(1-M^2)}\left(1-\frac{Mx}{\sqrt{x^2+(1-M^2)(y^2+z^2)}}\right)$$



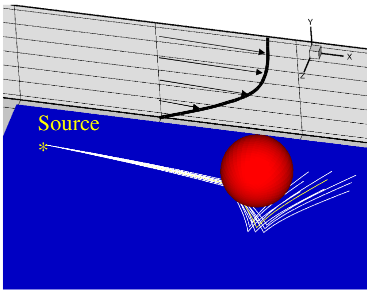
The sound source so far implemented in the ray tracing code is a monopole in a constant mean flow field.

The pressure field is solution of a convected wave equation.

Simple Refraction Examples



Monopole source in tanh-boundary layer



tanh-boundary layer and reflection
at a sphere. (Flow through the sphere!)

In order to give a brief demonstration of mean flow effects, this slide shows two simple ray tracing calculations for a parallel mean flow along a wall. The mean flow field is a tanh-boundary layer. The rays emanate from a monopole point source.

The left picture shows the reflection of the rays at the wall and the refraction of the rays by the mean flow field. One sees that the rays shown become trapped in the boundary layer.

The right picture shows additional reflections of the rays at a sphere. It has to be noted that the flow moves through the sphere, i.e. that the zero normal wall velocity condition is not fulfilled at the surface of the sphere.

Monopole in Front of Wall

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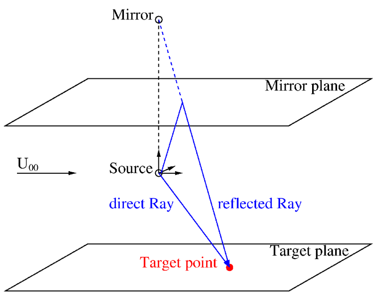
- Mirror plane above source
- Constant mean flow in x-direction
- 2 rays to every point of target plane



Target plane non-reflecting

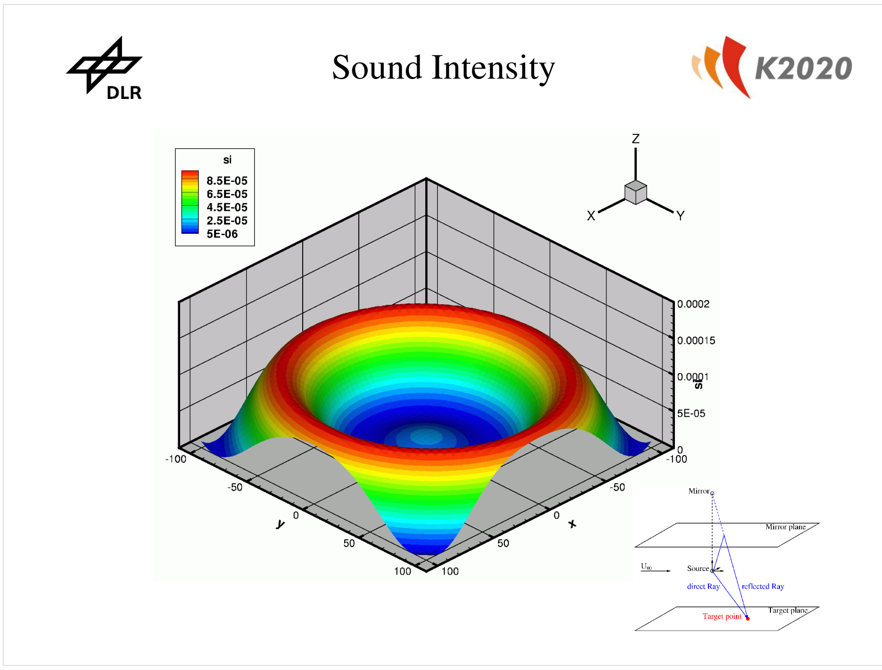
- Source in origin
- Mirror plane $z=2.7\,m$
- Target plane $z=-200\,m$
- Frequency $f=400\,Hz$
- Velocity $U_\infty=100\,m/s$

A first simple test case is the sound field of a monopole below a plane wall. In this case, an exact solution can be obtained even with a constant mean flow by taking into account the mirror of the source behind the wall.

It is easy to see that in a ray tracing calculation the mirror source is represented by the reflected rays.

In an analytical calculation, the sound field on the target plane is the sound field of the source and its mirror. In a ray tracing calculation the sound field is build up from direct and reflected rays to the target plane.

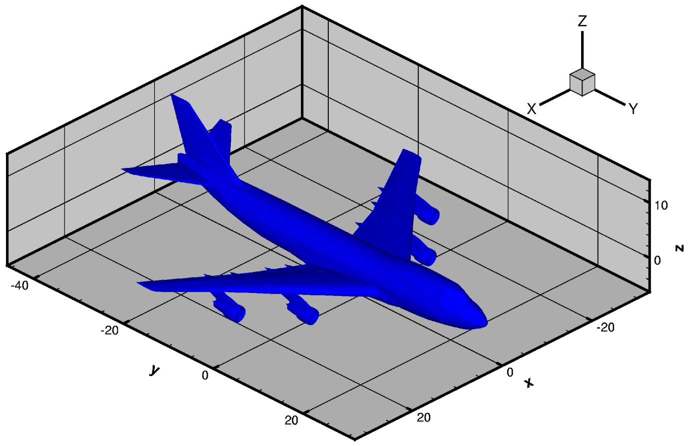
The parameter of this test case are choosen such, that a comparison of the calculated sound intensity with that obtained in case of the reflection of a sound source behind an engine of the Boeing 747 geometry is possible.



This slide shows the calculated sound intensity on the target plane, generated by the monopole source below the wall. In this case, the direct and reflected rays nearly cancel on the target plane directly below the source.

Boeing 747

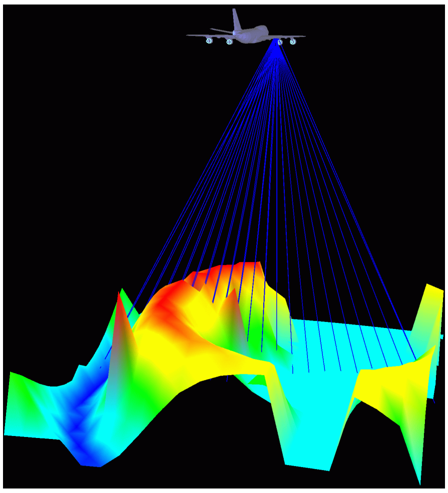
- 5700 triangles
- surface quality quite poor



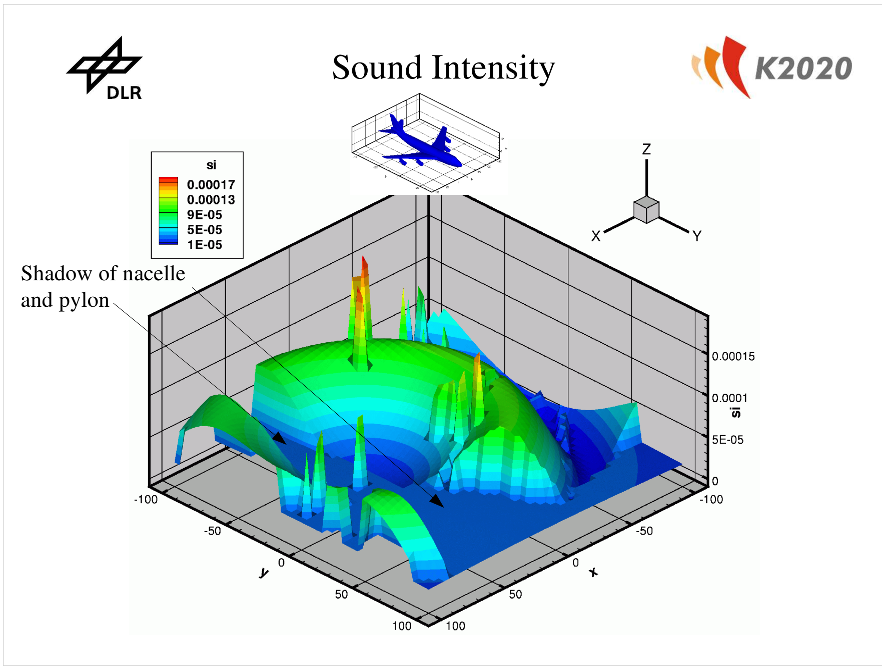
This slide shows the triangulated surface of the Boeing 747 geometry.
It consists of 5700 triangles. The surface quality (e.g. smoothness) is quite bad.

Test Case: Boeing 747

- STL surface 5700 triangles
- No mean flow
- No diffraction
- Monopole source behind engine 3
- Target plane 200 m below plane
- Target plane non-reflecting
- Sound intensity shown



This slide shows the sound intensity on the target plane generated by direct and reflected rays from a monopole source located behind the right inboard engine of the B747.
The large shadow area in the right half of the picture is the shadow of the engine nacelle and the pylon.



This is a detail view of the sound intensity on the target plane below the B747.
At x<0 one sees the acoustic shadow of the nacelle and the pylon of the right inboard engine. The peaks in the sound intensity are normally generated by the insufficient smoothness of the surface triangulation.

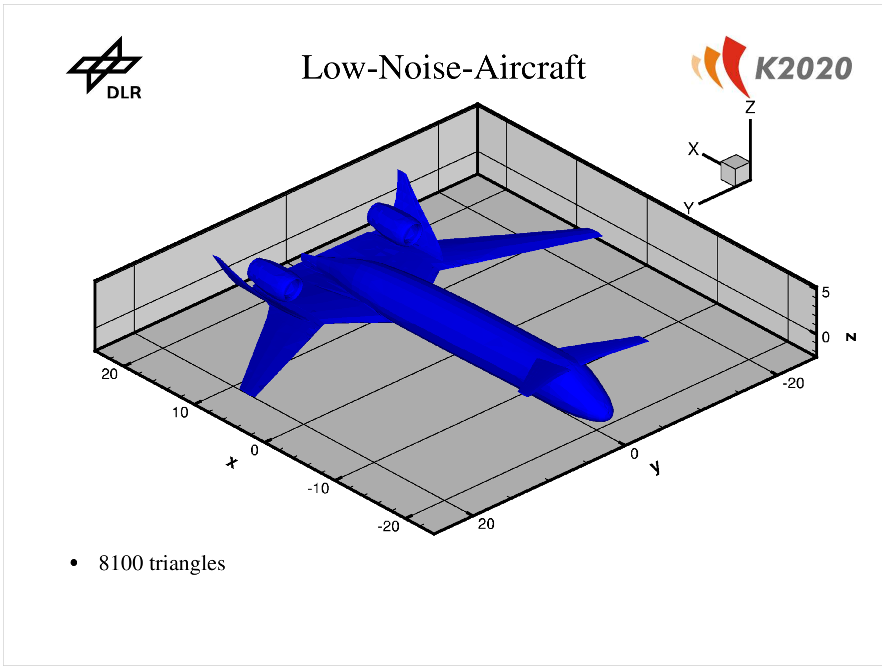
Low-Noise-Aircraft

Trying to obtain the maximum geometrical shielding effect:

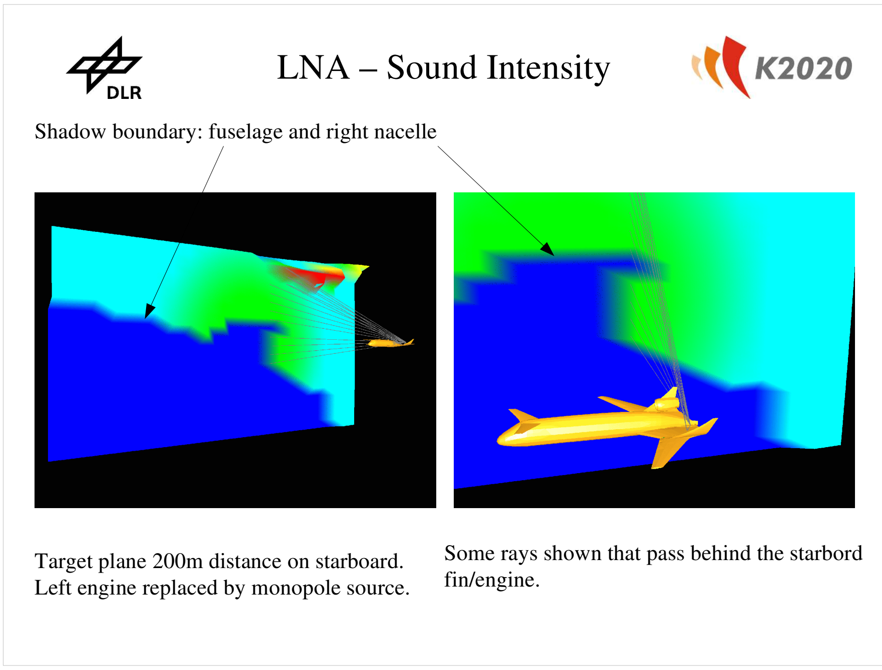
- Over wing mounted engines
- Back engine position (reducing cabin noise)
- Forward swept wing (shielding of fan noise)
- No jet noise shielding (but high-bypass engines)
- Turbine noise shielded
- Canard configuration

In the framework of the K2020 project a new low noise aircraft (LNA) configuration has been proposed, which tries to maximize the geometrical shielding effect.

This includes mainly over wing mounted engines, to minimize the direct sound emission to the ground, a back engine position for reducing cabin noise and a forward swept wing for the shielding of the fan noise.
Since it is very difficult to shield the jet noise, this task has not been tackled.

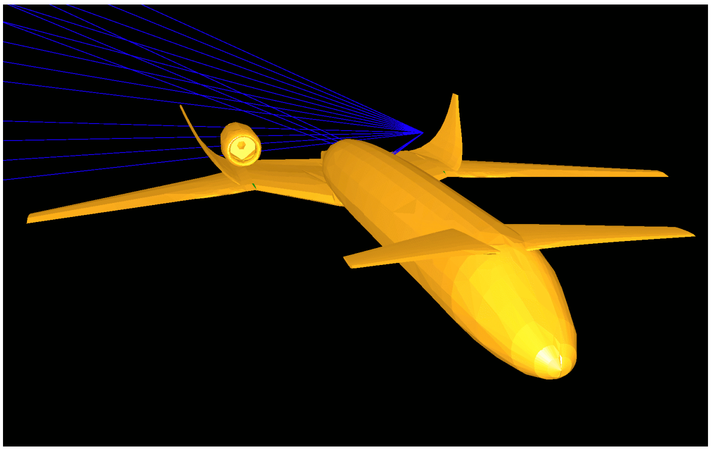


This slide shows the surface triangulation of the proposed Low-Noise-Aircraft configuration. It consists of about 8100 triangles.



This slide shows the sound intensity on a plane at the right side of the aircraft, calculated by the ray tracing code.
The left engine nacelle has been replaced by a monopole sound source.
On the target plane, one sees the shadow boundary of the fuselage and the right engine nacelle.
Additionally, some rays from the source to the target plane have been plotted.

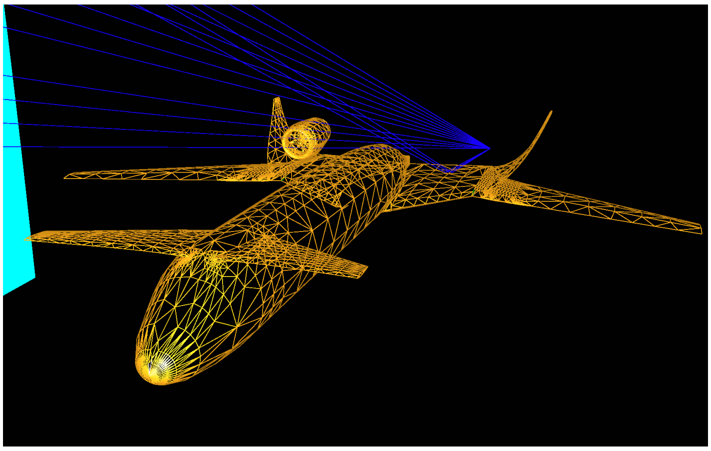
LNA



On inner port wing some reflected rays can be seen.

This slide shows a close-up of the LNA with some rays emanating from the sound source. Three rays are reflected from the upper surface of the left inner wing towards the target plane.

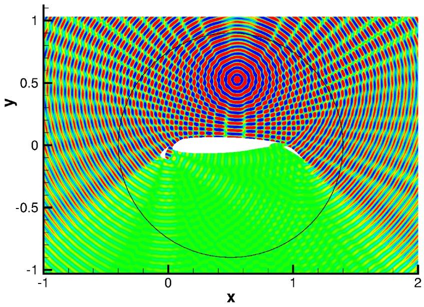
LNA

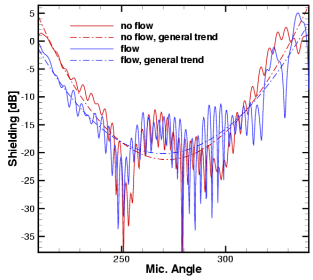


LNA surface and some rays.

This close-up shows additionally details of the surface triangulation of the LNA configuration.

Diffraction – CAA Calculations





Test case from Rosas project.
Acoustic shielding of a monopole source by a 3-element airfoil.
CAA calculation with the DLR-Piano code.

This slide illustrates the diffraction and mean flow effects, which are not yet included in the ray tracing code. The example is a 2-dimensional CAA calculation of the interaction of a monopole sound source with a 3-element airfoil. The maximum shielding is in the order of 20dB. The magnitude of the mean flow effects is up to 5 dB.

Diffraction

Problem: How do we deal with diffraction doing ray tracing ?
Work in progress: Collecting ideas!

- Apply Keller's Geometrical Theory of Diffraction (GTD)
  - Find the optical boundary of the body as seen from the source position.
  - Calculate shortest path from source to target point that runs across the optical boundary.
  - Calculate the diffraction coefficient (determines amplitude along diffracted ray). - How do we do this for complex geometries ?

So far, no diffraction effects are taken into account in the ray tracing code. This results in (absolute) silence in the optical shadow of the source.
The most appropriate approach for the inclusion of diffraction effects seems to be Keller's Geometrical Theory of Diffraction. In order to apply the GTD one has to find the optical boundary of the geometry as seen from the source position and to calculate the shortest path between source and observer point across this boundary.
Then one has to calculate an appropriate diffraction coefficient, which is determined by the local geometry near the point where the ray touches the optical boundary.

An open question is the complexity of the GTD approach for such a complicated geometry like that of an aircraft.

Optical Boundary

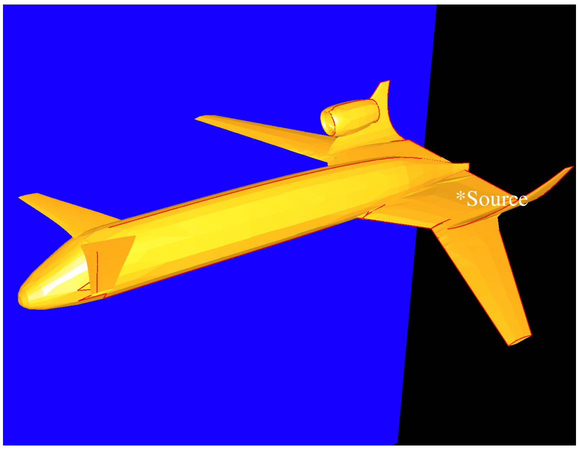
- For the treatment of diffraction of rays, one has to know the boundary of the geometry as seen from the source.
- The optical boundary in this context is the boundary of the body that is reachable from the source by rays. In case of no mean flow and constant sound speed it is the “usual” optical boundary.
- Searching of the boundary of the geometry as seen from the source by two steps:
  - Scan space by rays from the source:
    - If ray enters or leaves the geometry: mark the edges of all faces in a box around the ray tip, whose normals point against ray direction.
  - Check visibility of marked edges in a second pass by shooting. (Shoot to the edge and count hits of the geometry on the path.)

A first algorithm for the determination of the optical boundary, i.e. the boundary of the geometry as seen from the source, has been implemented in the ray tracing code.
It is based on a scan of the space directions from the source position.

DLR

Optical Boundary - Example

K2020



Engines/Source in forward top position. Boundary marked red.

This slide shows (in red) the calculated optical boundary of the LNA geometry as seen from a source at the left engine position.

Summary and Outlook

- Ray tracing allows the prediction of sound intensity
- Calculation of reflections at real geometries has been implemented
- Source description has to be improved
  - Directivity of a real engine has to be used
- Diffraction has to be included
  - Keller's geometrical theory of diffraction is the first candidate
- Mean flow has to be included
  - Treatment of caustics necessary

It should be emphasized here, that important physical effects necessary for a reliable prediction of acoustic shielding effects are not yet taken into account in the presented ray tracing approach.

The most important one (and most difficult one to implement) is surely the diffraction of sound waves on the geometry.

The source description has to be improved in order to take into account the directivity of an aeroengine. At the moment it is checked, whether a multipole expansion is suitable for the description of the sound field of an engine.

Finally, mean flow effects have to be taken into account. This requests the introduction of a volume grid around the surface geometry of the aircraft. The mean flow field will then be interpolated from the CFD grid. While the integration of the ray equations in case of a mean flow seems not to be complicated, the possibility of caustics will request further (and probably quite complicated) approximations.