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Noise predictions of two hypersonic air transport vehicle concepts during the landing and take-off cycle

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Executive summary

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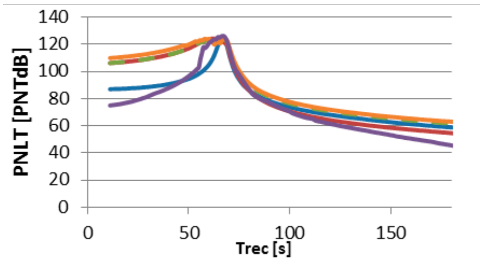

Problem area
The work described in this article is performed in the framework of the European project "HIgh speed Key technologies for future Air transport - Research & Innovation cooperation scheme" (HIKARI).

Description of work
The noise performance of two hypersonic passenger aircraft concepts, during the landing and take-off cycle, is assessed. Based on jet noise models, a noise analysis is carried out at certification points (ICAO Annex 16). The jet noise model of Stone is used with a shape correction for rectangular nozzles. The models are implemented in NLRs in-house prediction tool ENOISE.

Results and conclusions
When engine performance is the only design criteria it is challenging to obtain a concept which has a comparable noise level as the Concorde and Tupolev Tu 144. These hypersonic concepts however are designed to have a higher action radius, cruise velocity and a greater number of passengers on board. Noise regulation is lacking for super/hyper sonic aircraft, but when considering noise as an engine design driver, it should be possible to design a concept that is more silent than Concorde. It will however be challenging for first generation hypersonic aircraft to become as silent as modern day aircraft.

Applicability
The results can be used to enforce noise regulation for future super/hyper sonic aircrafts.

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Noise predictions of two hypersonic air transport vehicle concepts during the landing and take-off cycle

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ABSTRACT

The work described in this article is performed in the framework of the European project "HIgh speed Key technologies for future Air transport - Research & Innovation cooperation scheme" (HIKARI). The noise performance of two hypersonic passenger aircraft concepts, during the landing and take-off cycle, is assessed. Based on jet noise models, a noise analysis is carried out at certification points (ICAO Annex 16). The jet noise model of Stone is used with a shape correction for rectangular nozzles. The models are implemented in NLRs in-house prediction tool ENOISE. When engine performance is the only design criteria it is challenging to obtain a concept which has a comparable noise level as the Concorde and Tupolev Tu-144. These hypersonic concepts however are designed to have a higher action radius, cruise velocity and a greater number of passengers on board. Noise regulation is lacking for super/hyper sonic aircraft, but when considering noise as an engine design driver, it should be possible to design a concept that is more silent than Concorde. It will however be challenging for first generation hypersonic aircraft to become as silent as modern day aircraft.

1 INTRODUCTION

This work is performed in the framework of the European project "HIgh speed Key technologies for future Air transport - Research & Innovation cooperation scheme" (HIKARI). The main objective of the HIKARI project is to define a roadmap towards the realisation of a high speed passenger aircraft in a joint cooperation between Europe and Japan. One major concern is the amount of noise which will be produced by the engine. In addition, ICAO Annex 16, Chapter 12, dealing with noise certification of supersonic aeroplanes, states that there is no noise standard developed yet. As guideline, Chapter 3 certification standards for subsonic jet aircraft are recommended.
The objective is to investigate the current noise performance of hypersonic passenger aircraft concepts, during the landing and take-Off (LTO) cycle.
In this paper we show the used modelling approach to calculate the noise levels of two hypersonic aircrafts during the LTO cycle. A comparison is made with maximum allowable noise levels as provided by ICAO Annex 16 chapter 3 (applicable for subsonic jet aeroplanes) and with certification noise levels of relevant aircrafts that are available in open literature.
Section 2 describes the two high speed concepts and in section 3 the noise modelling will be described. This section consists of a general part about the modelling approach, followed by a description of the used shape correction. The simulation setup, such as flight trajectory and engine conditions, is described in section 4. Section 5 present the results of the noise simulations including a comparison with noise levels as provided by the ICAO standard and certification noise levels of relevant aircraft that are available in open literature. The final chapter give conclusions and recommendations.

2 HYPERSONIC PASSENGER AIRCRAFT CONCEPTS

Two hypersonic passenger aircraft concepts have been investigated. The HyperSonic passenger aircraft Technology (HST) of JAXA relies on a single pre-cooled turbo jet engine to provide its propulsion during the complete flight (take-off, cruise at ±20 km height and landing). The four engines of the HST are placed underneath the aircraft next to each other. This way a rectangular jet with a bevel is obtained. This shape is not included in the semi empirical jet noise model, which is based on a circular jet. To compensate for this a shape correction is used. An illustration of this concept is shown in **Figure 1**.

Figure 1: Hypersonic passenger aircraft concept, left: artist impression of JAXA HST, right: Low-speed wind tunnel test (http://www.aero.jaxa.jp/eng/).

The second concept under consideration is the Long-term Advanced Propulsion Concept And Technologies (LAPCAT MR2.4) of ESA [2]. The propulsion plant of the MR2 vehicle consists of a dual-mode ramjet (DMR) and six air turbo-rocket expander engines (ATR) [3][4]. Both DMR and ATR engine types are mounted in parallel, highly integrated within the aircraft and hydrogen-fuelled.
Each of the two engine bays, sideways of the aircraft, comprise three air turbo-rocket engines (**Figure 2**). The turbo-machinery of each air turbo-rocket expander consists of a two-stage counter-rotating fan and a hydrogen pump driven by a counter-rotating hydrogen turbine. The purpose of the air turbo-rocket expander engine is to accelerate the aircraft during take-off, through ascent and up to the dual-mode ramjet takeover speed, at about flight Mach number 4 to 4.5.
The air is not precooled prior to fan compression. Since the inlet recovery temperature is about 1000 K at Mach 4 and rises to 1400 K at Mach 4.5, the fan design relies on light high-temperature high-strength materials, like the titanium matrix composites [12]. The hydrogen is re-generatively heated through both cooling liners mounted on the ATR combustion chamber and the nozzle walls.

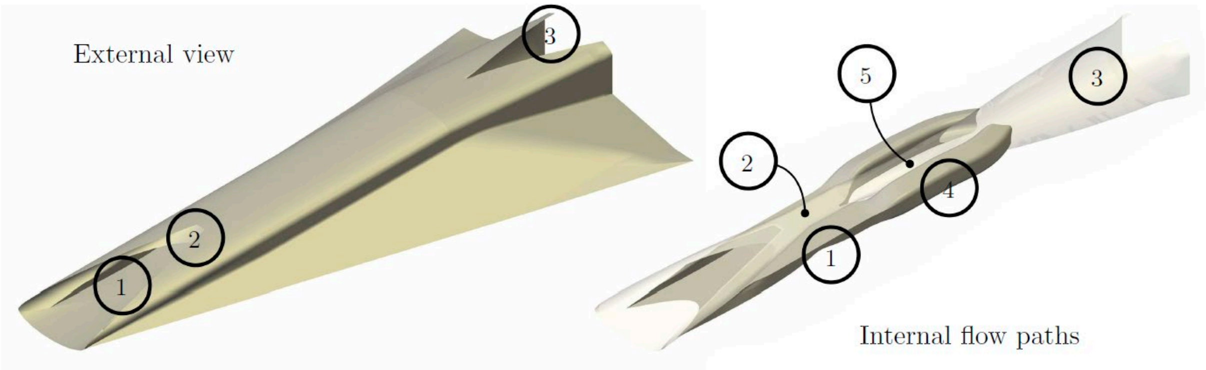

Figure 2: Rendering of the Mach 8 cruise aircraft: 1 low speed intake, 2 high speed intake, 3 nozzle, 4 ATR duct, 5 DMR duct [4].

A summary is given in **Table 1** of the velocity, weight and the number of passengers for hypersonic passenger transportation aircrafts. **Table 1** shows these values for the Concorde, the Tupolev Tu-144 and the two concepts.

Table 1: Weight and number of passengers for hypersonic passenger transportation

	Concorde	**TU-144**	**JAXA HST**	**ESA LAPCAT MR2.4**
Velocity	Mach 2	Mach 2.35	Mach 4	Mach 4.5
Gross Take-Off Weight	± 185 tons	± 180 tons	± 376 tons	± 400 tons
Number of passengers	± 128	± 140	± 128	± 300

The two new concepts have a velocity and a gross take-off weight twice as high as the Concorde and the Tupolev Tu-144. The LAPCAT MR2.4 of ESA should be able to transport more than twice the number of passengers.

3 NOISE MODELLING

3.1 Modelling approach

The assumption for a hypersonic passenger aircraft is that during the LTO cycle the main noise source is the engine and the dominant source will be the jet. Only jet noise has been modelled, noise sources like the fan, compressor, turbine and airframe are excluded from this research. There is much unknown at this stage making it hard to model these noise sources. At this moment only a rough estimation is made to give momentum for the design of hypersonic passenger aircrafts. A semi empirical jet noise model for a single stream is implemented in NLRs in-house prediction tool Engine NOIse Simulation Environment (ENOISE) [5]. **Figure 3** shows a diagram of the steps which are needed to calculate the noise of a hypersonic passenger aircraft at a certain observer. The green blocks are new modules which are implemented in ENOISE. The grey blocks were already available in ENOISE.

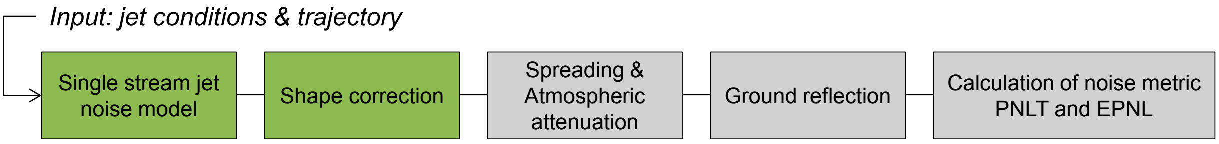

Figure 3: Diagram of the steps taken during the modelling in the ENOISE prediction tool, green blocks are new implemented steps, grey blocks are standard in ENOISE.

The used jet noise model is an implementation of the semi empirical model of Stone [6]. This model only holds for annular jets. The semi empirical model of Stone is still one of the more consistent models even compared to statistical models [7]. Effects on the noise emission due to exhaust size, jet speed, jet temperature, broadband shock noise and the flight are included. The model only includes jet noise mixing of the jet plume with the atmosphere. Sources like screech tones and internal engine noise are disregarded. The model of Stone consists of two main sources, mixing noise and shock noise. For the JAXA concept a shape correction has to be applied. The applied shape correction is described in section 3.2. For the simulations atmospheric attenuation [8] and ground reflection [9] are taken into account.
Furthermore, note that the LAPCAT concept is expected (from numerical simulations) to have boundary layers of approximately 0.5m thickness at the engine outlet. This is a deviation from the top-hat velocity profile for conventional jets. This is not accounted for in the noise simulations that are based on classical round jets. The expectation is that LAPCAT type of jet with thick initial shear layers is more silent, which makes this a conservative noise estimation.
The PNLT is the instantaneous perceived noise level corrected for spectral irregularities (ref. [10] appendix 2 paragraph 4.1). The PNLT is expressed in PNTdB. The EPNL is the effective perceived noise level which is a single number evaluator of the subjective effects of aircraft noise on human beings. The EPNL is adjusted for spectral irregularities and the duration of the noise (ref. [10] appendix 2 paragraph 4.6). The EPNL is expressed in EPNdB.

3.2 Rectangular jet correction

The jet noise model of Stone is valid for round jets. In general, the nozzles of high speed transportation aircraft are square. The proposed pre cooled turbojet (PCTJ) engine by JAXA has a rectangular shape and furthermore, is placed underneath the aircraft. For this a correction has to be applied.
Bridges [11] has performed acoustic measurements on round and rectangular nozzles with a bevel. These measurements were performed in the small hot jet exhaust rig at NASA Glenn research centre in Cleveland, Ohio. Different aspect ratios were tested with different bevel lengths. Based on these measurements a shape correction is derived.
The data was measured with 24 microphones placed on an arc. The microphones were spaced at 5º increments over a range of polar angles form 50º to 165º. To nozzle was rotated to obtain the azimuthal dependence, this was done with increments of 30º. The acoustic spectra are given for different Mach numbers and engine flow conditions. For each condition the power spectral density is given at the dimensionless Strouhal number (St).

Bridges concluded that the noise at the peak frequency is reduced, and that the noise at frequencies below the peak frequency increases with increasing aspect ratio. It was also concluded that rectangular jets produce more noise directed away from their wide sides compared to their narrow sides. With an extended bevel, the noise levels increases in all directions.

The nozzle configuration matching closest to the proposed PCTJ engine of JAXA was selected, which is the nozzle with an aspect ratio of 1:4 and a maximum bevel. So this shape correction is only valid for this specific case. To determine the correction factor the difference between the round jet and the rectangular jet was calculated. The small difference in area between the round jet and the rectangular jet are incorporate in the power spectral density. No smoothing is applied; just the difference between the raw measured acoustic spectra is used. The corrections are placed in a 4D space based on the following values:

- Jet Mach number (3): 0.5, 0.7 and 0.9
- Azimuth Angle (7): 0, 30, 60, 90, 120, 150 and 180
- Polar Angle (24): 50, 55, 60, … 155, 160 and 165
- Log(St) (≈100): -1.25, -1.225, -1.2, … 1.425, 1.45 and 1.475

Log(St) is the logarithm of the Strouhal number. **Figure 4** depicts the determination of the shape correction factor.

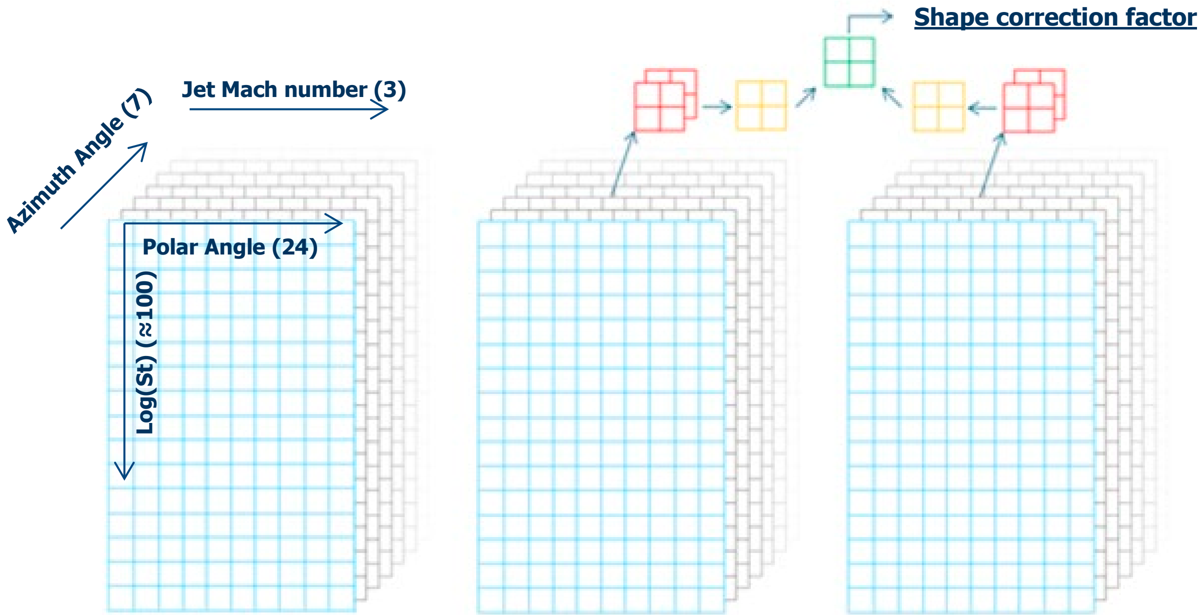

Figure 4: Shape correction factor determination.

To calculate the shape correction factor an interpolation was made in the 4D space with corrections. The determination of the shape correction uses a look up table method. At first four 2x2 matrixes are selected based on the closest values. After that the matrixes are interpolated to get a single value which corresponds to correct quantities. The 4D space holds the difference in SPL between the round and rectangular nozzle. Therefore it is possible to use a linear interpolation. In the case of extrapolation, the closest value is maintained (fixed value extrapolation).

4 SIMULATION SETUP

The flight path and the engine specification are needed to perform the simulations. The modelled flight paths are based on the certification procedures as described in chapter 3 of the ICAO standard annex 16 [10]. The engine performance inputs for these procedures are specified by the concept developers (JAXA and ESA).

4.1 Flight path

In chapter 3 of ICAO annex 16 two certification procedures are defined, a take-off reference procedure (ref. [10] paragraph 3.6.2) and an approach reference procedure (ref. [10] paragraph 3.6.3). The take-off reference procedure consists of two reference noise measurement points; flyover and lateral full-power. The approach reference procedure consists of only one reference noise measurement point. **Table 2** describes the location of the three reference noise measurement points.

Table 2: Reference noise measurement points as defined in chapter 3 of the ICAO standard

Reference noise measurement point	Description
(K1) Flyover	the point on the extended centre line of the runway and at a distance of 6.5 km from the start of roll
(K2) Lateral full-power	the point on a line parallel to and 450 m from the runway centre line, where the noise level is a maximum during take-off
(K3) Approach	the point on the ground, on the extended centre line of the runway, 2.000 m from the threshold. On level ground this corresponds to a position 120 m (394 ft) vertically below the 3° descent path originating from a point 300 m beyond the threshold

ICAO annex 16 states for the take-off reference procedure an average engine take-off thrust or power from the start of take-off to the point where at least a height of 210 m above the runway level is reached. Upon reaching a height of 210 m, the thrust or power may be reduced as long a climb gradient of 4 per cent is maintained, or in the case of multi-engine aeroplanes, level flight with one engine inoperative can be maintained. For the approach reference procedure the main guideline is that the aeroplane shall be stabilized and following a 3° glide path.
At this point not all the information about the proposed hypersonic passenger aircraft is known. Therefore some values have been used from past and contemporary aircrafts to obtain the modelled flight paths. **Figure 5** shows the modelled flight paths for JAXA and ESA concepts.

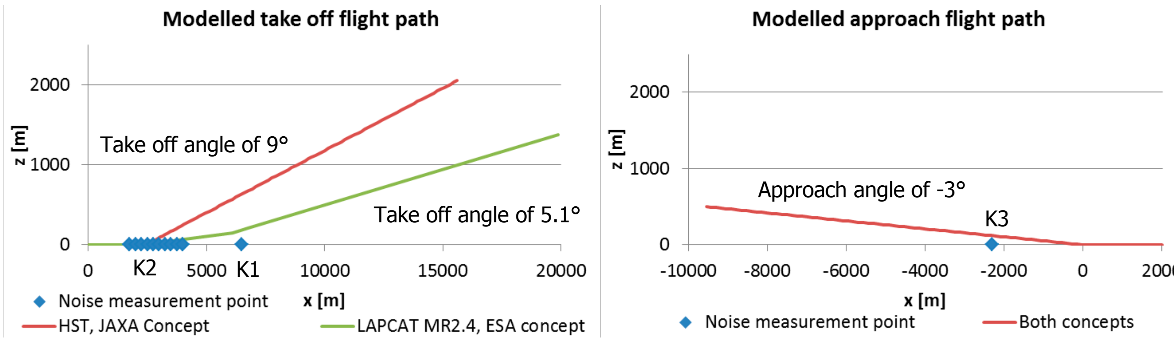

Figure 5: Modelled flightpaths for both concepts. Left) Take off Right) Approach

For the take-off reference procedure two different flight paths were modelled, one for the JAXA concept (HST) and one for the ESA concept (LAPCAT MR2.4). For the JAXA concept the acceleration and lift off angle are set equal to conventional aircrafts, no performance simulation was performed. The JAXA concept starts with an acceleration of 1.866 m/s^2. At (x=2470,y=0,z=0)m the airplane starts its lift up with a constant angle of 9°. The JAXA concept does not apply a trust cutback at a height of 210 m. For the ESA concept a performance simulation was performed by ESA, this flight

path will correspond to the real case. The ESA concept starts with an acceleration of 2.95 m/s^2. At (x=2240,y=0,z=0)m the airplane starts its lift up with a constant angle of 2.25°. At a height of 150m the climb angle is increased towards 5.1°. This angle is retained for the rest of the flight path.
For the approach reference procedure a single flight path is modelled. At a distance of 9550m and at a height of 500m the airplane starts its descent with an angle of -3°. The approach speed is specified by the concept developers. At touchdown the airplane starts braking and decelerates with 4 m/s^2.

4.2 Engine parameters

The engine parameters (e.g. jet velocity, temperature etc.) are required as input to the noise model. The input for the engines of the two hypersonic passenger aircraft concepts are provided by JAXA and ESA. All inputs for the noise simulations were generated by simulations. The engine input is given for both certification procedures (take-off and approach). The values specified by JAXA are constant during the complete flightpath. ESA delivered two inputs, an original where no effort was made regarding noise and an optimised engine setting, considering noise. The required parameters and values are specified in **Table 3** and **Table 4** for respectively JAXA and ESA.

Table 3: Input for jet noise simulation provided by JAXA

	Take-off	Approach	Unit
Jet diameter at nozzle exit	4.734	4.734	(m)
Jet velocity	1219	693	(m/s)
Flight velocity	140	129	(m/s)
Jet total temperature	1973	1200	(K)
Jet density	0.069	0.080	(kg m^{-3})
Heat capacity ratio	1.25	1.34	(-)
Jet Mach number	1.35	0.73	(-)
Nozzle design Mach number	2.4	2.4	(-)

Table 4 : Input for jet noise simulation provided by ESA

	Take-off		Approach		Unit
	original	optimised	original	optimised	
Jet diameter at nozzle exit	2.98	4.69	1.72	4.12	(m)
Jet velocity	981	745	822	553	(m/s)
Flight velocity	225	164	143	121	(m/s)
Jet total temperature	2337	2500	1938	2500	(K)
Jet density	0.133	1.125	0.155	0.122	(kg m^{-3})
Heat capacity ratio	1.245	1.247	1.26	1.247	(-)
Jet Mach number	1.1	0.75	1.2	0.55	(-)
Nozzle design Mach number	3.8	1	4.8	1	(-)

The ESA engine was optimized as follows. Originally the turbo-ramjet engine on-board was assumed to be operating in supersonic mode. It can also operate in subsonic jet mode by redefining the throttle and throat settings, retaining the required performance during the take-off phase of the flight. This is the case for the optimised engine input. Analysis showed that it is possible, when using the full high mass flow, passing by the ATR-fans at subsonic speeds, to still guarantee a take-off with an acceleration of 0.3g.

5 SIMULATION RESULTS

5.1 Noise levels at certification reference points

Figure 6 shows the PNLT versus reception time at the three noise certification reference points for the both concepts, during take-off (lateral and flyover) and approach.

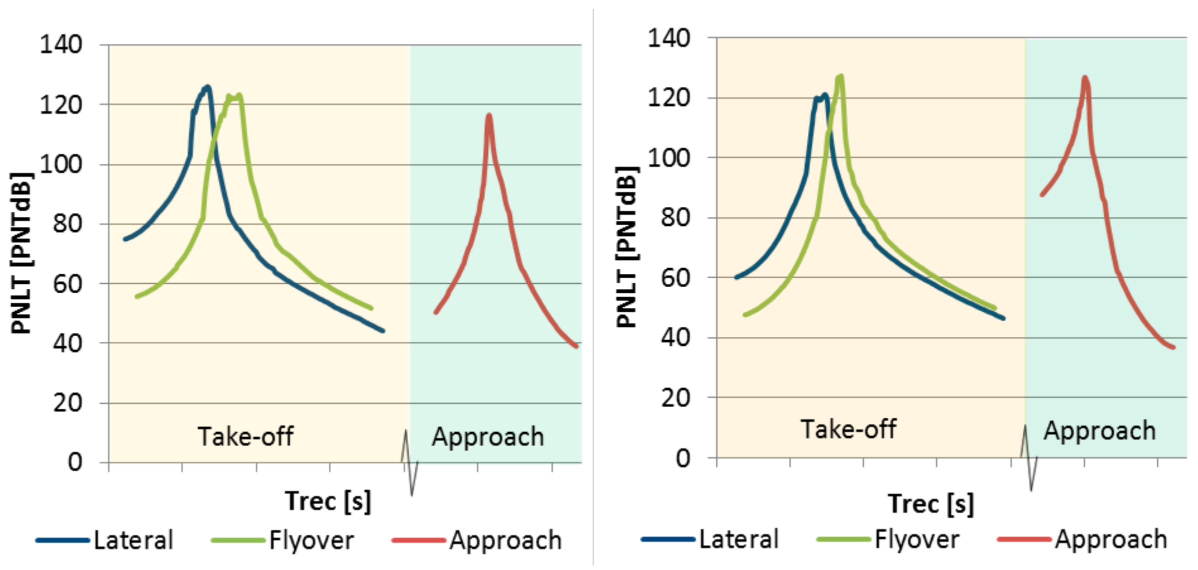

Figure 6 : PNLT results for the three reference noise measurement points, left: JAXA concept, right: ESA Concept.

The corresponding EPNL values are shown in **Table 5.** Furthermore, the maximum allowable noise levels for conventional jet aircraft according ICAO, Annex 16, chapter 3 is given and the measured noise certification levels for the Concorde and TU-144 supersonic aircraft.

Table 5 : EPNL values found in the literature and compared to the two concepts

	ICAO* **[10]**	**Concorde [12]**	**TU-144 [12]**	**HST JAXA**	**LAPCAT MR2.4 ESA**
Lateral	103	112.2	117.0	124.4	119.7
Flyover	106	119.5	115.5	123.0	123.0
Approach	105	116.7	114.5	110.3	121.5

*) Values at maximum weight

Both concepts exceed ICAO chapter 3 limits. Note these are limits not applicable to hypersonic aircraft, but merely serve as reference point to compare with modern-day conventional aircraft. Furthermore, predictions show that the considered concepts are in general several dBs noisier than the Concorde and Tupolev Tu-144. It should be considered though that these aircraft are designed to have a higher action radius, cruise velocity and in case of the LAPCAT a greater number of passengers on board.
Furthermore, it is noted that for approach reference points the JAXA HST concept shows lower noise levels than the supersonic aircraft and the ESA LAPCAT concept. The reason is that the engine settings were such that the jet Mach number does not exceed Mach 1 during the approach phase. Therefore, no shock noise is generated, greatly reducing EPNL. Note that in this case air frame noise might become relevant; which was not considered in the current work.

5.2 Decomposition of noise components

A decomposition of the different noise components is made to obtain greater understanding of the relevance of each noise component. **Figure 7** shows the PNLT curves decomposed in the different noise components. The total noise is decomposed in mixing noise (blue line), shock noise (red line), the sum of mixing and shock noise, shortened to jet noise (round), (dashed green line), jet noise

after rectangular jet correction is applies, shortened to jet noise (rectangular), (orange line) and noise level after applying propagation effects, shortened to final, (purple line). The ESA concept has a round jet, therefore no results are visible for jet noise (rectangular).
The first observation made is that for take-off shock noise and mixing noise are approximately of equal importance. Shock noise emits strongest in the forward direction whereas mixing noise emits strongest in the rearward direction. This can cause two local sound level maxima and results in a relative long duration of the noise event compared with a single component of jet noise. This is illustrated clearly by the simulations for the JAXA HST approach procedure where no shock noise occurs due sub sonic jet velocities.
A second observation, shown by the purple curve, is that ground absorption strongly attenuates jet noise in the first phase of take-off when the aircraft is near the surface and sound propagates parallel to the surface. As the aircraft climbs, the effect is reduced rapidly.
Some wiggles are shown in the orange/purple PNLT curves. These were caused by the experimentally based shape correction for which no smoothing was applied.
The rectangular jet is louder compared to the round jet. This increase due to the rectangular shape was also found by Bridges [11] for jets with an extended bevel. The difference between the rectangular and round jet depends on the flight procedure. In this case the rectangular jet is approximately 1 EPNdB louder compared to the round jet for the take-off reference procedure. For the approach reference procedure the difference is 2 EPNdB. These differences are based on the EPNL values.

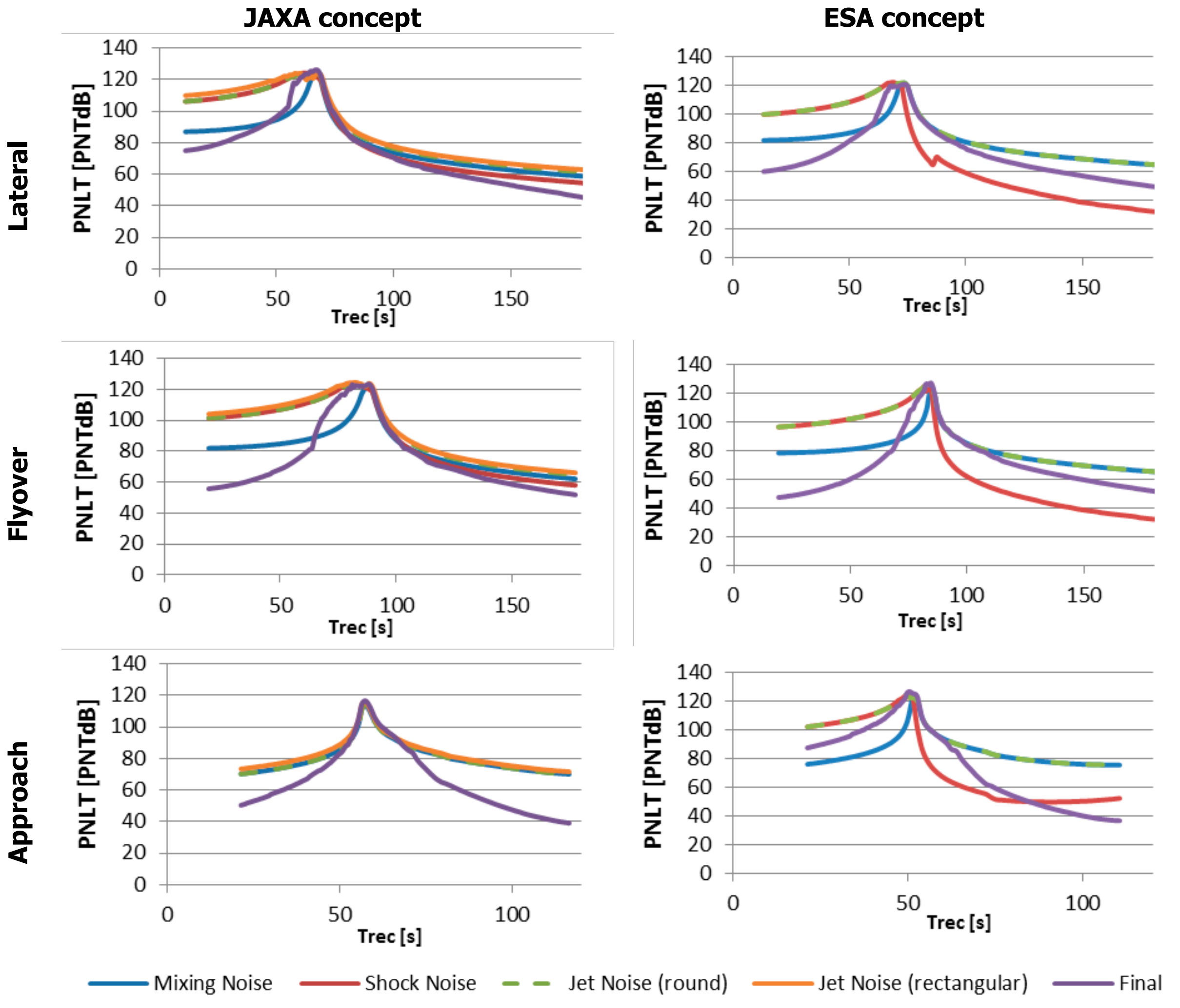

Figure 7: PNLT results for the different contributions for the two concepts, JAXA (left) and ESA (right) at the three reference noise measurement points, lateral (top), flyover (middle) and approach (bottom).

5.3 Noise mitigation

A preliminary investigation is carried out on noise mitigation measures. A high acceleration take-off is considered for the JAXA-HST concept and an optimized engine configuration for the ESA concept.
The high acceleration take-off is a hypothetic case in which the effect of a single parameter is investigated. In the original case already an assumption was made for the acceleration of the JAXA-HST concept. In the high acceleration case another value is assumed. Also in this case no performance check was performed. For the high acceleration take-off the acceleration equals 3.732m/s^2 (compared to 1.886 m/s^2). The take-off location and climb angles have been kept equal. The rationale is that if the aircraft velocity is higher, the relative jet velocity decreases and hence the noise levels should decrease as well. The results are shown in **Table 6.**

Table 6 : EPNL results for different take-off procedures.

	JAXA concept	
	Normal take-off	**Fast take-off**
Lateral	124.4	124.2
Flyover	123.0	123.1
Approach	N.A.	N.A.

The differences in EPNL values for the two accelerations applied on the JAXA concept are negligible. This shows that the noise levels are relatively insensitive to this parameter. Note that for a complete analysis also the take-off location should have been modified, which would yield a higher altitude at flyover reference point and lower noise levels. Flight path optimization was unfortunately not in the scope of the current work. This and thrust cut-back procedure is however, a viable and legit method to reduce noise levels at the flyover reference point.
Secondly, a set of optimized engine data was provided by ESA. By redefining the throttle and throat settings, the engine is able to operate in subsonic jet mode (instead of supersonic mode). Making full use of the high mass flow that can pass by the ATR-fans at subsonic speed, take-off can still be guaranteed with an acceleration of 0.3g. The results are shown in **Table 7**.

Table 7: EPNL results for different take-off reference procedure and optimised engine setting.

	ESA concept	
	Original engine setting	**Optimised engine setting**
Lateral	119.7	106.8
Flyover	123.0	110.1
Approach	121.5	102.3

The optimisation of engine operation for noise of the ESA concept gives a great reduction in noise (15dB on average). This demonstrates that taking noise as a design parameter for the engine is needed. This should be considered prior to looking into more advanced noise reduction concepts (e.g. serations, fluidic actuators etc.). All though the EPNL levels are still not within ICAO regulation norms for subsonic jet aircraft, the predicted levels are now on average 10dB below Concorde levels.

5.4 Comparison with conventional aircraft

To put the predicted noise levels in perspective of existing aircraft **Figure 8** shows noise certification level for small to large subsonic aircraft (old and new models), supersonic aircraft and the hypersonic aircraft concepts.

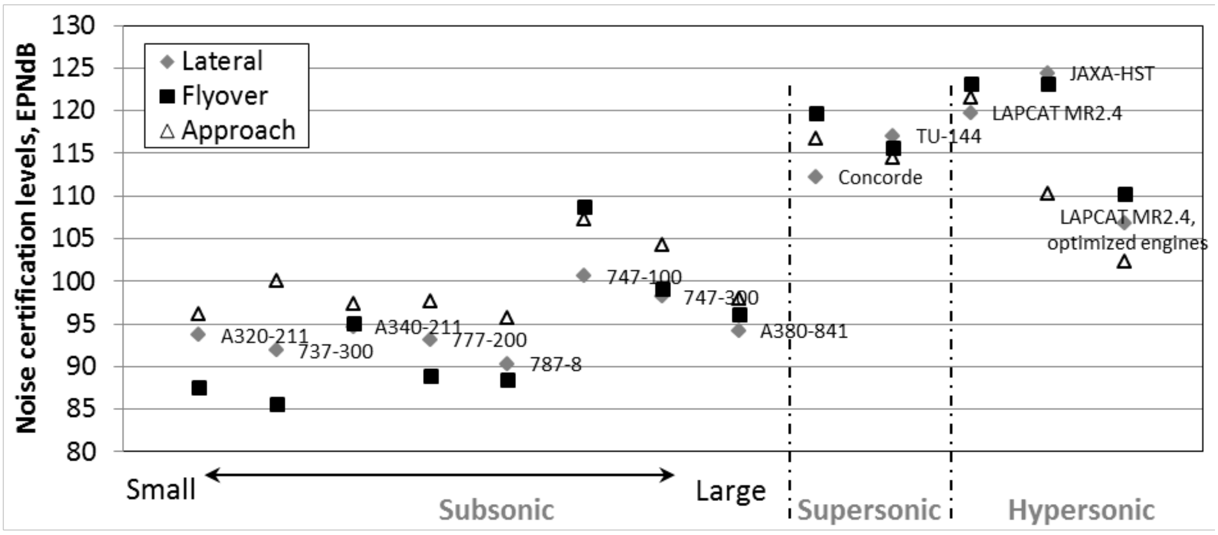

Figure 8: Overview of noise certification levels of conventional aircraft, supersonic aircraft and the predicted noise levels for two hypersonic aircraft concepts.

This shows that the predicted noise levels for the optimised engine LAPCAT configuration is roughly as noisy as a first generation Boeing 747. It can therefore be stated that it is not realistic to expect that first generation hypersonic aircrafts will be as silent as modern-day civil aircraft. It does seem feasible though, to design a hypersonic aircraft that is more silent than the Concorde (<115EPNdB).

6 CONCLUSIONS AND RECOMMENDATIONS

HIKARI tries to define a roadmap towards the realisation of a high speed passenger aircraft. Noise is one of the possible bottlenecks. The objective was to investigate the current noise performance of hypersonic passenger aircraft concepts, during the LTO-cycle.
The calculated EPNL values all exceed ICAOs limits as stated in chapter 3. These limits are however applicable for subsonic jet aircraft. Clear noise regulation is lacking for super/hyper sonic aircraft, which should be developed to give clear guidance to hypersonic aircraft OEMs. When noise is considered as an engine design parameter, a design is feasible that is more silent than Concorde (<115EPNdB). Although not all noise mitigation possibilities were yet explored (e.g. flight procedures, further optimization of the engine, etc.), it will be challenging for first generation hypersonic aircraft to become as silent as modern day aircraft.

The following recommendations are made:

- In the absence of noise regulations, aim for a design that is more silent than Concorde.
- Research on the perception and mitigation of Sonic boom is required. Additional to noise hindrance during the LTO-cycle.
- Basic research on jets configurations typical for hypersonic transport, e.g. rectangular shaped, thick initial shear layers, is recommended.
- Research on jet noise reduction techniques that are suitable for hypersonic aircrafts.
- Engine designs that allow low jet speeds during LTO-cycle are preferable. Aim at subsonic jet velocities to avoid shock related broadband noise.

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NOMENCLATURE

ATR	Air Turbo-Rocket
DMR	Dual-Mode Ramjet
ENOISE	Engine NOIse Simulation Environment
EPNL	Effective Perceived Noise Level
ESA	European Space Agency
HST	HyperSonic passenger aircraft Technology
HIKARI	HIgh speed Key technologies for future Air transport - Research & Innovation cooperation scheme
ICAO	International Civil Aviation Organization
JAXA	Japan Aerospace Exploration Agency
LAPCAT	Long-term Advanced Propulsion Concept And Technologies
LTO	Landing and take-off
NASA	National Aeronautics and Space Administration
NLR	National Aerospace Laboratory
PCJT	Pre Cooled TurboJet
PNLT	Perceived Noise Level Tone-corrected
St	Strouhal number