Drivers of Jet-flap interaction noise: The thrust vs. shear layer difference velocity experiment

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Abstract

The fundamentals of jet-flap interaction (JFI) are not fully known. One of the open questions is the search for the velocity scaling similarity parameter. While the scaling exponent is known to be n=5…6 from static JFI experiments (single-phase), the two-phase flight ops JFI problem produces more than one suitable flow parameter candidate. Promising scaling parameters are thrust velocity and shear layer (S/L) difference velocity.

These two velocity parameters are played out against one another in order to force a definitive experimental result. The changes in build length due to using different operational parameters are calculated.

The experimental parameter room is limited by max velocity limits of wind tunnel air and pressurized air (volumetric limit or sonic jet velocity), by quasi-static velocity ratio (for closed-circuit wind tunnel) and either upper limit of JFI effect or velocity profile type (here strong normal velocity profiles, $\bar{U}>\Delta U$).

The derived experiment is tailored to force a definite result wrt. thrust or S/L velocity. If this experiment does not give a clear result, JFI scaling cannot be easily modelled. A next step could be for example the measurement of downwash-velocities, i.e. flow properties which are more complex to determine and may require a build-dependent model.

Definition of velocity parameters

The so-called thrust velocity is here defined with the help of the thrust definition (equation 1). The relationship of thrust velocity to the S/L difference velocity is defined in equation 5.

Thrust definition $$F := \rho_j A_j \cdot U_j\left(U_j - U_\infty\right) \tag{1}$$

Velocity ratio $$r_U = \frac{U_\infty}{U_{jet}} \tag{2}$$

Thrust velocity $$U_{th} := \sqrt{\frac{F}{\rho_j A_j}} = \sqrt{U_j\left(U_j - U_\infty\right)} = U_j\sqrt{1 - r_U} \tag{3}$$

S/L Difference velocity $$\Delta U := U_j - U_\infty = U_j(1 - r_U) \tag{4}$$

Thrust-ΔU - relationship $$U_j = \frac{U_{th}}{\sqrt{1-r_U}} = \frac{\Delta U}{(1-r_U)} \tag{5}$$

Equation 5 can be exploited to create academic velocity profiles with same S/L difference velocity and changing thrust velocity (Fig. 1). If the thrust velocity is the crucial parameter for JFI, then it scales with n=5...6. Velocities can be measured within r_U=0.05 (quasi-static assumption for closed-circuit wind tunnel) to r_{U2}=0.2 (high jet speed) or r_{U2}=0.3.

Thrust-ΔU – relationship for U_{th} $$U_{th}(\Delta U) = \sqrt{1 - r_U}\,\Delta U \tag{6}$$

Scaling range (ΔU=const.) $$\Delta SPL_{Uth} = n \cdot 10 \cdot \lg\left(\frac{\sqrt{1-r_{U1}}}{\sqrt{1-r_{U2}}}\right) = 55\ \lg\left(\frac{\sqrt{1-r_{U1}}}{\sqrt{1-r_{U2}}}\right) \tag{7}$$

Assuming the mean value n=5.5, the spectra should have a scaling range of 2dB (for r_{U2}=0.2) or 3.6dB (r_{U2}=0.3). The larger the scaling range, the lower the systematic error. ~2dB (for r_{U2}=0.2) is a rather low value;

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going for ~3.6dB (r_{U2}=0.3) is better, but also more limited in operations: As AWB max wind tunnel speed is 60m/s, the ΔU parameter should be fixed to a constant value in between ΔU = 120 … 140 m/s.

Contrary to the prior assumption, the S/L difference velocity could be the true scaling parameter. If this is true, then the scaling range for different thrust velocity is zero, and the scaling range for the S/L difference velocity at constant thrust velocity is 3.6dB (r_{U2}=0.3). This is the same magnitude (equation 9, different sign) as calculated before (equation 7).

Thrust-ΔU – relationship for ΔU
$$\Delta U(U_{th}) = \frac{\mathrm{U}_{th}}{\sqrt{1-r_U}} \tag{8}$$

Scaling range (U_{th}=const.)
$$\Delta SPL_{\Delta U} = n \cdot 10 \cdot \lg\left(\frac{\sqrt{1-r_{U2}}}{\sqrt{1-r_{U1}}}\right) = -\Delta SPL_{Uth} \tag{9}$$

Four settings between ΔU = 120 m/s and 140 m/s are to be spaced by the same factor k_U:

$$\mathrm{k_U} = \left(\frac{140\frac{m}{s}}{120\frac{m}{s}}\right)^{1/(4-1)} = 1.0527 \tag{10}$$

The missing velocity ratios between r_{U1}=0.05 and r_{U2}=0.30 are

$$r_{U,b} = 1 - k_U^2(1-0.3) = 0.224 \tag{11}$$

$$r_{U,a} = 1 - k_U^2\left(1 - r_{U,b}\right) = 0.140 \tag{12}$$

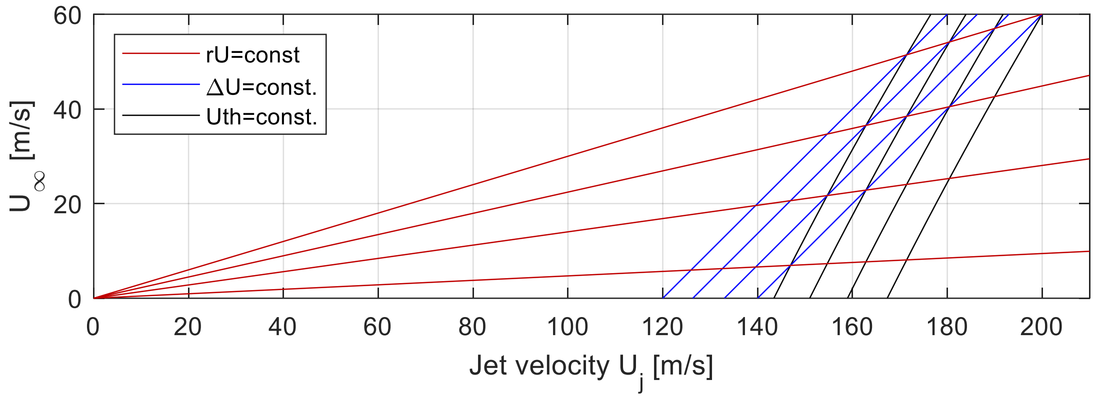

Fig. 1 Thrust vs S/L difference velocity. Academic test points are at the intersections between red and blue, as well as red and black, (here: 22 test conditions).

Calculation of length shifts for comparing different velocity ratios

The 1D shear layer width conservation theory replaces the engine to a mere S/L deliverer and assumes for comparison the same delivered jet S/L thickness at the flap trailing edge (or the same theoretical jet impingement area). Since jet opening angles change with different operational parameters, the build length changes (equations 11 and 12)

$$\delta_\omega = C_1 \cdot (L - x_0) \cdot \frac{1-r_U}{1+r_U} = const. \tag{13}$$

$$\frac{(L_2-x_0)}{(L_1-x_0)} = \frac{1-r_{U1}}{1+r_{U1}} \cdot \frac{1+r_{U2}}{1-r_{U2}} = 1.68 \tag{14}$$

A r_{U2}=0.3 measurement at L_2-x_0=300mm will provide the same shear layer thickness at the flap trailing edge as a r_{U1}=0.05 measurement at L_1-x_0~178mm. The test rig must allow the change of either engine or wing to be moved by ΔL=122mm.

Even though each velocity ratio r_U corresponds to its own build length, it is advised to measure all operations for each build and draw conclusions post experiment.

References

[1] Christian Jente and Jan Delfs. Velocity scaling of shear layer noise induced by cold jet flow with co-flowing flight stream. In 25th AIAA/CEAS Aeroacoustics Conference, Aeroacoustics Conferences. American Institute of Aeronautics and Astronautics, 2019.