29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

COMPARISON OF DUCTED AND UNDUCTED COUNTER ROTATING FAN MODEL NOISE

Yuri Khaletskiy, Victor Mileshin*
*CIAM, 2, Aviamotornaya str. 111116, Moscow, Russia

Keywords: noise, counter rotating fan, open rotor, combination frequency

Abstract

Nowadays different novel aviation engine architectures are being investigated in order to provide further fuel consumption benefit, noise reduction and emission decrease simultaneously. The most popular are the solutions taking into account further increase of engine bypass ratio and Open rotor configuration design.

In 2000 leading aero engine companies returned to investigation of Open rotor scheme on a new level on base of 3D design methodology. Experimental data received in static conditions during tests of engine prototype JE-36 with Open rotor showed that the aircraft powered by the Open rotor engine could comply with the ICAO Chapter 4 requirements. Though some papers devoted to the Open rotor noise issues, demonstrated optimistic views on progress in terms of noise reduction, noise issue is still the main challenge in practical realization of OR design.

CIAM has C-3A test facility equipped by the counter rotating drive system for CR fan model experimental investigations and an anechoic chamber for taking acoustic measurements in forward and rear hemispheres simultaneously.

Results of acoustic measurements of unducted pulled type propfan and ducted pulled type propfan of identical rotor blade design received at C-3A test facility with the anechoic chamber are represented. It is shown that in all operating conditions under study the Open rotor noise spectrum contains only discrete components at blade passing frequency of first and second rotor and discrete components at summary frequency BPF1+BPF2.

Comparison of ducted and unducted counter rotating fan models noise spectra discovered significant difference, especially in terms of broadband noise components. Thus at approach mode the ducted counter rotating fan model broadband noise component is on 8-10 dB lower that the same of the Open rotor. However the most intensive tonal components of both fan models (BPF1+BPF2) turned out to be practically identical.

Nomenclature

CRF – counter rotating fan; (биротативный винтовентилятор),
CROR – unducted CRF (Open Rotor);
GTF – geared turbofan;
BPF1 – blade passing frequency of first rotor;
BPF2– blade passing frequency of second rotor.

1 Introduction

Nowadays different novel aviation engine architectures are being investigated in order to provide further fuel consumption benefit, noise reduction and emission decrease simultaneously. The most popular are the solutions providing further increase of bypass ratio, such as Geared Turbofan engine (GTF), Counter Rotating Fan engine (CRF) and Counter Rotating Open Rotor (CROR).

Previously, the CRF models performances were investigated within the scope of CRISP program (Counter Rotating Integrated Shrouded Propfan) [1, 2]. The fan of 400 mm diameter has been driven from the refrigerating turbine. By means of the differential reduction gearbox its rotors were counter rotated with identical circumferential speeds of about 227 m/s. However this program has been closed due to excessively high sound pressure levels (SPL) generated during operation.

Schemes of turbofan engine with counter rotating fan (CRF) have been attracted attention of Russian aircraft engine designers for a long time. So, CRF engine NK-93 had been developed and passed bench tests in design bureau named after N.D. Kuznetsov (Samara, Russia). Its bypass ratio was equal to 16. However in those years the realization of this engine has not been finished.

The subsequent development of engine design technique has caused a renewed interest to CRF architecture. Within the frame of European program VITAL the experimental research of acoustic performances of three CR fan models has been carried out. The main results of this project have been stated in [3-5].

Particularly it was demonstrated that the typical CRF noise spectrum differed significantly compared with the typical single rotor fan (SRF) noise spectrum by presence of large quantity of tonal components at the blade passing frequencies and their harmonics of both fan rotors and rotor of the booster stage. Also, the CRF noise spectrum includes combination frequencies due to the interaction of rotating rows. At the same time these discrete noise components at combination frequencies are the most energy carrying. Hovewer when comparing noise levels of an airplane powered by the conventional turbofan and CRF engines it was revealed, that CRF engines provided decrease in cumulative noise level on 7 EPNdB.

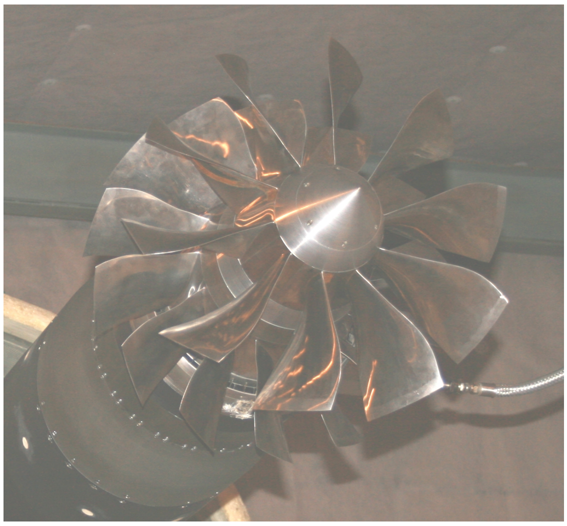

Fig. 1. Unducted Counter Rotating Fan model CRTF2A

Usually tests of CROR models are carried out in wind tunnels, where the fan model operates in conditions of incident flow with the speed corresponds to the real flight conditions [3-4]. It is not possible to conduct such tests in conditions of C-3A test facility. Moreover, the fan model was designed only for a nacelle configuration, i.e. angles of attack were far from the optimum. Therefore the results of the given study have a preliminary character, interesting in terms of detecting correlations between noise levels of the CROR and CRF main tonal noise sources.

2 Basic features of fan acoustic performances

2.1 CROR model noise

The CROR tonal noise includes three groups of components: blade passing frequency of the first rotor, blade passing frequency of the second rotor and rotors interaction noise. The blade passing frequencies of rotors is defined by equations:

$$F_{1m} = mZ_1f_1 \text{ и } F_{2n} = nZ_2f_2,$$

where Z_1 and Z_2 – blades count, f_1 and f_2 - rotors rotational speeds, m and n - arbitrary integers. In its turn, the noise spectrum of rotors interaction is defined by the relationship:

$$F_{mn} = mZ_1f_1 + nZ_2f_2$$

where m and n – arbitrary integers. Note, that in the last equation one of the integers may be equal to zero. In this regard, BPF noise and interaction noise separation generally represents not a trivial task. This challenge, however, is greatly facilitated by the fact that due to different physical nature the noise of rotation and the interaction noise have different directivity diagrams. Rotation noise directivity diagrams have lobed shape, while interaction noise directivity diagrams may have several peaks, some of which can be directed at a small angle to the CROR axis.

The relative contribution of various components to CROR noise depends on the operating mode. It is known, that rotors interaction noise dominates at modern CROR at Take-off. Even at frequencies which are multiples of BPF the noise radiation may have the directivity diagram typical for the interaction noise. On the contrary, at Cruise mode rotation noise dominates, the basic contribution is given by the buzz-saw noise generated on blades operating at transonic speed.

The important feature of CRF is the possibility of interaction noise generation at frequencies lower, than rotor BPF frequencies. In the case, if rotation speeds of both rotors have common multiple period the lower limit frequency at which the fan radiates may correspond to this period in theory (in reality this frequency usually is usually slightly higher as it is simple to demonstrate on a specific example). If there is no common multiple period, then in some cases the spectrum may contain harmonics of indefinitely low frequencies. Low frequencies radiation could lead to the design complexity of the aircraft noise reduction system. So, there is a common point of view according to which rotational speeds of rotors should be identical.

In this case the lowest frequency is equal to the rotational speed multiplied by number of spatial periods of the fan keeping within 2π. But it is necessary to note, that generally [3.2] the interaction noise at low frequencies for which one of the numbers “m” or “n” is negative (according to the equation above), should be essentially more quietly than the harmonics noise for which both numbers are positive.

In current experimental campaign the fan model rotational speed changed from 24% up to 100% in regard to the nominal mode.

As examples Fig. 2 and 3 present the narrow-band spectra of the CROR model at operating modes corresponding to Flyover and Approach in terms of thrust in the direction of maximum radiation in the rear hemisphere. It is clearly seen, that only discrete components at frequencies BPF1+BPF2; BPF1 and BPF2 are really significant in the noise spectrum.

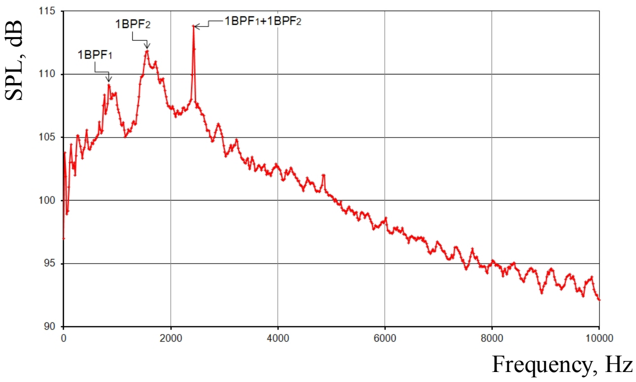

Fig. 2. CROR model narrowband noise spectrum at Flyover in direction 110°

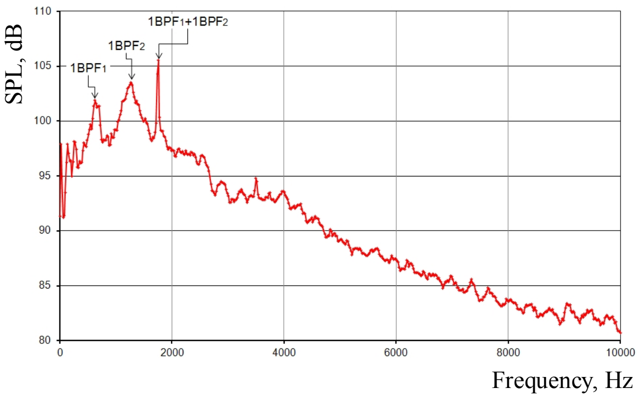

Fig. 3. CROR model narrowband noise spectrum at Approach in direction 110°

Figures 4-6 show directivity diagrams of the most intensive tonal noise components for the CROR model at 0.84 N (maximum mode), 0.75 N (Flyover) and 0.54 N (Approach). Unlike the ducted CRF having two peaks in front and rear hemispheres, the CROR directivity diagram has only one peak at 100-110 degrees. The level of the maximum in the rear hemisphere is on 5 dB or more higher than the levels in the front hemisphere (10…70 deg) for all three considered modes.

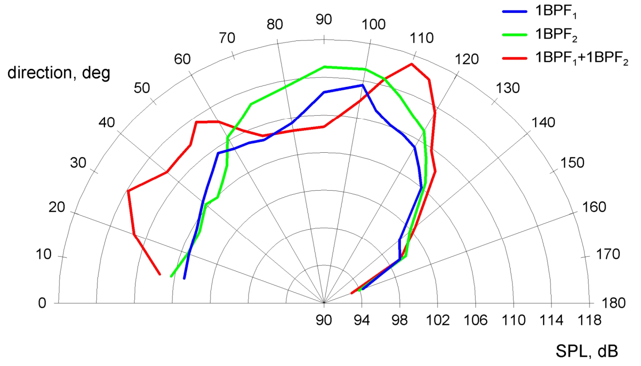

Fig. 4. Directivity diagrams of the most intensive fan tonal components of the CROR model at maximum mode 0.84 N

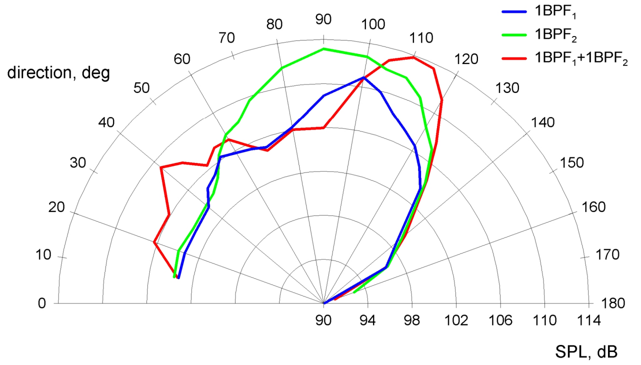

Fig. 5. Directivity diagrams of the most intensive fan tonal components of the CROR model at 0.75 N (Flyover)

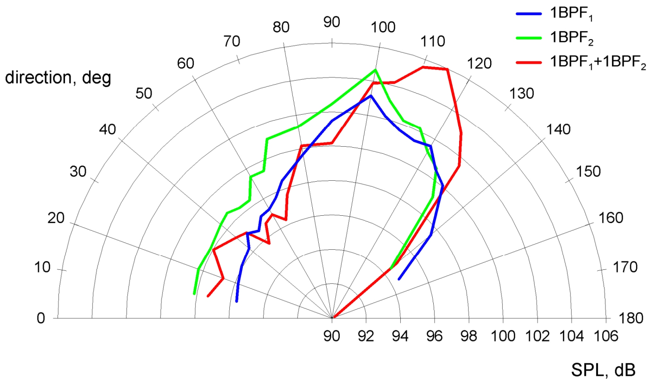

Fig. 6. Directivity diagrams of the most intensive fan tonal components of the CROR model at mode 0. 45 N (Approach)

2.2. Ducted fan model noise

Previously, the ducted CRF model acoustic performances have been investigated experimentally and theoretically [5-10]. It has been established, that the main CRF model noise was generated by its two rotor wheels (R1 and R2), rotating in opposite directions, and one rotor (R3) of the booster stage rotating with R2 turns. Levels of tonal noise components with frequencies mf_1 and nf_2 ($m > 0$ and $n > 0$) and their harmonics turned out to be lower in comparison with combination components with frequencies $f = mf_1 + nf_2$ ($m > 0$ and $n > 0$).

The CRF noise spectrum is characterised by presence of big quantity of discrete noise components with blade passing frequencies of three rotors and their harmonics and also with combinational frequencies including its interaction with basic tonal noise sources. Exactly these discrete noise components with combination frequencies determine the CRF acoustic response within the whole frequency range.

2.3. CRF and CROR noise spectrum comparison

Since we compare noise spectrum of different types fan the impulse of the exhaust jet, proportional to the engine thrust, was selected as the criterion of operating modes equivalence. Figure 7 represents measured values of the exhaust jet impulse versus shaft rotational speed.

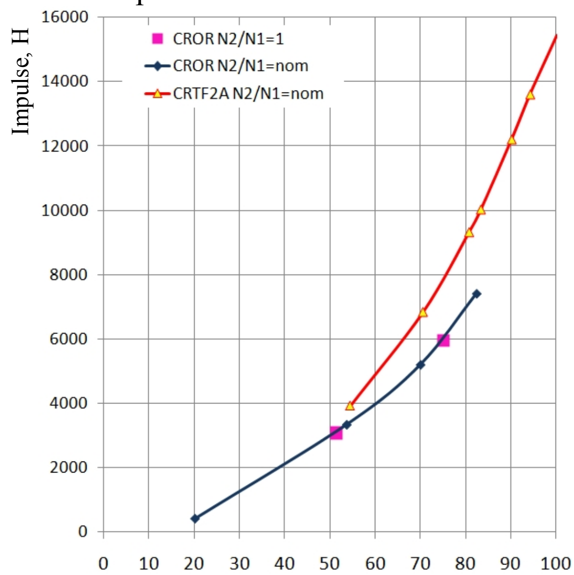

Fig. 7. Dependance of jet impulse versus operating mode (N)

From the plot on figure 7 it is clearly seen that operating modes similar in terms of jets

SPL, dB

impulse lie within the range of 4-7 kN, which corresponds to Approach and Flyover modes.

Figures 8-11 represent ducted (CRTF2A) and unducted (CROR) models noise spectra in Approach and Flyover. As it was mentioned above, the tonal components at BPF frequencies of R1 and R2 and at sum frequency dominate in the spectra of the CROR model at both operatimg modes. For the ducted CRF model tonal components at BPF frequencies BPF1 and BPF2 are essentially lower as compared with the sum frequency BPF1+BPF2, though at the same time exceeding on 10 dB the broadband noise. Dominant tonal components of the ducted CRF model noise at sum frequency BPF1+BPF2 also have quite significant harmonics, mostly the first, i.e. at the frequency (2BPF1+2BPF2). But in Flyover mode in the rear hemisphere there are significant tonal components at second harmonic (3BPF1+3BPF2) and at combination frequency (3BPF1+2BPF2) (Fig. 11). The broadband noise of the unducted CROR model turned out to be much higher, on average by 15 dB, as compared with the ducted CRF model. This difference in broadband noise component of the considered fan models can be attributed to the lack of incident airflowing of the unducted CROR model simulating the real flight conditions

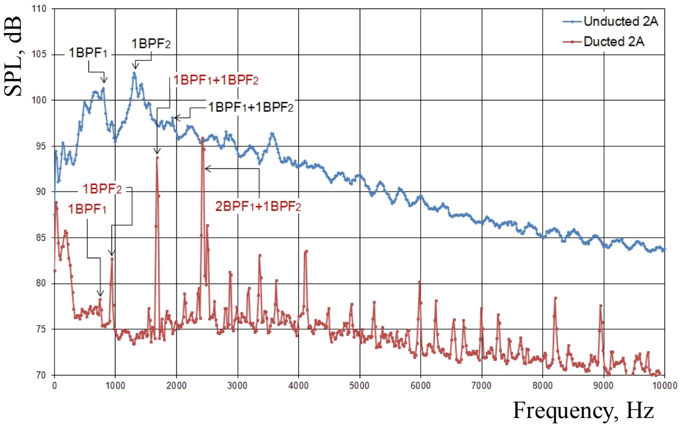

Fig. 8. CRF and CROR noise spectrum at Approach in front hemisphere

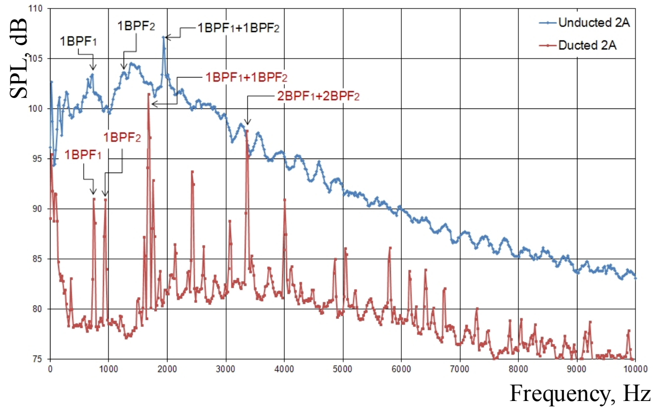

Fig. 9. CRF and CROR noise spectrum at Approach in rear hemisphere

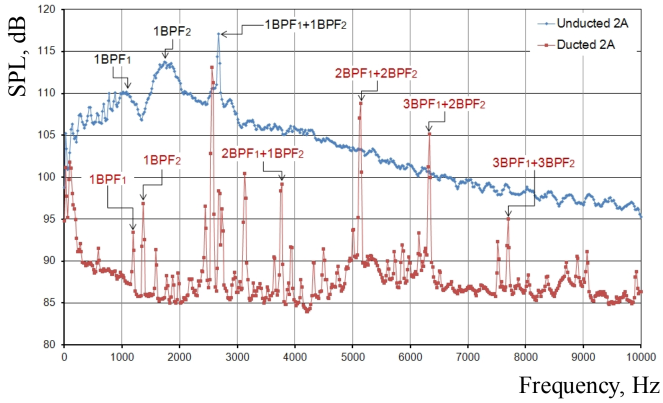

Fig. 10. CRF and CROR noise spectrum at Flyover in front hemisphere

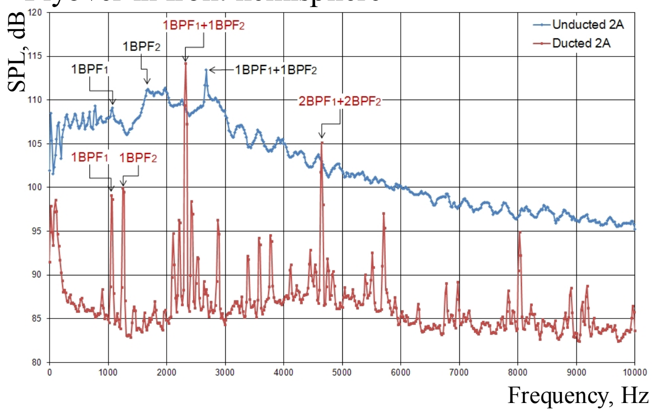

Fig. 11. CRF and CROR noise spectrum at Flyover in rear hemisphere

Conclusions

Comparison of ducted and unducted counter rotating fan models noise spectra demonstrated that both models generate the most powerful tonal noise at combination frequency BPF1+BPF2 and its harmonics. In addition, spectra include tonal components at blade passing frequency of first and second rotor.

Unlike the CRF model, the CROR model noise directivity diagrams have showed significant exceeding of noise levels in the rear hemisphere relative to the forward hemisphere on 5-8 dB.

Apparently considerable exceeding of the broadband noise component of the CRF model as compared to the CROR model is due to the methodological measurement conditions in the anechoic chamber without incident airflow.

References

[1] Holste F., Neise W. Experimental determination of the main noise sources in a propfan model by analysis of the acoustic spinning modes in the exit plane. *14th AIAA Aeroacoustics Conference,* Aachen, Germany, Paper DGLR/AIAA 92-02-138, 1992

[2] Holste F., Neise W. Acoustical near field measurement on a propfan model for noise source identification. *16th AIAA Aeroacoustics Conference,* Munich, Germany, Paper CEAS/AIAA-95-178, 1995.

[3] Woodward R. Noise of a Model High Speed Counterrotation Propeller at Simulated Takeoff/Approach Conditions (F7/A7). *11th AIAA Aeroacoustics Conference,* Sunnyvale, California, AIAA-87-2657, October 19-21, 1987.

[4] Khalid S.A., Wojno J.P., Breeze-Stringfellow A. and others. Open Rotor Designs For Low Noise And High Efficiency. *Proceedings of ASME Turbo Expo 2013,* June 3-7, 2013, San Antonio, Texas, USA, GT2013-94736

[5] Khaletskiy Y., Mileshin V. and Shipov R. Acoustic test facility for aero engine fans. Acoustics 2008 Paris.

[6] Khaletskiy Y. Results of C-3A Test Facility Development and CRTF1 Acoustic Features. Book of Abstract. VITAL Final Workshop, Budapest, 9-10 March 2009, p. 60

[7] Khaletskiy Y., Mileshin V., Shipov R. Study of counter rotating fan noise at anechoic chamber. Proceeding of the 8th European Conference on Noise Control «EuroNoise», 2009, Edinburgh, Paper 0268

[8] Khaletskiy Y, Shipov R, Mileshin V and Povarkov V. “Experimental Study of the Counter Rotating Model Fan Noise”, Ecological Problems of Aviation, Proceedings of Central Institute of Aviation Motors #1347, Moscow, 2010, pp 76-83.

[9] Khaletskiy Y, Mileshin V, Talbotec J, Nicke E. Study on Noise of Counter Rotating Fan Models at CIAM Anechoic Chamber. Proceeding of the ICAS Conference, Paper 897, 2012, Brisbane, Australia.

[10] H. Brouwer, “Analytic description of the noise radiation from single- and contra-rotating propellers”, ICAS2010-5.2.3, 27-the International Congress of the Aeronautical Sciences, 19 - 24 September 2010, Nice, France.

Copyright Statement