TWO VS. THREE BLADE PROPELLER - COCKPIT NOISE COMPARISON

Dubravko Miljković[1], Jurica Ivošević[2], Tino Bucak[2]

[1]HEP Zagreb, Vukovarska 37; [2]University of Zagreb, Faculty of Transport and Traffic Sciences, Department of Aeronautics, Vukelićeva 4, Zagreb, Croatia
dmiljkovic@hep.hr, jurica.ivosevic@fpz.hr, tino.bucak@fpz.hr

Abstract: *The noise generated by propeller efficiently masks other noise sources in GA aircraft and is composed of tonal and broadband components. The former are more dominant than the latter ones and comprise fundamental blade passing frequency along with harmonics that are dependent on number of propeller blades and propeller rotational speed. Cockpit noise arises when propeller noise in the form of pressure pulses enters the cabin through the windshield and excites the interior air volume. While aircraft performance envelope with two vs. three blade propeller can be quite narrow regarding cruise speed vs. faster acceleration and improved climb, interior noise levels and spectrum may differ significantly. In this paper the contribution of two vs. three blade propeller to overall aircraft interior noise will be investigated. Furthermore, spectral properties of interior noise, human preference and influence to speech intelligibility will be analyzed.*

Key words: propeller, noise, cockpit

1. INTRODUCTION

General aviation aircraft are most often equipped with two- and three-blade propellers. There is a small performance difference between a two-bladed verses a three-bladed propeller. A three-bladed propeller gives more thrust and better climb rate, while sacrificing a little cruise speed. The big advantage of using a multi-blade is that they have more ground clearance and are less noisy (particularly outside). Three blades are much smoother and give a touch better climb. Two-blade propeller have slightly larger diameter and achieve higher tip speeds at the same rotational speed, making them a little bit noisier.

2. THE SOURCES OF AIRCRAFT NOISE

Aircraft noise contains the following main components: engine noise (with engine compartment elements such as pumps and alternator, and an exhaust system), propeller noise, airframe noise and structure borne noise (as a particular kind of airframe noise), [1]. Aircraft interior noise is combination of all mentioned components, Fig. 1, that, with various degrees, penetrate into the aircraft cabin.

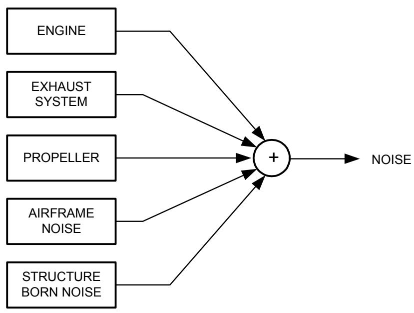

Fig. 1 Contributions to aircraft noise

2.1. Propeller Noise

In a single engine aircraft propeller noise enters the cabin through front window in the form of pressure pulses. Propeller noise is composed of tonal and broadband components. The tonal component contains basic frequency and harmonics. The basic frequency f_1 or BPF (blade pass frequency) is the product of propeller rotation speed and number of propeller blades:

$$BPF = \frac{N_R N_B}{60} \tag{1}$$

where is:

BPF basic frequency of tonal propeller component
N_R propeller rotation speed (rotations per minute)
N_B number of propeller blades

Beside the base frequency also there are also harmonic components:

$$f_N = f_1 N \quad (2)$$

where is

f_n frequency of *n-th* harmonic
f_1 basic tonal frequency
N number of particular harmonic

RPM (N_R)	2 blades	3 blades
900 – Idle	30	45
1500	50	75
2400 – TO/GA*	80	120

*take off/go around

Table 1 Blade Pass Frequency (BPF) in Hz for various rotation speeds (RPM) and number of blades

Blade Pass Frequency for various combinations of number of blades and rotational speed is given in Table 1. Broadband component is caused by turbulent air flow and whirling. The biggest single factor in propeller noise is tip speed that depends on the diameter of the propeller and its rotational speed.

where is

v propeller tip speed
D propeller diameter
N_R propeller rotation speed (rotations per minute, RPM)

$$v = \frac{D N_R \pi}{60} \quad (3)$$

As the tip speed of propeller approaches the transonic range, the noise level outside the aircraft takes a huge increase, [2]. The transonic range begins about 1005 kmh^{-1} (543 knots), or Mach .85, and continues until the speed of sound or Mach 1 at sea level. Beginning at approximately 1005 kmh^{-1}, the tip of the propeller is going fast enough to cause compression of the air, generating at least two mini sonic booms per revolution. This increase in noise is much more apparent outside the aircraft than inside.

Diameter (inch)	Rotational speed - RPM								
	2400	2450	2500	2550	2600	2650	2700	2750	2800
74	236	241	246	251	256	261	266	271	276
75	239	244	249	254	259	264	269	274	279
76	243	248	253	258	263	268	273	278	283
77	246	251	256	261	266	271	277	282	287
78	249	254	259	265	270	275	280	285	291
79	252	257	263	268	273	278	284	289	294
80	255	261	266	271	277	282	287	293	298
81	259	264	269	275	280	286	291	296	302
82	262	267	273	279	284	289	295	300	305
83	265	270	276	282	287	293	298	304	309
84	268	274	279	285	291	296	302	307	313
85	271	277	283	288	294	300	305	311	317
86	275	280	286	292	297	303	309	315	320
87	278	284	289	295	301	307	312	318	324
88	281	287	293	298	304	310	316	322	328
89	284	290	296	302	308	314	320	326	331

Table 2 Propeller tip speed (in ms^{-1}) for various propeller diameter and rotation speed (RPM), yellow color denotes noisy and red color loud speeds

At worst, a propeller creates a supersonic shock wave at each of its tips, where the combination of blade length and engine rotational speed means that the outermost part of each blade is traveling at or very near the speed of sound. From Table 2 it becomes apparent how important sometimes even a 100 RPM reduction could be for diminishing noise level.

2.2. Engine Noise

Piston engine noise is the result of pressure pulses at intake and exhaust (engine exhaust noise) during engine four cycles. The engine exhaust noise originates at the exhaust tailpipe openings and is transmitted through the cabin walls, firewall, and nose gear bay into the cockpit. In the case of piston engine, noise spectrum is dependent on rotational speed N_R (in RPM) and number of cylinders. Following two parameters influence engine noise spectrum. Cylinder firing rate (C_{FR}) is dependent on rotational speed:

$$C_{FR} = \frac{N_R}{60} \quad (4)$$

Engine firing rate (E_{FR}) is dependent on C_{FR} and the number of cylinders (N_C):

$$E_{FR} = N_C C_{FR} \quad (5)$$

2.3. Airframe noise

Airframe noise is the result of air flow (relative wind around the airframe). It is of the broadband flow mixing type except where a resonant cavity is formed (e.g. at control surface gaps). Its main characteristic is a great dependence on aircraft speed. Noise intensity is related to aircraft speed with the following equation:

$$I = kv^n \quad (6)$$

where v is the speed of an aircraft and the exponent n varies between 5 and 6 and is dependent on the shape of fuselage.

2.4. Interior noise levels

Interior noise level depends a lot on the aircraft and its engine and propeller, but on average the values are 80 dB and above, up to 110 dB in case of some piston aircraft (eg. Cessna 210). For some phases of flight (takeoff) some general aviation aircraft do not provide adequate acoustic protection, [3]. At such levels, acoustic protection is necessary because 50 percent of all general aviation pilots have measurable threshold hearing shifts after 10 years of flying practice [4].
At low RPM, interior noise is dominated by engine and exhaust noise, while at higher RPM, due to propeller tip speed, the influence of propeller noise becomes considerable. In flight, the noise generated aerodynamically gradually increases with the speed.

3. THE EXPERIMENT

The experiment was performed on static aircraft (parked at a/d Lučko) so that higher frequency broadband aerodynamic noise present in flight (with the exception of propeller wash) was not incorporated in analysis.

3.1. Aircraft used in experiment

Two Cessna 172 aircraft were available, both single engine piston equipped: Cessna 172N, 9A-DAS, with two-blade propeller, Fig. 2, and Cessna FR172F, 9A-DMJ, with three-blade propeller, Fig. 3.

Cessna 172N

Cessna 172 N Skyhawk was introduced for the 1977 model year. It is equipped with two-blade propeller. Following are some important engine and propeller technical data:

- Engine: Avco Lycoming O-320-A2HD four cylinder 160 HP, normally aspirated
- Static RPM Range: (carburetor heat off and full rich mixture) 2280-2400 RPM
- Propeller: McCauley 1C160/DTM7557, metal
- Propeller diameter: max 75 inch, min 74 inch

Fig. 2 Cessna 172N

Cessna FR172F Reims Rocket

Cessna FR172F Reims Rocket is French version of Cessna 172, with more powerful engine. It is equipped with three-blade constant speed propeller.
Following are some important engine and propeller technical data:

- Engine: Continental IO-360DB six cylinder 210 HP, injection
- Static RPM Range (carburetor heat off and full rich mixture) 2280-2400 RPM
- Propeller: Hoffmann HO-V123F-180R, composite
- Propeller diameter limitation 73,4 inch

Fig. 3 Cessna FR172F Reims Rocket

3.2. Measurement equipment

Noise levels were measured using a Norsonic Nor140 Sound Analyser. Acoustic noise recordings were obtained using external measurement condenser microphone ECM8000 (Behringer) and M-Audio Fast Track Pro USB Audio Interface connected to a notebook computer with Cool Edit software. Recordings were done with 22050 Hz sample rate and 16 bit.

3.3. Measurement procedure and layout

Interior sound measurements were performed in three successive regimes. For each regime (and corresponding engine rotational speed) noise level measurement and noise waveform recording was performed. Every waveform sound clip consists of following three regimes: idle (900 RPM), 1500 RPM, maximal take-off power (2400 RPM) and back. Measurement position was at head level between front seats, Fig. 4. Sound recordings were later amplitude normalized using Cool Edit Pro. 2 software.

Fig. 4 Noise measurement

4. MEASUREMENT RESULTS

4.1. Measured noise levels

Measured noise levels are shown in Table 3.

RPM	Aircraft interior noise L_{Aeq}, dB(A)		Difference dB(A)
	Cessna 172N 2 blade propeller	Cessna FR172F 3 blade propeller	
900	69,5	69,0	0,5
1500	82,3	83,0	-0,7
2400 TO/GA*	93,3	91,0	2,1

*TO/GA Take Off/Go Around power

Table 3 Aircraft interior noise for aircrafts with two and three blade propeller and different rotational speed (RPM)

Because aircraft was static, noise measurements include combination of engine noise, exhaust noise and propeller noise plus some aerodynamic noise due to propeller wash. At low RPM noise is dominated by engine and exhaust pipe noise, while influence of propeller noise become significant at higher RPMs. Overall, slightly lower interior noise was measured with three-blade propeller. This small difference may be partly caused by louder engine used in FR172F, but also A-weighting used in noise measurements (better suites human hearing) that attenuates lower noise frequencies of two-blade propeller and four-cylinder O-320 engine better than higher frequencies of three-blade propeller and six-cylinder IO-360 engine with higher engine firing rate, E_{FR}, (4), (5).

4.2. Noise recordings

Waveforms of noise recordings for both aircraft after amplitude normalization are shown in Fig. 5 and Fig. 6. Recordings are of duration of about 50 s and one can clearly note recorded regimes: 10s idle, 10s of 1500 RPM, 10s of take-off power, 10s of 1500 RPM and 10s of idle.

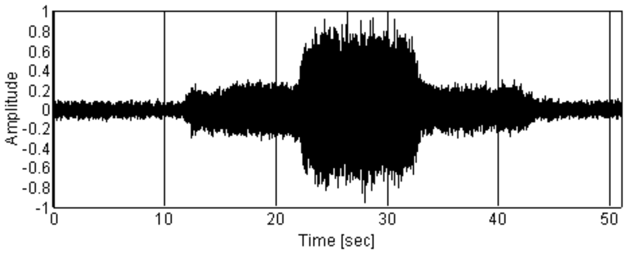

Fig. 5 Cessna 172N Normalized

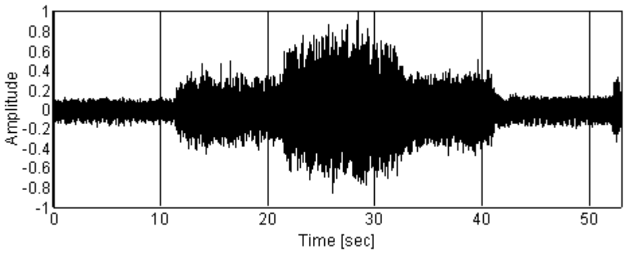

Fig. 6 Cessna FR172F Normalized

Spectral representations of the recorded interior noise at various RPM are illustrated in Fig. 7-9. Blue color lines represent Cessna 172N with two-blade propeller and green line Cessna FR172F with three blade propeller. Discrete nature of spectrum at lower frequencies due to propeller and engine harmonics can be seen. Differences between two propellers are particularly clear in Fig. 9.

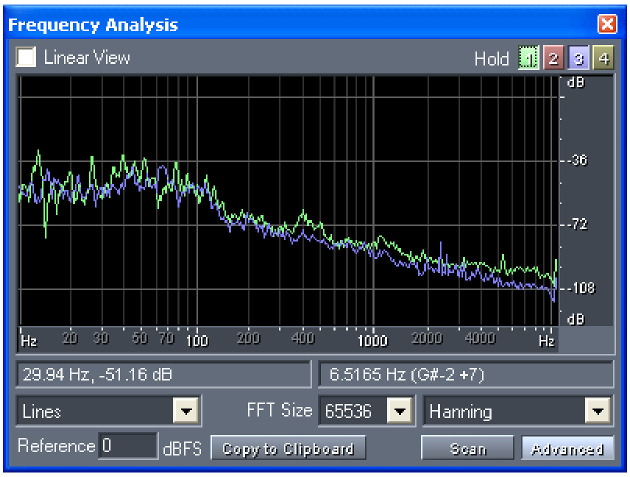

Fig. 7 Spectral representation - idle

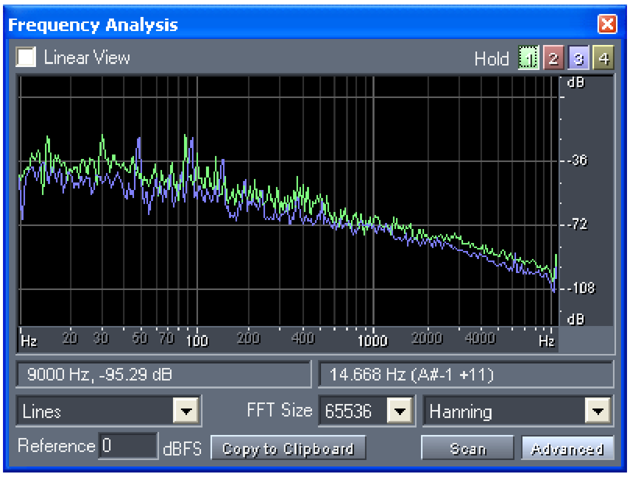

Fig. 8 Spectral representation – 1500 RPM

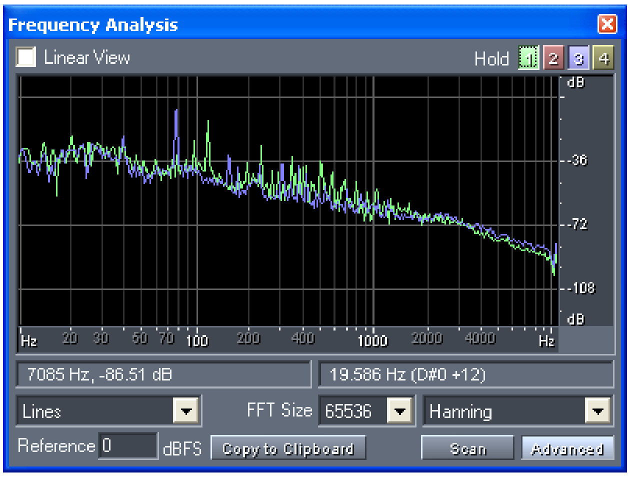

Fig. 9 Spectral representation – TO/GA

5. HUMAN NOISE PREFERENCE

A questionnaire survey was undertaken with 16 participants listening to the interior noise recordings.

RPM	Propeller blades	Preference
900	2	15 (94%)
	3	
	NDD*	1 (6%)
1500	2	10 (63%)
	3	6 (7%)
	NDD*	
2400 TO/GA	2	12 (75%)
	3	4 (25%)
	NDD*	

*NDD - Not Discernible Difference

Table 4 Human noise preference

Contrary to expectations that three blades give more pleasing sound causing less fatigue, preference was given to combination of two blade propeller and four cylinder engine, Table 4. Partial credit for this may be given to engine noise that is dominant at lower RPMs, but also to lower frequency noise of two blade propeller and four cylinder engine that could be, due to human hearing curve, perceived as less loud. As the RPM increases and propeller and engine frequencies shift to higher values, the number of participants that find combination of three blade propeller and six cylinder engine noise more appealing is increasing. This is primarily interesting for passengers as pilot often use noise canceling headset.

6. SPEECH INTELLIGIBILITY

Aircraft interior noise interferes with speech communication. Speech intelligibility can be determined objectively by an Articulation Index (AI). Relation between AI and background level is shown in Fig. 10, [5]. Reading from the slope of the regression line with slope r=-0.82 for various background levels values of AI are presented in Table. 5 (much the same for both aircrafts).

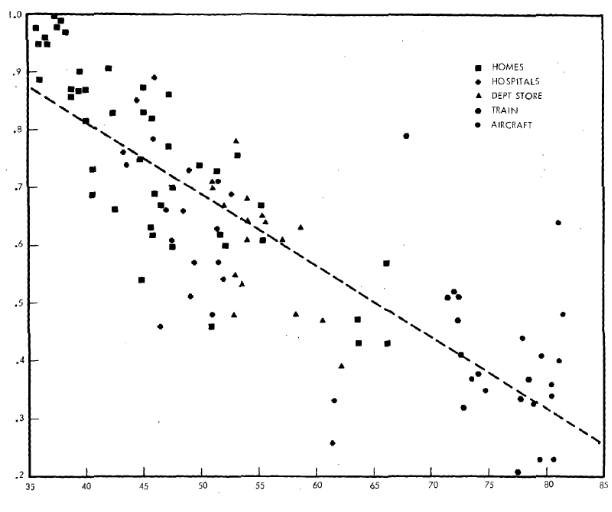

Fig. 10 Articulation Indexes for Communication in Various Environments

RPM	Cessna 172N Two-blade propeller	
	Noise Level L_{Aeq} dB(A)	Articulation Index (AI)
900	69,5	0,45
1500	82,3	0,28
2400 TO/GA	93,3	< 0.20 (0.15)*
RPM	Cessna FR172F Three-blade propeller	
	Noise Level L_{Aeq} dB(A)	Articulation Index (AI)
900	69,0	0,45
1500	83,0	0,28
2400 TO/GA	91,0	< 0.20 (0.17)*

*Extrapolated outside graph

Table 5 Articulation Index for various RPM and aircraft

7. CONCLUSION

Some general aviation aircraft use three-blade propellers instead of two blades. It provides small aerodynamic difference noticeable in slightly better climb, somewhat lower cruise speed and better ramp appeal. Despite the diversity in number of propeller blades, there are only small differences in interior noise levels. They are so small that can be attributed to different engines and slight variations of cabin interior (seats and furnishing). Spectral differences are present due to diverse blade pass frequencies and its harmonics. Three-blade propeller generates 50% higher blade pass frequency. One would expect that higher tones (at low frequency range) would be more pleasing to pilot and passengers. However, in hearing noise preference tests listeners preferred two-blade propeller and four cylinder engine combination instead of three-blade propeller and six cylinder engine combination. This could be due to human hearing curve that discounts lower frequencies, so that combination of three blade propeller and six cylinder engine, despite more pleasant sound, is perceived as louder and more annoying. Speech intelligibility determined by Articulation Index (AI) from noise levels was similar.

ACKNOWLEDGMENTS: This study is a part of the project No. 135-1352339-2349 supported by the Ministry of Science, Education and Sports of the Republic of Croatia. Cessna 172N and Cessna FR172F Reims Rocket were provided by Croatian Aviation Training Center (HZNS) and Ecos Pilot School Zagreb, respectively.

REFERENCES

1. D. Miljković, M. Maletić and M. Obad, **Comparative Investigation of Aircraft Interior Noise Properties**, Proceedings of the 3rd AAAA, 27-28 September 2007, Graz, Austria
2. Propeller Noise, PMLAA, http://www.pmlaa.org/old_news.htm, 24 Aug. 2012
3. H. G. Morgan, **Trends in Aircraft Noise Alleviation**, *Vehicle Technology for Civil Aviation*; pp. 301-315, Jan 1, 1971
4. W. Burns: ***Noise and Man***, J. B. Lippincott Co., 1969
5. K. S. Pearson, R. L. Bennett and S. Fidell, ***Speech Levels in Various Noise Environments***, EPA-600/1-77-025, EPA, May 1977