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EFFECT OF NON-UNIFORM ROTATION ON ACOUSTICS AND AERODYNAMICS OF PROPELLERS

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ABSTRACT

This numerical study investigates the influence of non-uniform rotation on the aerodynamics and acoustics of multi-blade propellers. Non-uniform rotational motion is inherent to piston engine driven propellers.

The effect of rotational speed non-uniformity is the generation of excess harmonic noise due to unsteady aerodynamic blade-loading. In case of a mismatch between the periodicity of non-uniformity and the basic blade passing frequency, additional harmonics are generated due to the complex blade kinematics. For a periodicity coincidence the effects are masked due to overlapping of the frequencies. The level of such extra harmonics may be high enough to dominate the overall A-weighted noise level. Propeller noise radiation for non-uniform rotation is no longer omnidirectional along azimuth and exhibits also a different characteristic in the polar direction.

INTRODUCTION

Rising concern for aviation noise as a source of community annoyance has led to the introduction of increasingly stringent noise certification regulations for all aircraft. To meet the permitted noise levels for piston engine driven propeller aircraft, both the engine and the propeller are under scrutiny with the aim to develop new designs which reduce the noise emission levels with a minimum of penalty in performance.

To exploit fully the noise reduction potential, all components of the propeller drivetrain - engine with its accessories, muffler, engine mounting, etc. - as well as the structural environment and flow conditions in which the propeller operates, have to be considered. The present work addresses a part aspect of this complex and multidisciplinary problem, prompted by a recent finding by W. Dobrzynski and B. Gehlhar [1], [2]. They found that the non-uniform propeller rotation produced by the piston engine causes a periodic variation of blade loading. This generates noise in excess to that observed during uniform (electrical motor driven) propeller rotation.

The objective of the work presented is to analyse the effect of the order and amplitude of non-uniform rotation on the characteristics of the noise generated. A single harmonic of a particular order and amplitude is used at a time to perturb the uniform rotation of the propeller. Test objects are a set of three propellers with 2, 3, and 5 blades, designed to generate the same thrust at a constant rotational speed.

Variation of the order of perturbation harmonic or the number of blades allows a study of the effect of the presence or absence of a coincidence between periodicity of the perturbation and the blade passing frequency. Analysis presented is based on the computation of the unsteady propeller blade loading with an unsteady panel method (UPM), [3]. The results of the UPM serve as input to a FWH analogy acoustics code [4], to evaluate the noise levels.

DESCRIPTION OF THE METHOD

The Unsteady Panel Method

Concepts to simulate flow around propellers with the panel method are well known and documented in the literature (see e.g. [5], [6]). In the specific case of unsteady flow, the boundary condition of flow tangency on the blade surface at every instant in time needs to be satisfied by the solution.

The model of the lifting propeller blade used in the UPM (at any time instant) consists of ([3]):

- a source/sink distribution over the blade surface to simulate the displacement effect of the blade of finite thickness
- a vortex distribution over the blade camber surface to simulate the lift generation of the blade
- a short zero-thickness elongation of the blade trailing edge (Kutta panel) to fix the direction of shed wake and the strength of blade circulation

The numerical procedure consists of dividing the blade, and the camber surface into small surface elements, which carry a source/sink or vorticity distribution respectively, of unknown strength.

Imposing the flow tangency condition at a collocation point on the blade surface elements (panels) and the Kutta panels leads to a system of linear algebraic equations whose iterative solution gives the source/sink or vorticity strengths at the panel collocation points for each time (computation) step. From this the velocity at the collocation points can be evaluated. Finally, the pressure is calculated using the unsteady Bernoulli equation. A detailed description of the procedure is given in [3].

The Aeroacoustics Code

The aeroacoustics code used to analyse the propeller acoustics is based on the Formulation 1a of Farassat [4], which is an integral of the FWH equation with thickness and loading terms only. Quadrupole noise is believed to be small in the incompressible propeller flow considered here. The computations are performed in the time domain resulting in an acoustic time history which is Fourier-analysed to obtain the acoustic spectrum. A detailed description of the code is given in [4].

RESULTS AND DISCUSSION

As a validation exercise for the numerical approach underlying all the results presented in this paper, the aerodynamics and aeroacoustics of a two-blade round tip general aviation aircraft propeller, which has been extensively tested in the German-Dutch Wind Tunnel (DNW), [7], were calculated.

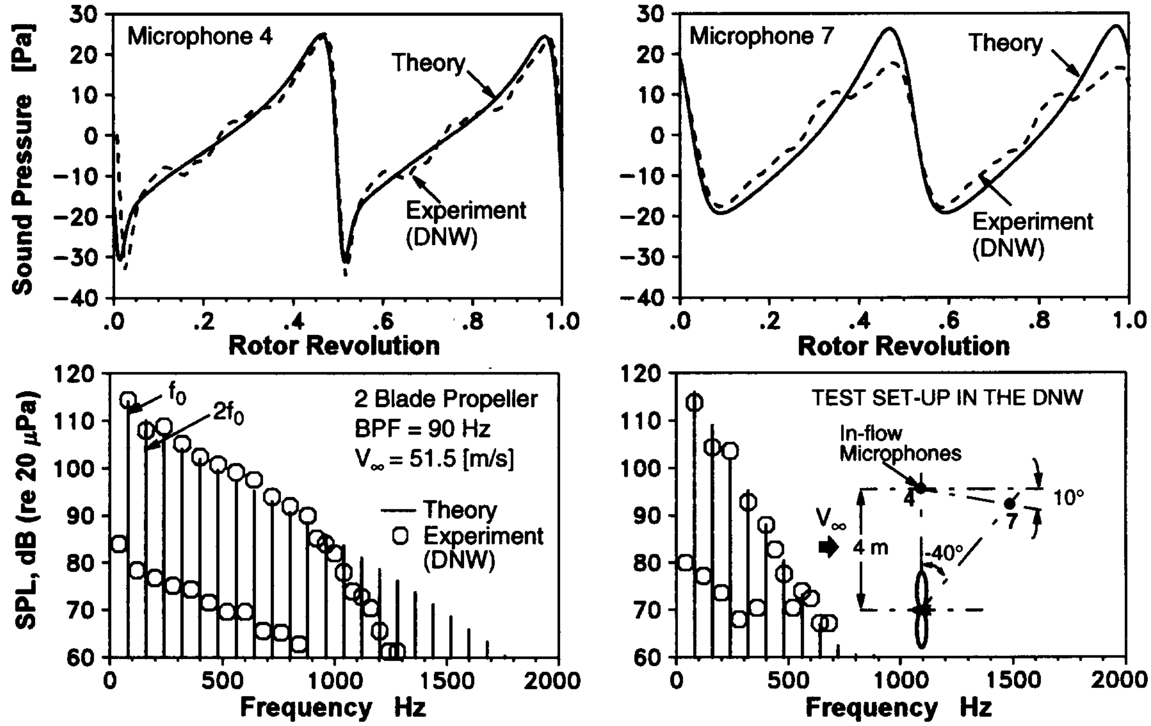

Fig. 1 Sound pressure time history (top) and sound pressure level spectrum at two microphone locations. Comparison of computations with DNW measurements, [7]. 2-blade propeller

Fig. 1 shows the comparison of computed and measured sound pressure (SP) time history and the corresponding results for the narrow band sound pressure level (SPL) spectra at the in-rotation-plane location (microphone 4) and at the -40° downstream location (microphone 7). The SP time history data from experiment exhibits some contamination due to sound reflections from the microphone support structure, as noted in [7]. Otherwise the correlation between the computed results and SP time history for this **uniform** rotational speed case is good. Also, the SPL's are in good agreement with the experimental data. However, the measured spectrum contains subharmonics which could be the contribution of extraneous noise sources and reflections generated in the wind tunnel.

To get a deeper insight into the effect of non-uniform rotation on the aeroacoustics of propellers, it is worthwhile to systematically change the characteristics of the non-uniformity.

To this effect, a single harmonic perturbation of a particular order and amplitude was imposed on the uniform rotation ω_0 such that

$$\omega(\chi)/\omega_0 = 1 + A_p \cos(n_p \omega_0 t) . \tag{1}$$

Here ω denotes the instantaneous and ω_0 the uniform rotational speed, χ the azimuth angle, A_p the amplitude and n_p the order of the perturbation harmonic referred to propeller shaft rotational frequency f_0, and t the time.

As a representative result of the effect of the order of perturbation harmonic on the propeller aeroacoustics, Fig. 2 shows the SP time history for 1 revolution and the corresponding

SPL spectrum for a three-blade propeller operating at 2700 rpm. The upper two plots depict results for $n_p = 2$ and the lower two for $n_p = 6$. In both cases the amplitude of the perturbation A_p was 1% of ω_0.

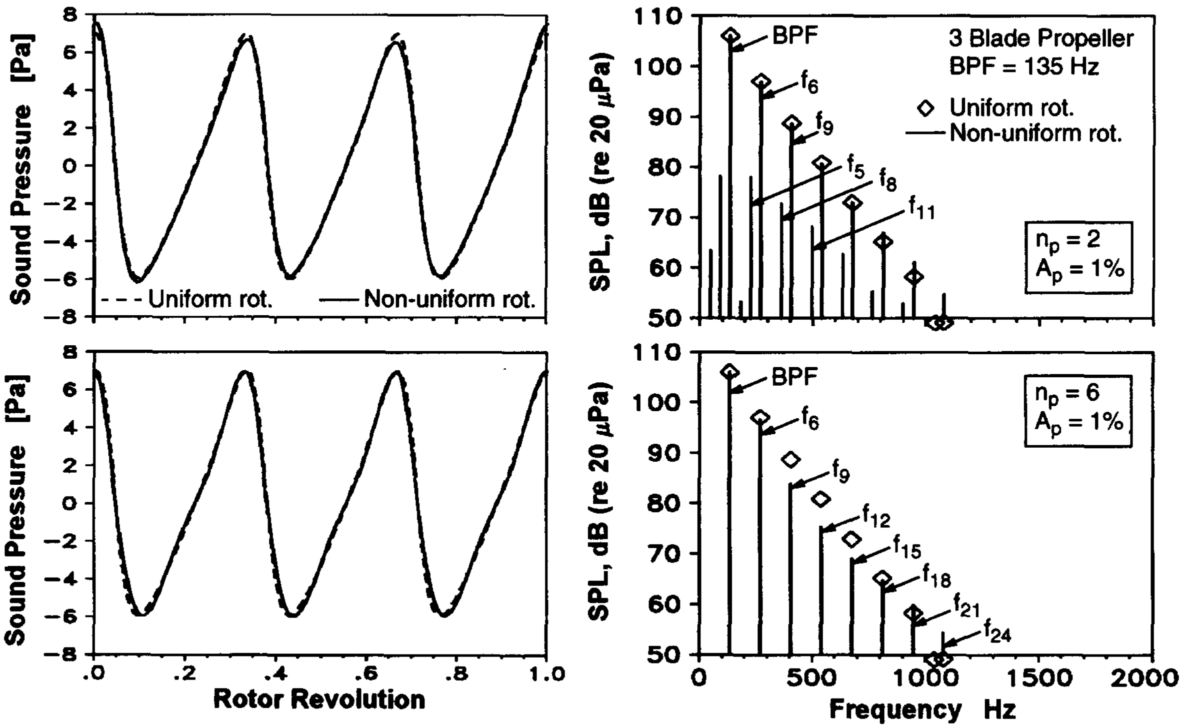

Fig. 2 Effect of order of perturbation harmonic on sound pressure time history and sound pressure level spectrum. Top: $n_p = 2$, $A_p = 1\%$. Bottom: $n_p = 6$, $A_p = 1\%$. 3-blade propeller

In case of a mismatch between blade passage frequency (BPF) and n_p (for example BPF $= 3\ f_0$ and $n_p = 2$ for the top right plot in Fig. 2), subharmonics of the order f_1, f_2, f_4, f_5, f_7, f_8, etc. with $f_n = nf_0$ (besides the harmonics present during uniform rotation viz. f_3, f_6, f_9, ... are generated. The SPL's for uniform rotation are indicated by "diamond" symbols. The reason for the generation of these subharmonics is the change in the kinematics of the propeller rotation caused by the periodic perturbation. For a stationary observer, the BPF serves as a carrier of the imposed perturbation which "rides" over it, so that the net effect for the observer is the perception of additional harmonics. Interesting to note is that subharmonics f_5, f_8, f_{11}, ... exhibit significant SPL's, which decay slower than the "steady" harmonics f_3, f_6, f_9, ...

The bottom right plot in Fig. 2 shows the results for a coincidence between (twice) the BPF and the harmonic order of the perturbation, namely 6. The effect of this coincidence between the frequencies is the absence of the subharmonics. The perturbation generates harmonics which coincide with the BPF or its integer multiples, thus masking the magnitude of its contribution. A comparison with the SPL's for uniform rotation - indicated by "diamond" symbols - shows that a modulation of the SPL's does take place, and this may even lead to a decrease in SPL's for certain frequencies.

The results for the SP time history in Fig. 2 are less dramatic in that the variation for the uniform rotation (broken line) deviates slightly near the peaks and valleys from the corresponding curve for perturbed rotation. However, the generation of the harmonics seen in the spectrum is the consequence of the change in the gradient of the SP time history, which is obviously more significant than can be discerned from the plots on the left in Fig. 2.

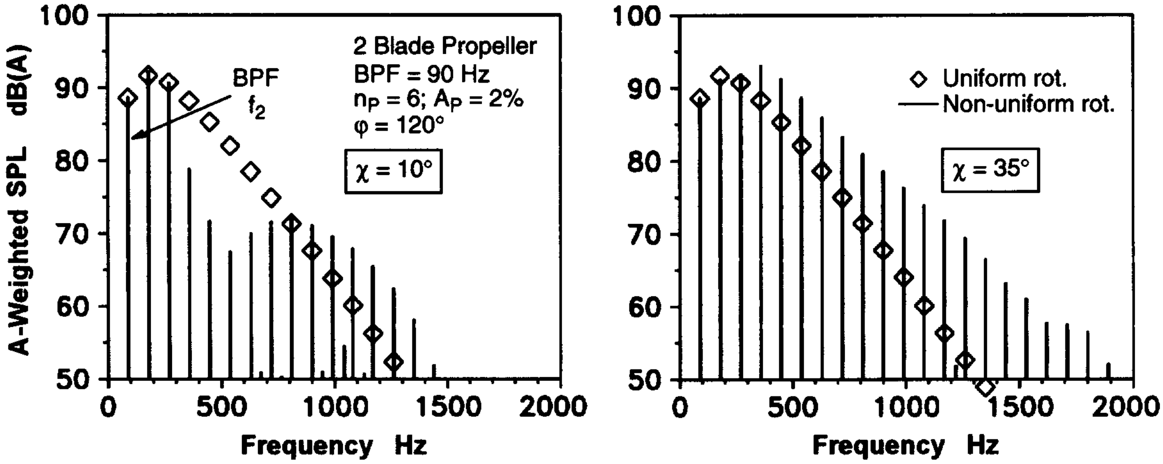

Fig. 3 Variation of A-weighted sound pressure level spectrum with azimuth angle χ. 2-blade propeller

To bring out yet another effect of non-uniform rotation, Fig. 3 shows the A-weighted SPL-spectrum for a 2-blade propeller at two azimuthal observer positions, namely at $\chi = 10°$ and 35°. The uniform rotation is perturbed by a harmonic of $n_p = 6$ and amplitude $A_p = 2\%$. The SPL's for uniform rotation at 2700 rpm are indicated with "diamond" symbols. For the azimuthal observer location of $\chi = 10°$ (and polar location $\varphi = 120°$), the A-weighted SPL's in the range of 300 Hz to 700 Hz are reduced and beyond 900 Hz increased over the values for uniform rotation. The situation at the same polar location but at an azimuth angle of $\chi = 35°$ exhibits an increase in A-weighted SPL's for all frequencies above 300 Hz as compared to the values for uniform rotation.

Summarising from Figs. 2 and 3, a mismatch between BPF and order of perturbation harmonic leads to generation of subharmonics affecting the tonal quality of the noise. The effect of non-uniformity on the SPL can be high enough to affect the overall A-weighted level. Coincidence between BPF and integer multiples of perturbation harmonic order can result in an increase or decrease of A-weighted SPL's in the spectrum, depending on the azimuthal location of the observer.

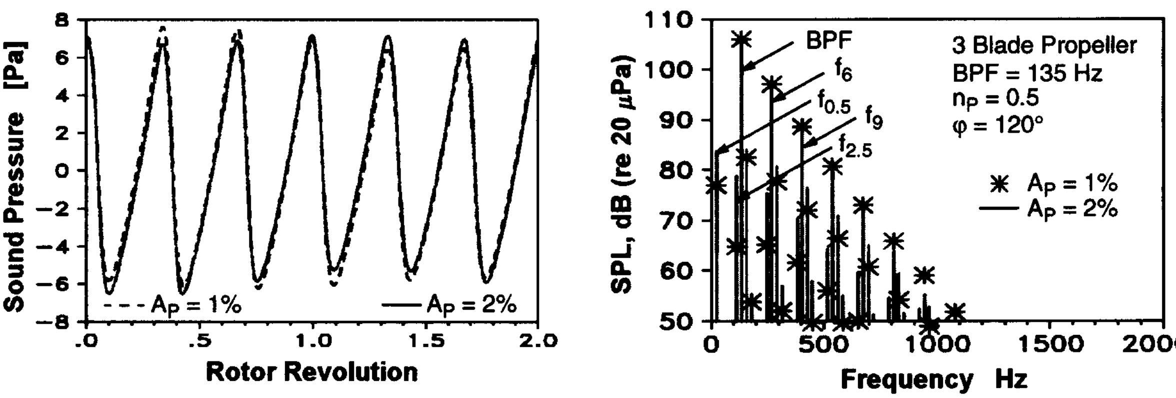

Fig. 4 Effect of perturbation amplitude on sound pressure time history and sound pressure level spectrum. Polar angle $\varphi = 120°$. 3-blade propeller

Fig. 4 demonstrates the effect of a doubling of the perturbation amplitude on the SP time history and SPL's of the spectrum. Considered is a three-blade propeller rotating at 2700 rpm with a perturbation harmonic $n_p = 0.5$ imposed alternatively with an amplitude A_p of 1% or

2%. The SPL's for A_p = 1% are indicated with an "asterisk" in the spectrum plot. Since BPF and n_p do not match in this case, subharmonics $f_{0.5}$, $f_{2.5}$, etc. are visible in the spectrum. The effect of a change in amplitude manifests itself, as expected, in a general increase in the SPL's of the individual subharmonics. SPL's for frequencies coinciding with BPF or its integer multiples, are reduced somewhat (for the non-uniform rotation) in the frequency range above 800 Hz. The SP histories for the different amplitudes (left plot of Fig. 4) differ only slightly from one another.

An interesting effect of the rotation non-uniformity is the change in the azimuthal directivity as evident in the plot of Fig. 5 where the SPL's for the frequencies f_8, f_{10} and f_{12} are plotted over the azimuth angle χ. Considered is the two-blade propeller operating at 2700 rpm with a perturbation of n_p = 6 and an amplitude A_p = 2%. The observer location is at a polar angle of φ = 120° on the rearside of the propeller plane of rotation.

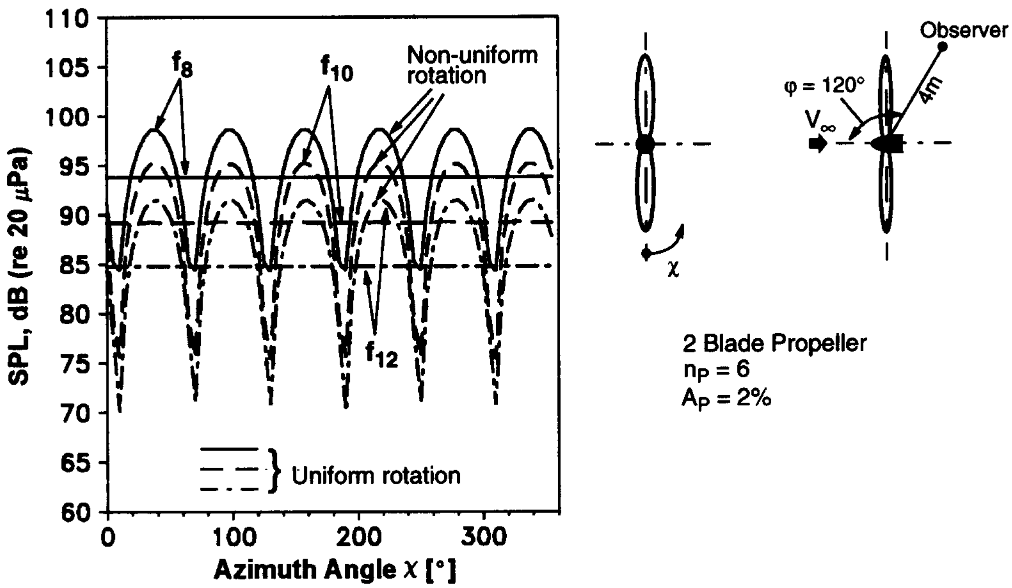

Fig. 5 Effect of perturbation on azimuthal directivity. n_p = 6, A_p = 2%. 2-blade propeller

While uniform rotation produces a constant SPL's over the azimuth, the imposition of n_p = 6 non-uniformity generates a six per rev. periodic variation of SPL for all the frequencies considered. The relative increase in the SP (over the value for uniform rotation) turns out to be higher for the higher frequency (e.g. f_{12}) than for the lower frequencies. The omnidirectional character of the azimuthal directivity is changed thus to a n_p-coincident periodic function.

Fig. 6 shows results of the polar directivity for three frequencies viz. f_8, f_{10} and f_{12} for the two-blade propeller operating under conditions described in Fig. 5. Plotted in each frequency diagram are the directivity curves for the azimuth angles χ = 5°, 40° and 60°. Also shown (lowermost curve) is the directivity for χ = 5° at the reduced rpm of 2500 but with the same value of n_p as for the higher rpm.

The non-uniformity distorts the polar directivity curve for uniform rotation - from a double peak curve, as shown for f_8 in the Fig. - to a curve with two to three peaks, with the peaks located ahead, at and in the rear of the propeller plane of rotation. The shape of the directivity curve depends on the azimuthal position and shows large SPL variation in the azimuth angle range of χ = 5° to 60°. Significant variations of SPL's with polar angle is restricted to values of φ approximately between 40° and 140°. As seen in Fig. 6, a reduction in the operating rpm from 2700 to 2500 lowers the SPL's particularly in the polar angle region between 60° to 120°.

The reason is that with reduction of rpm the magnitude of unsteady loading relative to steady loading increases, as also the noise.

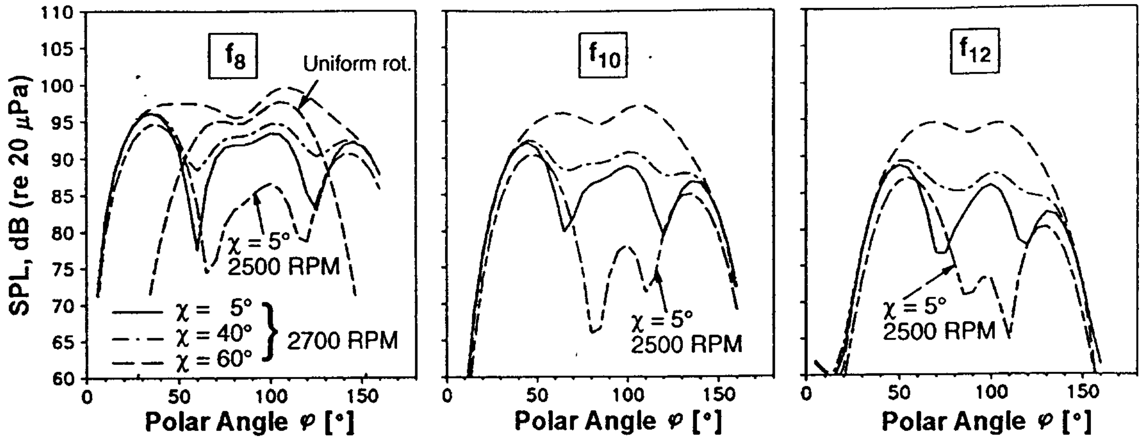

Fig. 6 Effect of perturbation and rpm on polar directivity. $n_p = 6$, $A_p = 2\%$. 2-blade propeller

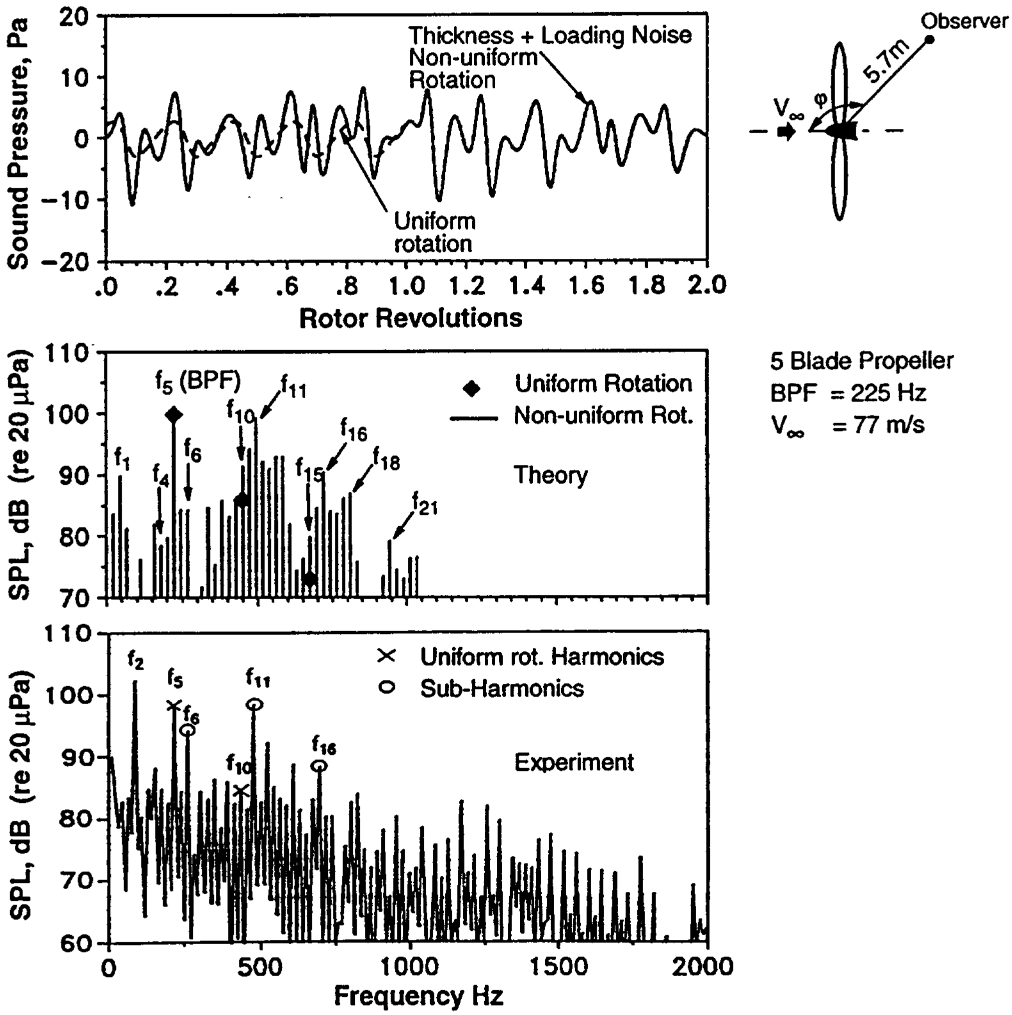

Fig. 7 Sound pressure history and sound pressure level spectrum for a "flight data" non-uniformity. Comparison of computation with DNW measurements, [2].

As a final example of the performance of the UPM-FWH code, Fig. 7 shows the computed SP history and SPL spectrum together with corresponding data from DNW measurements for an observer position P as indicated in the Fig. On a uniformly rotating five-blade propeller a non-uniformity which was measured during flight tests was imposed. The measured non-unifomity was simulated in the computation with a set of 18 harmonics, evaluated from a FFT analysis of flight data. The same 4 cylinder 4-stroke piston engine of the flight test aircraft was then installed in the DNW to drive the five-blade propeller and its acoustics measured.

The imposition of "real life" non-uniformity on the uniform rotation radically distorts the SP time history. The distorted time history repeats itself after two revolutions, which is typical for a 4-stroke engine. A look at the corresponding computed SPL's shows the generation of numerous subharmonics which have their counterparts also in the measured spectrum, shown in the lowermost diagram of Fig. 7. Of particular interest are the excessive SPL's for the frequencies f_{11}, f_{16}, f_{21}, ... etc. which are exhibited both by the computations and the wind tunnel results. This shows that the dominant non-uniformity, which seems to be a characteristic property of this particular 4-stroke engine, has a value $n_p = 6$ and hence the predominance of frequencies which result from addition of BPF or its integer multiples and n_p (e.g. $(5 + 6)f_0$, $(10 + 6)f_0$, etc.). This example demonstrates the ability of the developed code to capture the complicated physics of the non-uniformly rotating multiblade propellers.

CONCLUSIONS

The presented results show the feasibility of predicting the aerodynamics and acoustics of propellers with the developed numerical scheme. More investigations and analysis of results is needed to explain fully the various effects resulting from the rotation non-uniformity.

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