Takeoff vibrations of a jetliner: simulating possible cause

Stanislaw Raczynski
Universidad Panamericana, Mexico
stanracz@stanr.com

ABSTRACT

Using a gas flow simulation tool, the oscillations of the air around the wing are analyzed. It is pointed out that the flow behind and below the wing oscillates with sub- or low acoustic frequencies. Such external excitation may enter into resonance with the natural vibration frequencies of the wings and fuselage, which can produce a dangerous effect. The point of the article is that the fuselage vibration on take-off depends mainly on what happens in the surrounding air flow. The tool used for flow simulation is equipped with the frequency analysis procedure that shows the spectrum of the oscillations (pressure) in selected points. This permits to identify the main frequencies and amplitudes of the oscillation. The results show that there are several sub-acoustic frequencies (infrasound) that may produce oscillating forces of up to several hundreds of kilograms per square meter of the wing.

The topic is closely related to the safety issues.

Keywords: airplane takeoff, simulation, aircraft vibrations, takeoff vibrations, flight safety

INTRODUCTION

In many occasions passengers complain due to the strong vibrations of the fuselage during lift-off. The fuselage interior noise grows, which makes the taskeoff unpleasent. The efforts to avoid the noise consist mainly in active vibration control. Minishakers attached to the exterior wall of the fuselage can help in vibration measurements (Fuller, 2005). The use of 'Aquaplas' material damping compound on a vibrating stringer skin combination is another way to reduce noise, discovered many year ago (Mead and Ae, 1960). Sophisticated vibroacoustic method are being applied in vibration modeling, like the artificial spring technique and the integro-modal approach are presented in the literature (Missaoui and Cheng, 1999). Zhao and Sheng (2012) discuss the influence of the stiffeners on the plate-shell coupled structure's vibration characteristics is analyzed to show how to reduce the peaks of the vibration curves and the cylindrical shell's acceleration level. Bhat and Wilby (1971) present the measurements of the acoustic power radiated by an airplane fuselage due to the turbulent boundary layer pressure field. A comparison of some methods of the turboprop and unbalance tones of the turbojet vibration control can be found in Flotow et al., (1997).

The low frequency vibrations of the airplane are identified as follows (see Cosner et al. 2012).

Vibration is oscillating, reciprocating, or any other periodic motion of a rigid or elastic body forced from a position or state of equilibrium. If the frequency and magnitude of vibration are constant, the vibration is said to be *harmonic*. When the frequency and magnitude vary with time, the vibration is *random*.

B*uffet* which is a form of vibration usually caused by aerodynamic excitation. It usually is random and associated with separated airflow. For example, buffet may be felt during the extension of speed brakes or during air turbulence.

Flutter is an unstable condition in which unsteady aerodynamics excite the natural frequencies of the structure over which the air flows. The resulting vibrations can grow to a magnitude that causes the structure to fail.

Other vibrations are classified as ***noise***.

The problem focused in the present paper is somewhat different. The low, infrasound frquency vibration during the takeoff are considered. Those are strong vibrations of the whole aircraft rather than the acoustic noise. As the frequencies are low, the acoustic noise is not very strong, but the aplitude of the vibration may be great. This can provoke airframe demage and mechanical failures. This is an important factor for safety issues. Such vibration can hardly be dumped by aquaplast or other dumping materials. The point is that the **takeoff vibrations are caused by what happens outside the fuselage**, mainly the forced vibration of the air between the aircraft and the runway, and the turbulent region behind the wings. Of course, what the passenger experiences is the combination of vibrations caused by many different sources. To be more specific about the topic of this article, let us note that it is focused on the vibrations caused by the movement of the air around the wing, resulted from the flow dynamics (described by the NS equation). We do not deal with the noise generated inside the aircraft structures, the pneumatic tire or dampers. The duration of the simulation varies from 0.36 to 0.8 seconds. The pressure changes result from governing NS equation. The results show just how the air moves, which may include resonance, turbulence and other dynamic patterns. A similar simulations could be carried out for the landing conditions, with different angle of attack and other parameters. This may be an interesting topic of another article.

As stated before, the theoretical framework is the NS equations. The validity of the equations has been well proved more that one century ago. We will not discuss here the mathematics of the NS model which has been treated in a huge literature, see, for example, Landau and Lifshitz (1963). The used CFD tool (Fluids6.3) solves the NS equations in their native form directly, without turbulence model such as in LES, RANS, etc., over a uniform spatial grid of up to several million points (see the next section for more information). It should be noted that the main aim of the simulations is not to see the turbulence or other flow patterns, but to obtain the plots of pressure changes and its spectra, like those shown in figure 3 and 4. The Fluid6.3 is a simplest and most appropriate tool for this purpose.

Simulation experiments have been carried out. In all experiments, the simulated flow never reaches any steady state. It is always oscillating and produces low frequency excitations on the wings and the fuselage.

THE SIMULATION TOOL

The Fluids6.3 program has been used. The main purpose of the program is to simulate shock waves in gases and liquids, and oscillating flows. The flow dynamics is modeled using the Navier Stokes (NS) equation.

The Fluids6.3 program just resolves the NS equations, so it is supposed to be valid for any physical system which obeys the equations. No specific "turbulence model" is used. As for the boundary conditions, all the sides of the regions are supposed to be open, except of the ground (closed boundary). The turbulences result in a natural way from the properties of the flow, governed by the NS equation. The program has been coded in Embarcadero Delphi language. Its main features are listed below. The program has been validated for several flow problems, not exactly for the flow around a wing. To validate the tool, wind tunel experiments should be done with pressure sensors to register the flow vibrations. Note, however, that if we perform such experiments, then we don't need to carry out any simulation experiments. The present experiments have been done exactly to replace the physical modeling and to **suggest a possible cause** of vibrations. Anyway, the author had no access to wind tunnel results for this specific case.

The advantages of Fluids6.3 are as follows.

1. The simulation is dynamic and three-dimensional. The movement of the media can be seen on animated images.
2. The user can select the points where the flow parameters (pressure, velocity, temperature) are recorded and then shown as functions of time.
3. The flow lines and the velocity field can be seen on 3D images.
4. The spectral analysis of the recorded parameter changes is being done, to detect the dominating frequencies in the oscillating flow.
5. The program includes the duct and an obstacle 3D editor that may be used to define the 3D shapes.

The main disadvantage of Fluids6.3 is that it is rather slow. The N-S equation is being solved in consecutive time steps, which cannot be augmented because of the numerical stability problems. Fluids6.3 uses a uniform 3D grid of points where the flow parameters are calculated. However, the grid is two times denser near the boundaries of the obstacles and of the flow region, to increase the spatial resolution. A model with 100 thousand of grid points is a small one. A reasonable number of points is between 500 thousand and one million, though greater models also can be simulated.

For more information about Fluids6.3 consult:
http://www.raczynski.com/pn/fluids.htm

EXPERIMENTS

We simulate air flow around a fragment of a wing, in a duct defined as a box like a wind tunnel, as shown on figure 1. The airfoil is (approximately) that of Boeing 737 with extended flaps, angle of attack 13.5 degrees. The initial liftoff angle for such aircraft is about 8-10^o and then reaches up to 18^o.

The air is forced to flow from the left to the right, through the open sides of the box. The other sides are closed. Air speed varies inside the tunnel. In the experiments the maximal air speed was about 260 km per hour. It is supposed that the flaps are partially extended. The tunnnel length was equal to 7 meters.

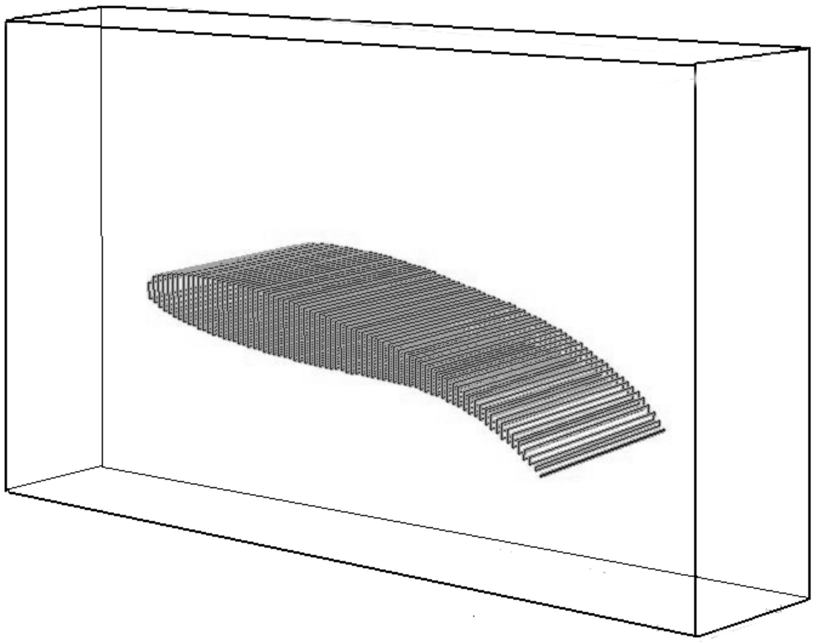

Figure 1. Wire frame image of the wing fragment in the tunnel.

In figure 2 we can see the air velocity field around the wing. This is a black and white version, the original images produced by Fluids6 show the velocity elements in color, depending on the velocity at the point, on the black background.

Several experiments have been done with different elevation (h) of the wing. The points marked as 1,2,3 and 4 indicate where the "probes" has been placed. The probe is just a point where Fluds6 will store the flow parameters (pressure, velocity) during the simulation. Then the corresponding plots are displayed where the parameter changes can be seen as functions of time. Each plot can be analyzed to show the frequency spectrum of the parameter. Out parameter was the vertical component of the air velocity. The simulated tunnel cannot be very big, because of the limitation of Fluids6 grid. In our case, the grid included about 850 thousand points. The simulation can be run in 3D or 2d mode. In our case all sections by the plane perpendicular to the wing are equal to each other, so the 2D simulation mode (only one "slice" of the tunnel) is expected to provide the result similar to the 3D simulation. A comparison has been done which confirmed this (not so obvious) fact.

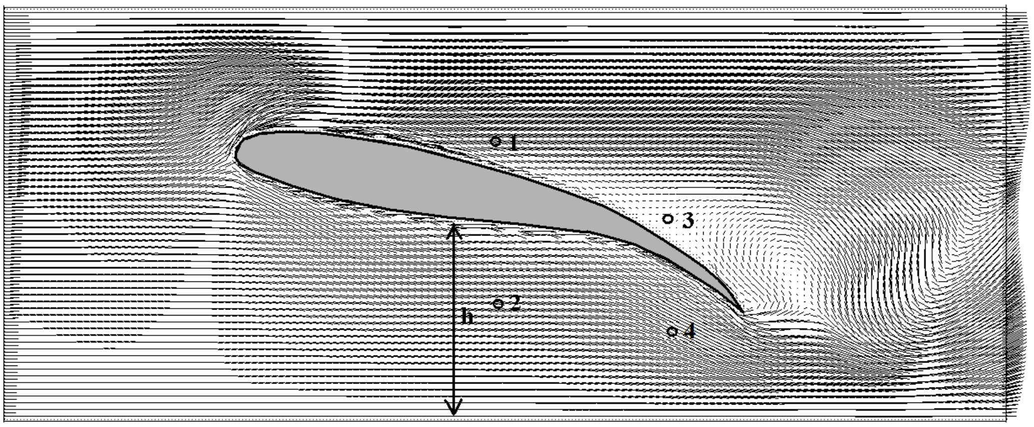

Figure 2. Velocity field.

The aim of the simulations was to detect the frequencies of the air oscillation near to the wing. The final model time for all simulations was 0.36 second, integrated in about 300,000 time steps. Figure 3 shows the plots of the air vertical velocity at points 1,2,3 and 4, as shown in figure 2. It can be seen that, after a short "warm up" initial interval, the velocity starts to oscillate in quite regular pattern.

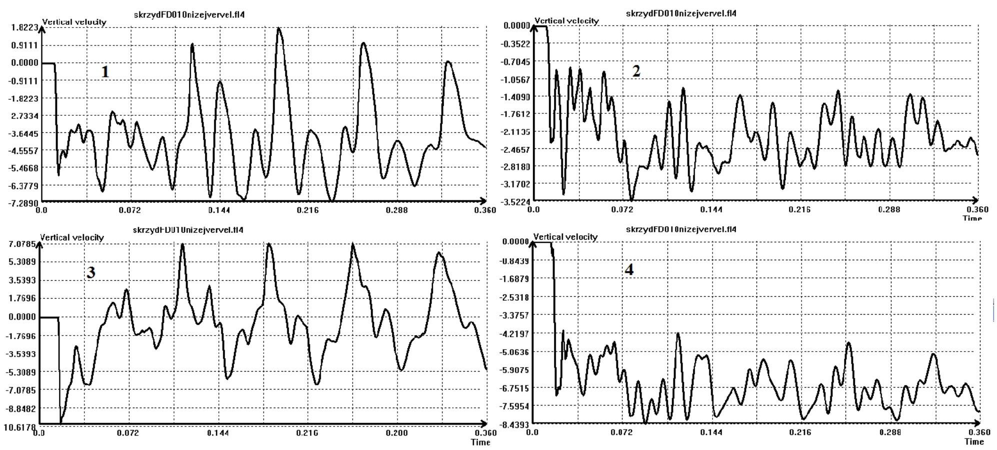

Figure 3. Plots for h=1.6m.

Figure 4 shows the results of the Fluid6 spectral analysis. It can be seen that some frequencies repeat in all probe points. Similar results have been obtained with the wing position at h=2 m. The dominating frequencies can be seen on the following table.

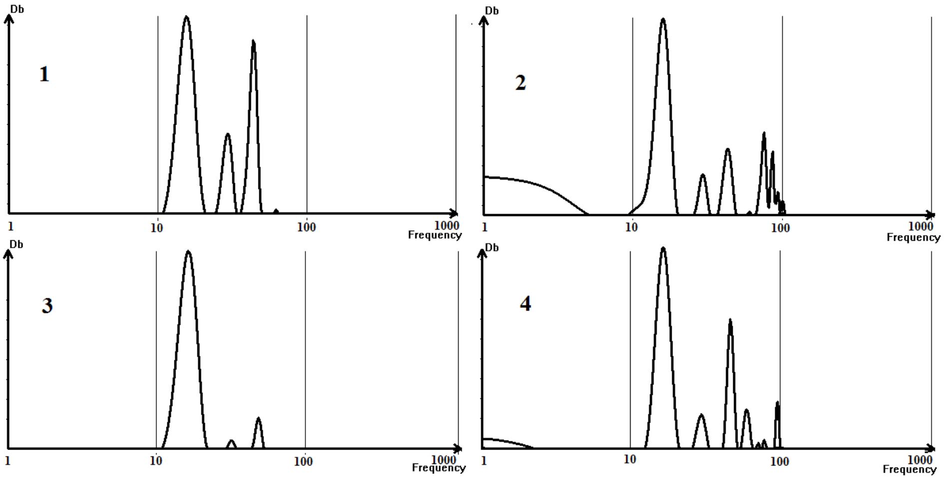

Figure 4. Frequency spectra for h=1.6m.

Frequency plots have the vertical scale in Db, normalized to 1 Db max. Frequencies with amplitude lower than –20 Db are ignored. It can be seen that some of the frequencies repeat. The frequency of 15 Hz dominates at all points. This is the frequency with which the flow oscillates in point 3, just above the flap.

Table 1

Point	h(m)	Frequencies Hz
1	1.6	14.6, 27, 42, 58
2	1.6	15, 27, 41, 50, 70.3, 82.7, 87.3, 94.7
3	1.6	14.6, 28, 43.2, 55, 64.8, 72.2, 87.3
4	1.6	15.4, 28, 43.2, 55, 64.8, 72.2, 87.3
1	2	15, 28.7, 35.7, 43.1, 63.1
2	2	15, 44.4, 61.4, 78.3
3	2	15
4	2	10, 15, 28, 38, 44, 56, 72, 82

Some additional simulations have been carried out in order to be sure that the detected frequencies are not the result of the resonance of the tunnel itself, and that they are related to the wing movement. The simulations with a horizontal cylinder and an arbitrary horizontal shape have been done, providing spectra quite different from those shown above. Another experiment was done to determine the natural (resonance) frequencies of the tunnel with the wing inside. The forced air flow was eliminated and replaced by a short internal excitation, like an explosion in a small region (market as X in figure

5). As the result the following dominated frequencies have been obtained: 8.2, 56, 82, 117, 134 and 171 Hz, where 82 and 117 Hz have been the strongest. None of these frequencies coincide with those of table 1. This means that the oscillations in the previous experiments are produced by the fluctuations of the turbulent parts of the flow around the wing in the movement.

It can be noted that changing from h=1.6 to h=2 makes some of the frequencies move to higher values. Perhaps this occurs because of higher qier velocities of the air below the wing, which makes the turbulance stronger.

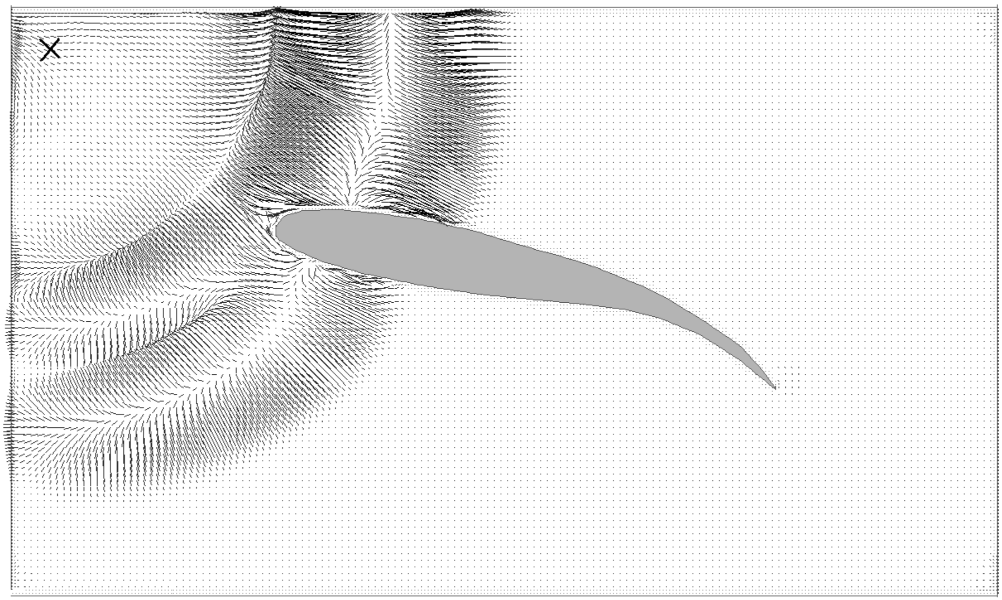

Figure 5. Explosion inside the tunnel, expansion wave.

The flow velocity field around the wing is highly oscillatory. Repeating the simulation, even with nearly the same parameters we can obtain quite different results. When the simulation is run for a longer model time interval, then the amplitude of some frequencies may grow significantly. In particular, the lower frequency oscillations may become more important. One of such experiments, for the wing elevation equal to 2.5m is shown on figure 6. Those are pressure oscillations in the point just below the wing. The frequency analysis of the curve shows two dominated frequencies, approximately of 8.5Hz and 17Hz, the second being the dominating one. These frequencies are not caused by the resonance of the tunnel itself, and they do not repeat so strongly with other wing elevations. The amplitude of the oscillations is worth attention. It is equal to 8.5 kPa (17 kPa between extremal points), this means 0.0838 atm. So, we have oscillating force applied to the wing, with a magnitude of 838 kg force per square meter of the wing. This results in strong oscillations of the whole fuselage, that disappears when the plane elevates. The vibrations are of low frequencies (infrasound), just as many of us experience during the takeoff.

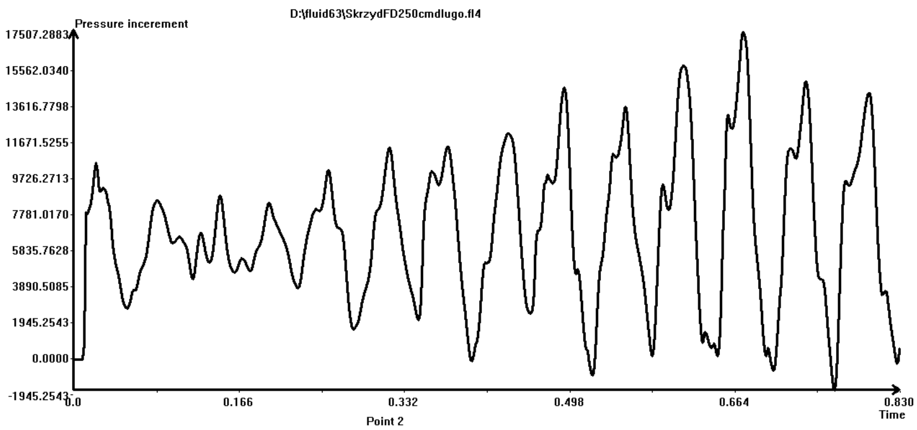

Figure 6. Low frequency oscillations

CONCLUSIONS

The air moving around the wing produces several infrasound frequencies. Perhaps those oscillations are not strong enough to produce a damage. However, these frequencies may enter into resonance with the fuselage that may produce queite strong effect. Fluids6 program does not support moving obstacles and obstacle vibrations, so this issue would need further research. During the take-off, some of such infrasound frequencies may also coincide with the natural frequency of the air column between the wing and the ground, that can multiply the effect.

It should be noted that the presented results arise from simulation only. The designers of modeling and simulation methods and tools attempt to reflect what happens or may happen in the reality admitting, however, certain simplifications. The results should be used to elaborate suggestions for further research and design. The model parameters used in the simulations are always charged with some degree of uncertainty. Perhaps, more useful is the qualitative outcome of the simulations, rather than the quantitative results.

Anyway, the problems considered here are closely connected to the aircraft safety, and their profound investigation may avoid accidents.

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