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Preliminary evaluation of interferometry measurements of the flow field in the vicinity of a self-excited single profile

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Abstract. This paper deals with the interferometry measurement of the flow field in the vicinity of the surface of the self-excited single profile NACA 0015 in subsonic air flow. The pressure and velocity on the profile surface, the total forces and total moments acting on the profile are evaluated in the range of the Mach number Ma = 0.18-0.45 and the Reynolds number Re = $(3\text{-}6)\cdot 10^5$. Since the interferogram processing was conducted with simplified assumptions of the isentropic changes of the flow field, the results have a limited accuracy especially in the case with flow separation. Results were not compared with the direct pressure measurement on the profile surface. The optical measurement method enabled the forces and moments to be evaluated separately for the suction and pressure surface of the airfoil.

1 Introduction

Flow-induced vibration (FIV) is a serious problem during operation of many technical devices such airplane wings, helicopter rotors, propellers, turbine / compressor blades, antennas or transmission wires. This phenomenon is caused due to the specific interaction between flow instabilities with elastic structures of a moveable device. Flutter is dangerous for many reasons: significant influence of lift and drag; the loss of efficiency of energy conversion; the occurrence of resonance effect if natural frequency is identical to frequency of vortex-induced vibration (VIV), etc.

A good understanding of self-excitation mechanism of single profile is necessary condition for studying much more complex arrangements – self-excited profiles located within a cascade. The oscillation of single profile with two degrees of freedom is solved quite commonly both numerically and experimentally. Classical flutter phenomenon [1] is characterized by the attached flow all the time of the airfoil movement. Unlike stall dynamic flutter [2] where airfoil has very high angle of attack (AoA) values while moving and boundary layer can be separated along all suction side resulting in rapid drop of lift force. Stall flutter has nonlinear reaction of aerodynamic forces to the airflow vibration. Thus, the basic instability and its principal features are explainable in terms of nonlinear forces and moment.

The aeroelasticity issues of profiles located in cascade are mentioned in literature rarely (e. g. [3], [4]). The information about self-induced profile inside cascade with pitch and plunge degrees of freedom was not found in the literature at all. The experimental research described in this article should help to start up a challenging investigation of self-excited profiles within turbine or compressor blade cascades [5].

This article follows previously conducted experiments with single profile NACA 0015 (e.g. [6]) which were carried out in high-speed wind tunnel of the Institute of Thermomechanics in Nový Knín. This tunnel is able to reach velocities up to Ma = 1.9 with turbulence intensity below 1%. The main result here is an analysis of interferometric measurement of non-stationary flow field in the vicinity of profile with pitch and plunge degrees of freedom. Self-induced vibration was observed during Mach number range from 0.2 to 0.45 for this particular geometry. Two distinct regimes for Ma = 0.28 and 0.45 (Reynolds number Re = $4\cdot 10^5$ and $6.5\cdot 10^5$) are presented. Both regimes are characterized by the existence of massive flow separation at suction side forthcoming by extreme pitch. Moreover, the lower velocity case is responsible for significant instability of the separation point position which has led to non-uniformity of plunge motion.

2 Experimental setup

The used profile NACA 0015 is an original design of previous experiments [6] from technical reasons. The airfoil had ideal chord length c = 67 mm and real length was 96% of ideal length. The profile shape and its support is depicted in figure 1. The profile has span dimension of 76.6 mm. The airfoil was adjusted to have a slot to install bearing and elastic element (rotary axes located at 1/3 of chord). A torsion rod was used to support elasticity of the rotation. Vertical profile guides were supported by flat linear springs enabling plunge motion. The guide was designed to have triangular cutout to not block the optical access in the vicinity of the profile surface.

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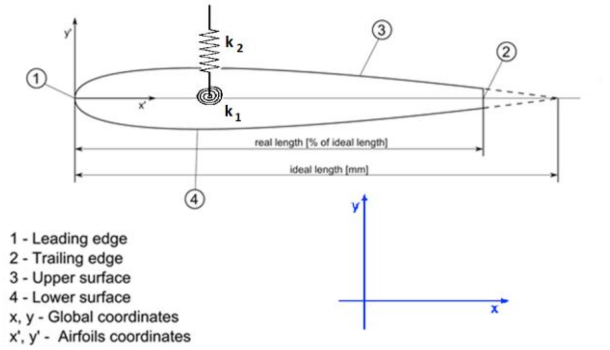


Fig. 1. Schematic view of used profile and its support using elastic elements.

The profile was fixed in a test section with dimensions 80 x 210 mm which was connected to the suction-type wind tunnel. The optical access for interferometry was provided by two glass windows with diameter of 160 mm and thickness of 20 mm. Precautions against scratching the glasses were performed. Compensating glasses are placed between the test section and the interferometer.

The interferometer of Mach-Zehnder type (Fig. 2) was utilized to measure the flow properties. The interferometer is sensitive to changing of density. The principle of this method is the phase shift variation between two collimated beams generating by splitting light from a single source (mercury lamp with wavelength 435.8 nm). One beam is guided through the compensator glasses and second one is guided through measurement section where density changes of moving air are present. An interferogram consisting of interference fringes of constant density are used then to evaluate the pressure distribution. Bigger width of measurement section is used, higher amount of fringes are present (our section had a width of 80 mm). The set of mirrors were set so that the fringe No. zero had infinity width (i. e. it corresponded to density of incoming flow). Fast CMOS camera with acquisition frequency of 1 kHz was used to capture the interferograms.

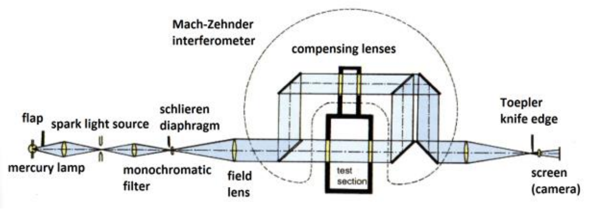


Fig. 2. The scheme of the optical measurements using Mach-Zehnder interferometer.

The evaluation of interferogram can be affected by several errors. The determination of a distinct fringe is possible with precision of a half fringe (one fringe is composed from bright and dark part). The fundamental condition is to determine correctly the fringe No. zero. The accuracy of measurement is dependent on the flow velocity (the number of fringes is decreasing with lower velocity values). The experience of an evaluator plays a crucial role as well as the contrast of interferogram itself. Sometimes several fringes can be covered by supported part of experimental device. The fringe contrast can be decreased by unsatisfactory two-dimensionality of the flow. The interferometry method does not detect the pressure loses due to dissipation of energy. Usually, this should be corrected using static pressure measurement along airfoil profile. This correction was not included because of the high technical demands. Future experiments will contain static pressure measurement along profile using small MEMS sensors.

An in-house software IFGPro was developed and used for the post-processing and evaluation of interferogram sequences. The software is semi-automatic with possibility to investigate arbitrary airfoil with two degrees of freedom. The constants used for density estimation: wavelength of light λ = 435.8 nm; heat capacity ratio κ = 1.4; specific gas constant $R = 287.67\ \mathrm{J \cdot kg \cdot K^{-1}}$; Gladston-Dale constant $K = 0.0002297\ \mathrm{m^3 \cdot kg^{-1}}$. The result is in form of pressure and velocity distribution, lift and drag force, moment, pitch and plunge coordinates etc. The example of GUI is in figure 3. One can see marked fringes (green lines) around whole profile, the atmospheric pressure value (purple line), the pressure distribution around airfoil (red line) and acting forces on the profile in the picture. This software enables to calculate forces acting on upper and lower sides separately which is crucial feature by investigation of both half-periods of movement. The asymmetry of the excitation motion can be then assessed.

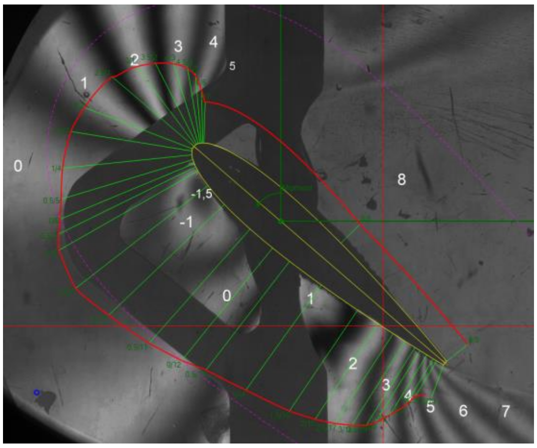


Fig. 3. The cut of GUI of post-processing.

3 Results

The self-excited profile oscillates for Mach numbers 0.45 and 0.28 with plunge frequency approximately 32 Hz and 26 Hz, respectively. This is the reason why both regimes will be compared for separately plotted graphs. Firstly the kinematics of the profiles will be solved. Consequently the acting forces and moment on the airfoil will be discussed.

3.1 Kinematics

The self-excited profile has performed a periodic motion in terms of pitch and plunge degrees of freedom. The pitch values during one period follow almost perfectly sinus wave without any distortion for both investigated Mach numbers. The example of the pitch-time dependency is given in figure 4. The pitch peak-to-peak value was 83° for higher Mach number and 78° for smaller Mach number. Figure 5 is plotted for plunge coordinate during one period for both examined Mach numbers. Peak-to-peak plunge values are 14 mm and 16 mm for Mach number 0.45 and 0.28, respectively. The plunge value reaches its maxima when the AoA is equal to zero. The curve of plunge motion is not perfectly smooth, especially at top dead position (for Ma = 0.45). There is one concave and one convex additional part which are superimposed to plunge curve to both sides from the main peak for lower Mach number. This may be connected with instability of the separation point and it will be discussed later.

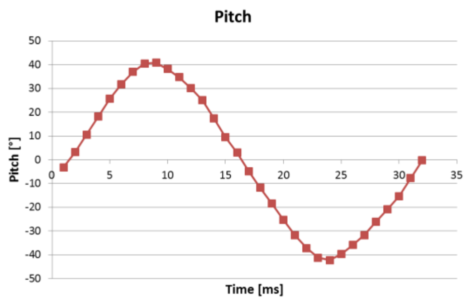


Fig. 4. Sine wave of pitch-time dependency, Ma = 0.45.

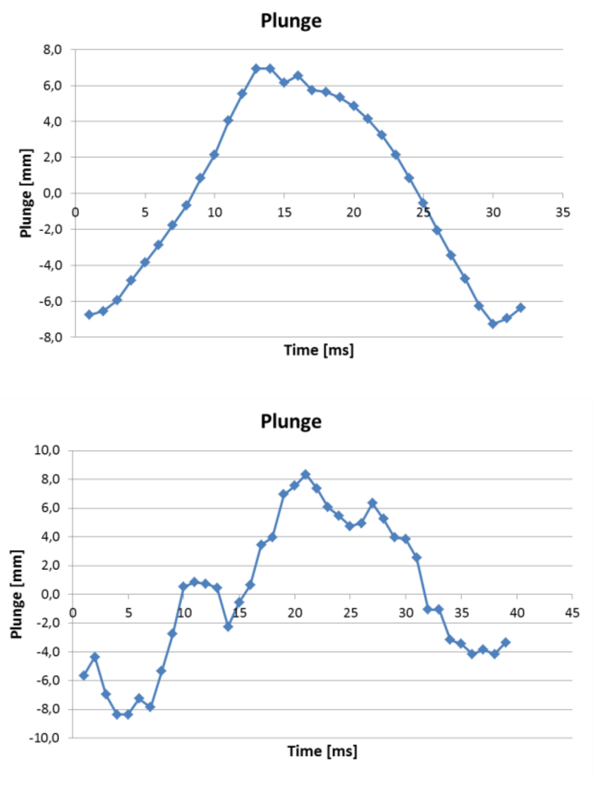


Fig. 5. Plunge-time dependency for M = 0.45 and M = 0.28.

The pitch velocity [°/s] and plunge velocity [m/s] are evaluated in figure 6 for Ma = 0.45. The biggest pitch velocity (about 7500 °/s) was observed for zero value of AoA. The maximal plunge velocity is approx. 2 m/s and the curve is wobbled for top dead position. The bottom dead position does not demonstrate this feature. This could be caused by the effect of gravity. Generally, it can be said that the profile is very sensitive to deep stall dynamic flutter under investigated flow velocities.

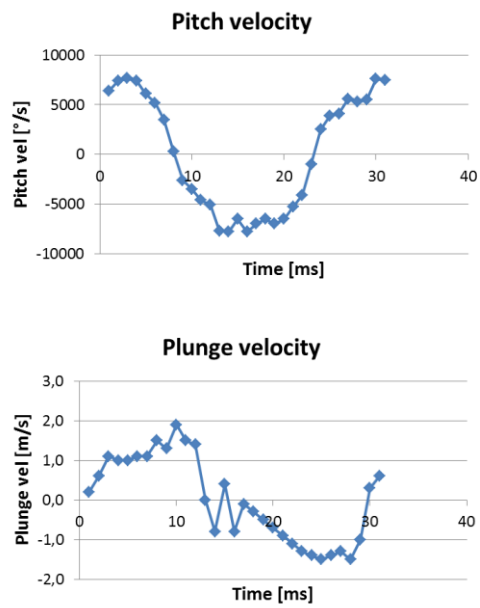
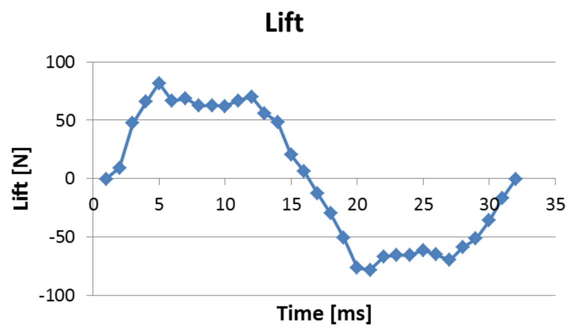


Fig. 6. Pitch velocity and plunge velocity, Ma = 0.45.

3.2 Forces acting on the surface

Henceforward, the flow of Mach number 0.45 will be described. The lift force oscillates between positive and negative values during one period of motion. The waveform is almost symmetric for both half-periods (see figure 7, 8). The peak value is about +/- 80 N. After that point, significant decrease of lift force is present due to massive flow separation. The separation is apparent for pitch values higher than approx. +/- 25° (the value differs slightly for both half-periods). Since the separation point position is more or less steady, the lift is kept at constant value of approx. +/- 60 N and then goes to zero. The drag distribution is perfectly symmetric for both half-periods. Also moment seems to be symmetric with sign of opposite sense than lift force.



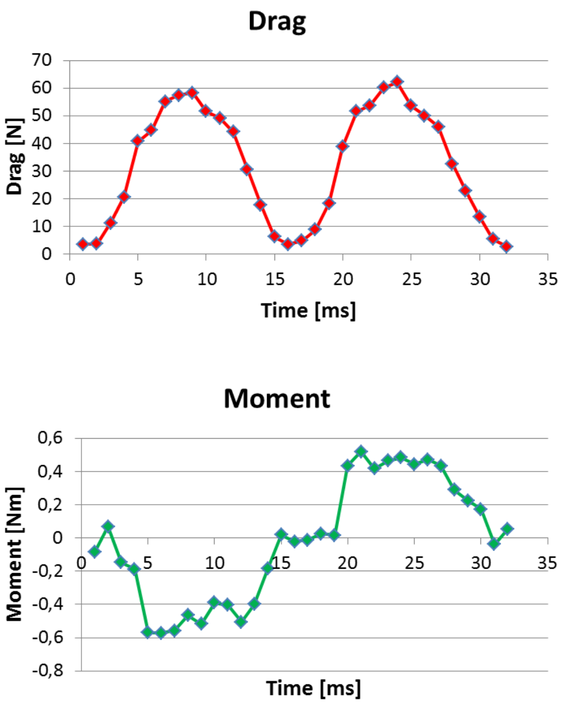


Fig. 7. Total forces: lift, drag and moment for Ma = 0.45.

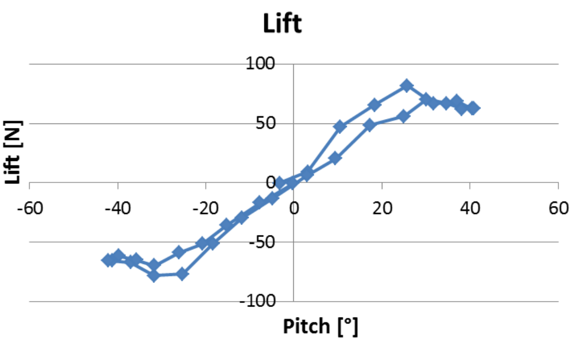


Fig. 8. Lift force in dependency on AoA, Ma = 0.45.

A useful feature of the evaluating program is a possibility to calculate acting forces separately for upper and lower part of the airfoil. Especially lift force will be presented here. Figure 9 is plotted to show the lift dependency on plunge coordinate for the entire airfoil and for both sides. It can be seen from both closed curves that the contribution from upper side does not correspond perfectly with lower side. The contribution of the lower profile part is more dominant in comparison with upper part. Lift force generated by upper and lower side in dependency on time is visible in figure 10. The asymmetry is clearly made visible here using polynomial interpolation. We can see that distance between both polynomials is not constant. Nevertheless, the contribution from upper side dominates during the first half-period while the lower side is dominating during second one.

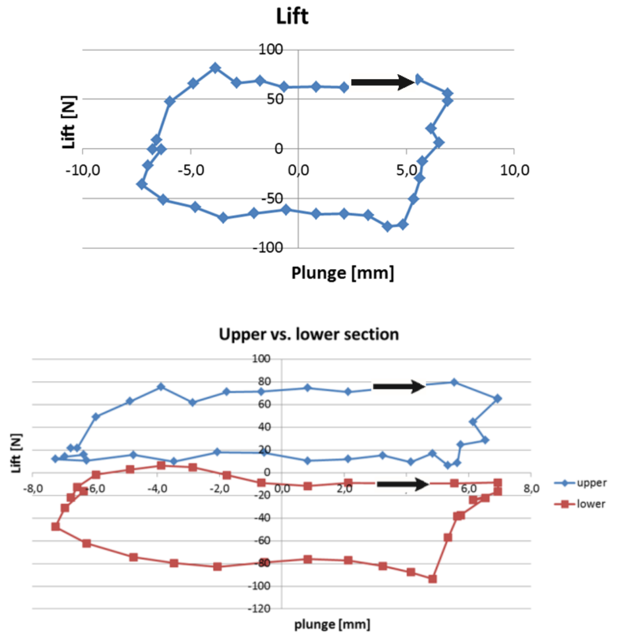


Fig. 9. Lift force in dependency on plunge coordinate, for entire shape, for upper and lower sides, Ma = 0.45.

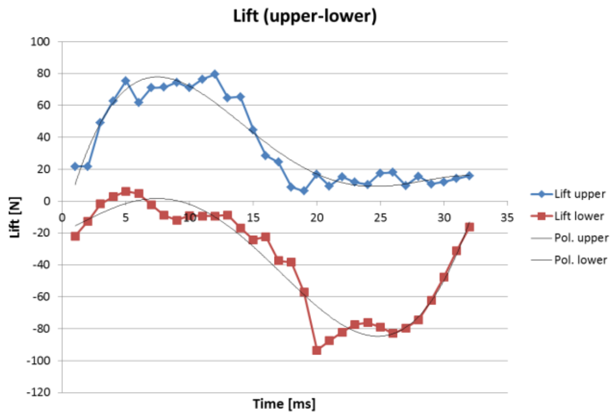


Fig. 10. Lift force divided for upper and lower sides, Ma = 0.45.

Last results will be devoted to case with Mach number equal to 0.28. The lift force, drag force and momentum are plotted in figure 11. All peak values are not so significant in comparison with previous case. More the curves are not so smooth. Especially, this is apparent for lift force divided for upper and lower side (figure 12). The curves are wobbled due to the fact that lower Mach number has led to lower number of fringes and thus worse resolution was available to calculate all quantities. Second reason, no less important, is the non-stationarity of the separation point and the whole flow field.

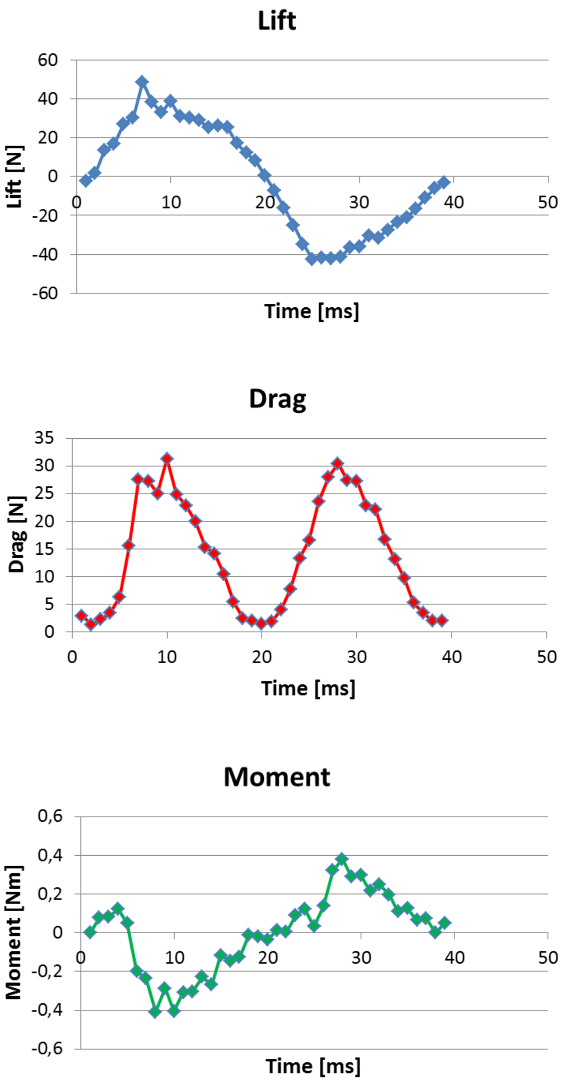


Fig. 11. Total forces: lift, drag and moment for Ma = 0.28.

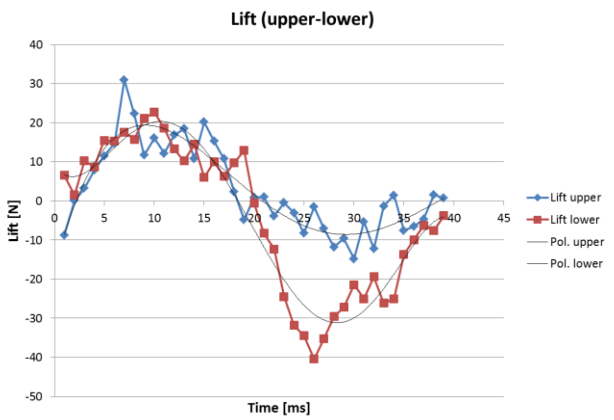


Fig. 12. Lift force divided for upper and lower sides, Ma = 0.28.

4 Conclusion

The flow around the self-excited single NACA 0015 profile was experimentally investigated using Mach-Zehnder interferometer. The acquired data were further analyzed using in-house evaluation software to detect complex information about profile movement with two degrees of freedom and about forces acting on the profile surface. It has been shown that the possibility to calculate forces separately for upper and lower airfoil side is very useful when interpreting data. Two regimes with different Mach number were compared.

The profile is very sensitive to deep stall flutter with peak-to-peak pitch value close to 80° and plunge value approximately 15 mm for both regimes. The biggest difference between both regimes is stability and stationarity of analyzed flow field. The point of separation is more stable for Mach number 0.45 since it is close to the limit of self-oscillation occurrence. On the other hand, the regime generated under Mach number 0.28 is characterized by dynamical changes of separation point location and insufficient two-dimensionality of the flow. This results in wobbled shape of the force waveforms and consequently the plunge movement is also choppy. The question is why the pitch waveform has almost perfect sinus shape (despite the fact that plunge has much higher inertia moment). The partial answer could be lower accuracy of evaluation for smaller velocities. However, the evaluation precision of pitch and plunge degrees remains the same regardless the selected regime.

There will be incorporated the effect of gravity in the future experiments. More detailed analysis is necessary to better understanding of the different contribution of upper and lower sides of the airfoil. Finally, the main future goal is to be able to examine the self-oscillation of the blades located inside a cascade.

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