

ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ – СОФИЯ

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FLOW – INDUCED VIBRATIONS OF PLATES – STATE-OF-THE-ART

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ABSTRACT

The flapping of flexible plate, immersed in a fluid flow is a fundamental problem in the fluid-structure investigations area. Here we examine and systematize experimental studies, connected with the instability of plates, subjected to such influences. We also reexamine the theoretical models, used up to now. A comparison between the experimental and theoretical obtained results shows fair agreement. Finally, we present the problems, standing before the modeling of these systems.

1. Introduction

Structural mechanics of flags, immersed in uniform fluid flow is a fundamental problem of that part of the science, which studies the “Fluid – Structure Interactions”. Although on the surface of it, the interaction seems to be relative simply, it is characterized by “rich” behaviour, related to broad area of engineering problems and nature phenomena. From a historical viewpoint, the term “flag” was often used for a two-dimensional (“plate-like”) structure with perfect flexibility (its bending stiffness tends to zero).

Nevertheless, when the bending stiffness is somehow taken into account, without any significance how small it is the limit between “flag” and “plate” vanishes.

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The thing in common between those similar systems is that their flapping results from a temporary instability around the initial plane equilibrium state. At lower flow velocities, the plate remains straight, in equilibrium. When the flow velocities grown up and reach the critical value, the plate loses its stability. The flutter occurs.

2. Review of experimental observations. Results

2.1. Experimental set-up

From a practical viewpoint, instability of plates, immersed in axial fluid flow can be found in the area of flapping flags, peoples snoring, operations with printing technics and other. With the aim of proof the obtained theoretical results, many experiments were conducted. The used experimental set-ups can be classified it two general types:

- Wind tunnels (with different geometry configurations and different maximal realizable flow velocities);
- A set-up using a soap film.

Experiments, conducted in wind tunnels can also be divided into two groups:

- Experiments, where the plate is flown by air;
- Experiments, where the plate is flown by water.

According to the material, used for the specimen:

- Metal;
- Plastic;
- Paper;
- Fabrics;
- Composites.

Configuration of the plate in the space has a relation to the influence of the gravity to the initial equilibrium state. Observations as with horizontal and with vertical plates were conducted.

On fig. 1 is shown the test set-up, used by Yamaguchi Et. Al. (2000) in their investigations, connected with the behavior of thin and flexible plates, immersed in axial flow. The specimens are with length 120 – 350 mm and width 30 – 90 mm. Their thickness is measured by dial gauge [7]. Using this data, all necessary geometry and mass properties of the specimens can be obtained.

A specimen is fixed at the beginning of the wind tunnel, whose cross-section has a square form with edge 300 mm. The flow velocity begins to increase gradually up to the moment, when the amplitude of the flapping plate suddenly grows up. Thus, the reached velocity is called “critical flow velocity” and is measured by Pitot tube at the end of the wind tunnel. A laser sensor measures the amplitude of flapping near the free end of the plate.

Next four general parameters have an essential significance by the investigation and comparison between analytical and experimental results:

- Mass ratio $\mu = \rho_s t_s / \rho_a L_a$;
- Relative stiffness $\beta = E_s I_s / ((1/2)\rho_a U_a^2 L_s^3)$;
- Reduced frequency $f_R = f L_s / U_a$;

- Surface friction coefficient (it has not been measured in the experiments. It is used as a parameter in the analysis) c_{f0} ,

where: ρ_s – plate’s density; ρ_a – fluid’s density; t_s – plate’s thickness; L_s – plate length; E_s – Young’s modulus; I_s – Second moment of plate’s section; U_a – flutter velocity; f – flutter frequency.

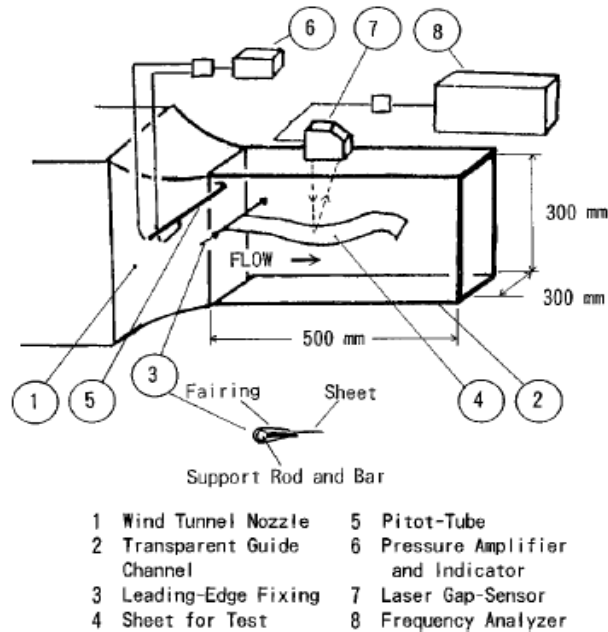


Fig. 1. Wind tunnel. An experimental set-up for testing flutter

Mass ratio is equal to a ratio of the mass of the sheet to a typical mass of the surrounding air. The smaller the mass ratio, the lighter relatively the sheet is. Relative stiffness is a ratio of the sheet stiffness to the aerodynamic force. The smaller the ratio, the more flexible the sheet is and the higher the flutter speed is [7].

The presented model of wind tunnel consists of all basic parts required for an investigation of plates in axial flow. Similar equipment was used also by Watanabe (2002) and Lemaitre (2005). Huang (1995) uses a tunnel with circular cross section. Shelley (2005) uses a tunnel with rectangular cross section, but the plate is in horizontal direction and the fluid is water.

Tang (2007) presents similar experiment, in which complicated equipment – vertical closed channel, leading water is used.

On Fig. 2, an experimental set-up used by Zhang (2000) is shown. He conducted some investigations with filaments, immersed in soap film. The “soap film system” is convenient system, similar to the two-dimensional problem of the hydrodynamic. Its advantage is the relative simplicity. The soap film (1.5% solution of a commercial brand of dishwashing liquid soap in distilled water) is passed in the vertical direction through a nozzle, which can regulate the flux. Thus, the formed area of fluid flow is 8.5 cm width in its middle, and the thickness of the film is 3 – 4 μm .

In the bottom end of the set-up, the soap film flows in a container. The upper end of the filament is fixed through a thin pipe, perpendicular to the flow, at 80 cm under the “entrance“ of the flow.

The filament is with diameter of 0.15 mm and length 2 – 6 cm. The fluid wets the filament, with surface tension forces constraining the filament to lie always in the plane of the film.

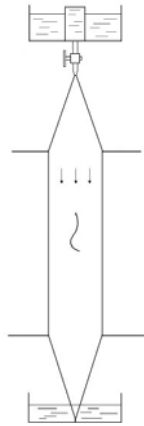


Fig. 2. Experimental set-up for investigation of filaments in soap film

a. Results. Comparison

On Fig. 3, a diagram of the relative stiffness β toward the mass ratio μ is shown. It is valid as for experiments with different materials, and for theoretical result, both conducted by Yamaguchi.

In order to be able to compare the results, some more of them, obtained by different authors, are printed – by Huang, related to plates with bigger mass ratios, by Watanabe – related to plates with different mass ratios[6], [7]. From the diagram, one can see strong dispersing of the experimental data. It can be explained by wrong measuring of physical properties of specimens, variable material properties etc.

In spite of everything, one can observe compatibility of results, namely: coincidence between the theoretical and experimental data in a region, approximately equal to 50% from the observed range. That gives clear global trend for the behavior of examined systems at wide range mass ratios, and confirms the accepted analytical model.

On the ground of obtained theoretical and experimental results, the values of mass ratio are divided into three regions:

- Region with high mass ratio $\mu > 0,7$

For $\mu > 1$ can be observed gradually increase of the relative stiffness and approximately constant reduced frequency with increase of mass ratio. For $\mu < 1$ and decreasing down to the limit value, relative stiffness drops sharply. In this zone is estimated, that the influence of friction is negligible.

- Region with medium mass ratio $0,7 > \mu > 0,05$

In this region, results are in a widely scattered band on the whole. A decrease in the mass ratio tends to cause the critical relative stiffness to become lower and the reduced frequency to increase. The tendency predicted in this region depends on the friction coefficient. The

increase of this coefficient leads to decreasing of the critical relative stiffness (fig. 3), and the frequency is increasing. One supposes that the increasing of friction leads to increasing of critical velocity and frequency.

- Region with low mass ratio $\mu < 0,05$

In this region, experimental data are insufficient and the tendency of behavior is not clear enough. Additional data can be found in some analytical investigations. In the transition region (roughly at $\mu = 0,06$) as the relative stiffness, as the reduced frequency change drastically. After that, they tend to nearly constant values and depend mainly on the friction coefficient.

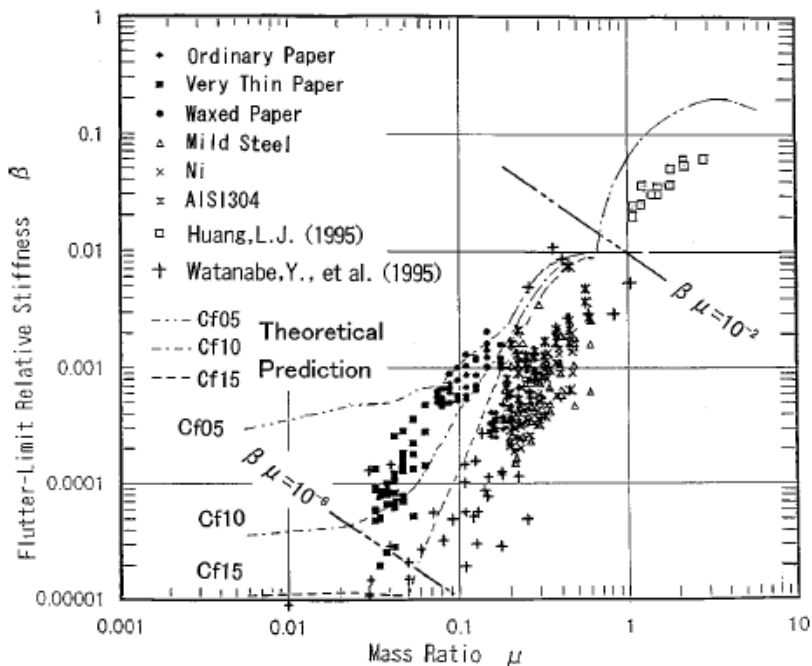


Fig. 3. Effects of mass ratios on the relative stiffness (Yamaguchi)

Phenomena, investigated in the experiments with soap film are related to features, often neglected in other set-ups – the filament’s tension, elastic rigidity and mass, in addition to the dynamic interaction of the filament with the fluid flow. Near the point, where the flapping state starts, the mass of the filament has come into balance with the mass of the interacting fluid, while the elastic energy of the filament balances the kinetic energy of the fluid. Namely, this balance of effects induces the bifurcation in the behavior and leads the flapping of the filament.

At fixed flow velocity, there is a critical filament length L_c , under which the filament remains stretched-straight and in line with the flow. If the length of the filament exceeds L_c the system becomes bi-stable and two different stable dynamical states can be observed.

On Fig. 4 these states are shown. The first, stretched – straight state is connected with small disturbances, which reveal the small oscillations of the filament. A narrow “von Karman” vortex street, shed from filament’s free end and waving downstream can be observed. Although the system remains static, behaving like a rigid body.

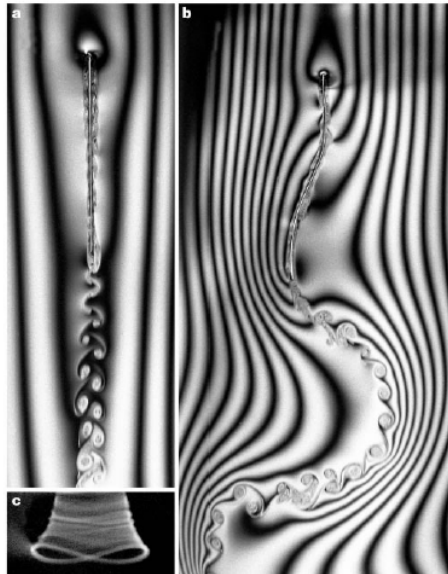


Fig. 4. Stable states of filament in soap film: (a) stretched straight state; (b) flapping; (c) trajectory of the filament's free end when it is flapping

The second state (Fig. 4b) shows the flapping. It is realized at a sufficiently large external perturbation. In contrast to a single pendulum, the undulation can be described very well by travelling wave with varying spatial envelope.

At length of the filament around 3 cm and flow velocity 280 cm/s a typical flapping can be observed, with amplitude (maximal excursion of the free end) around 1,5 cm and frequency approximately 50 Hz. A “von Karman” vortex street can also be observed, but now it is strongly modified by the large-scale flapping motion. If L becomes large enough, than the stretched straight state disappears and only the flapping state remains. It is difficult to be determined experimentally whether this is due to a loss of linear stability or is due to finite perturbation in the flow, sufficient to overcome the limit between the two stable states.

2. Theoretical models

First analytical investigations about oscillations by motion of a flag were made by Lord Rayleigh (1879). In his paper, devoted to the instability of jets he supposed, that through the theoretical approach, used by him, can be proven, that a plate with infinite dimensions will always be unstable. In 1934 Theodore Theodorsen released his paper, in which he gave mathematical and theoretical solution of the aerodynamic instability problems and the occurrence of flutter by the plane wings. His work is non-accidentally called a “Pioneer” in the area of Fluid-Structure Interactions. After that a lot of researchers were worked in the area of analytical determination of the flutter and aerodynamic instability, and in the field of numerical simulations of such a phenomena.

From a static viewpoint there are two possible models for plates – as a plate (two-dimensional object) and as a beam (simply supported or cantilever).

For a cantilever beam the equation of motion is given by formula (1).

$$D \frac{\partial^4 w}{\partial x^4} + C_d \frac{\partial w}{\partial t} + \rho_p h \frac{\partial^2 w}{\partial t^2} = \Delta p. \quad (1)$$

The only one paper, in our mind, where a solution about a two-dimensional plate can be seen is released by Shayo (1980). The equation, describing the motion of the system is given by formula (2):

$$D \left(\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right) + \rho_p h \frac{\partial^2 w}{\partial t^2} = \Delta p. \quad (2)$$

With the aim of estimating the effects, which appear from the aerodynamical wake, traveling downstream, after the trailing edge of the plate, Shayo make two approximations. Both are connected with neglecting of the effects of the wake – on the fluid pressure and on the pressure and velocity potential. The results show that, at relative small mass ratios, both models practically have no discrepancies. Analyses of cantilever plates, modeled as beams in different configurations can be seen and in papers released by Huang (1995), Balint и Lucey (2005), Guo and Paidoussis (2000), Yamaguchi (2000), Watanabe (2002), Argentina and Mahadevan (2005), Eloy (2007) and other.

In contrast to the universal tendency for the static model used in the investigations with plates, there are a bit more models for influence of fluid flow and computation of fluid loads. Some of them are given in Table 1

Table 1. Methods for computation of fluid loads

Method:	Can be seen in papers by:
According to Theodorsen	- Argentina и Mahadevan; - Huang; - Watanabe;
Bernoulli's equation	- Eloy; - Guo и Paidoussis; - Kornecki; - Shayo;
Panel methods	- Tang; - Howell, Lucey;

3. Problems, connected to the modeling of “Fluid-Structure Interactions” systems

Naturally, there is a tendency, all influences to be modeled as accurately as possible. When one accepts the approximation of cantilever beam, one supposes that the aspect ratio of the plate is big enough (at the best case it tends to infinity). It is proven that the deflection of the plate, perpendicular to the direction of the flow is negligibly small for flow velocities region around the critical value, as for hanging plates and for horizontal ones. On the other hand, fluid flow shall be modeled as three-dimensional, in order to be able to include the edge effects, and also the change in the magnitude of the fluid loads in the direction of the plate width.

Linear solution of such a problem cannot give us any information about the post-critical behavior of the system. Linear stability problem is usually transformed into an eigenvalue problem and frequency domain analysis. Nonlinear solution is usually connected with complicated mathematical expressions.

The way of how one represents fluid loads and the approximation of the fluid itself has a strong effect for the accuracy of the results. Usually one supposes that the fluid is incompressible and with no viscosity. Using of some empirical expressions, give one the opportunity to give an account of that there are not any no viscosity fluids, e.g. there are always boundary layers around the plate etc. The Kutta-Joukowski condition, on which the theory of Theodorsen is based, is a requirement for the continuity of the fluid loads and the flow velocity at the trailing edge of the plate.

Of the damping shall also be given an account. There are two reasons about that: first, it is inherent for all materials, which gives the opportunity for dissipation of energy and second, when one gives it an account, one can investigate the effect of dissipation on the stability of the system.

In conclusion, after detailed literature review, we can confirm, that the investigation of the dynamic of plates, interacting with fluid is a challenge. The accepted model shall be relatively simple, and at the same time shall give an account of basic physical laws.

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ТРЕПТЕНИЯ НА ПЛОЧИ, ПРИЧИНЕНИ ОТ ВЗАИМОДЕЙСТВИЕТО ИМ С ФЛУИД – СЪСТОЯНИЕ НА ИЗСЛЕДВАНИЯТА

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Ключови думи: флуид, плоча, взаимодействие, устойчивост

Научна област: механика

РЕЗЮМЕ

Трептенето на гъвкава плоча, потопена в поток от флуид, представлява основен проблем в изследването на взаимодействията флуид – конструкция. Тук се разглеждат и систематизират експериментални изследвания, свързани с неустойчивостта на плочи при подобен род влияния. Направен е преглед на теоретичните модели, прилагани досега за изследването им. Сравнение между резултатите, получени от експериментите и по теоретичен път, показва задоволително съответствие. На последно място са представени проблемите, стоящи пред моделирането на тези системи.

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