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AEROELASTIC COUPLING AND INSTABILITY IN TUBE ARRAY

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Abstract – Flow speed and frequency dependencies of vibration transfer by flowing air between tubes in a row are presented. The transfer is increasing linearly with dynamic pressure, but with frequency dependence it is a bit more complicated. Also time histories and frequency spectra of the tube vibration are caught and commented.

Keywords aeroelasticity, measuring of force, transfer function, nonlinear fluid-structure system

1. INTRODUCTION

Arrays of elastic bodies submerged to fluid (air, steam, water, etc.) can be found in some industrial applications as heat exchangers with tube arrays subject to coolant crossflow, overhead transmission lines in the air, blades of a steam turbine, etc.

Problems arise when fluid is flowing around a flexible structure and induce herewith vibrations, sometimes of large amplitude, which ultimately may lead to failure. There is several mechanisms causing the vibrations and several mathematical models describing them. They can be linear, non-linear, semi-empirical.

A review of the models is in [1]. A special case is a single flexibly supported tube in a tube bundle excited to vibrate by fluid-elastic instability mechanism (similar in nature to aerofoil flutter) of which non-linear model is in [2]. It is called Force state mapping and predicts the onset of fluidelastic instability.

This work targets mainly the vibration transfer in a row of tubes as investigated in [3], where coefficients of linear motion equations are presented.

Let's look at the tubes and flowing air as at a system [4] with elements and some couplings between them.

2. EXPLORING OF AEROELASTICITY

2.1 Aeroelastic Coupled System, Notations

Let's suppose one flexibly supported tube T_1 surrounded by fluid F and other rigid bodies around it, roughly as seen on Fig. 1.

To be simple, consider T_1 as a linear system. Its state can be described by instantaneous displacement, velocity and acceleration. The state of fluid F can be described by velocity vector field and static pressure field. Both systems are mutually interacting. F, T_1 and other bodies compose together a coupled fluid-structure system S, which is generally non-linear, sometimes also chaotic.

To describe behaviour of S, we need to know which conditions are crucial. Suppose the system is subject to uniform fluid flow described simply by its speed *w*. Thus the conditions for system S are reduced to flow speed *w*. System itself is described by its geometry and physical properties of fluid (mainly density) and structure (mass, damping and stiffness). Some of these parameters can be changed during experiment, so they become conditions as well.

To predict behaviour of S we must make a mathematical or physical model. Now consider the state of S defined as the instantaneous displacement y_1 of tube T_1. Time history of y_1 (and its derivatives) is a trajectory of the system S. We can observe several kinds of periods in the time record. An example of the record is in Fig. 3.

Further we can plot dependencies of $y_1(t)$, or just rms(y_1) on the conditions mentioned above. At the end we can create some mathematical formulas, or differential motion equations using measured parameters and explore stability of those equations.

But purpose of my work is just to show some dependencies on conditions like flow speed, natural frequency of the structure and vibrations of other bodies in the neighbourhood.

Sometimes this is useful to remind even the people that are interested in creating new models. Than they can decide which models are more suitable, which are not.

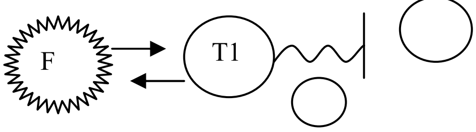

Fig. 1. Coupled fluid-elastic system

The sense of these models is to understand deeper the system S and to predict conditions at which the system behaviour is dangerous (too high amplitudes, impacts, fatigue) with respect to its service life.

2.2 Test Rig

To explore the system we have a wind tunnel. In measurring room, there is a row of 7 tubes, as in Fig. 2.

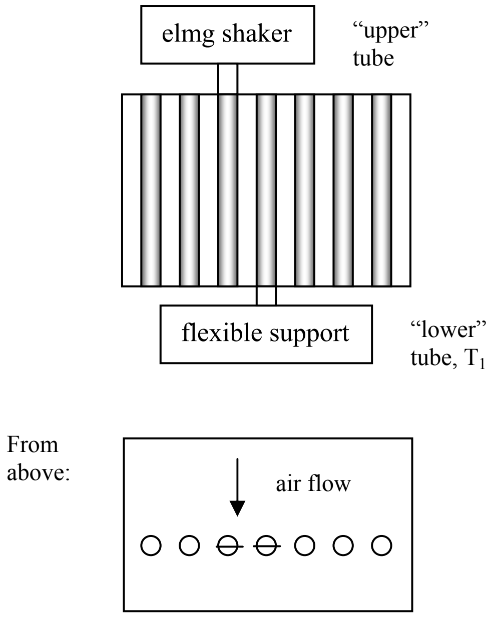

Fig. 2. Tube diameter: 20 mm, pitch betwwen tubes: 25 mm, tube and room height: 150 mm, room width: 200 mm. Two neighbouring tubes in the middle are flexibly suspended allowing them to vibrate in crossflow direction only.

The vibration excitation mechanisms recognized in the tube bundle (which we had installed before) are turbulent bufetting predominating at the onflow part, aeroelastic instability in the middle, jet switch at the outflow, vortex shedding and acoustic waves (as in a whistle) everywhere.

Thus to explore aeroelastic instability would be a tube bundle more suitable, but there are two reasons to use tube row only. It has a simple geometry. Also I was asked to compare our results with results of Chen [1]. He had searched for coefficients of linear equations for aeroelastic coupling between vibrating tubes in a row.

I had my doubts about magnitude and linearity of the coupling, thereupon I decided to find its characteristics.

2.3 Measurement Procedure

The goal of measurement is to find a dependency of vibration transfer on flow speed and vibration frequency, and to compare “transferred” fluid force with force causing self induced vibrations.

The idea of the experiment is to subtract data measured when only one tube is free to vibrate from data measured when there is another neighbouring tube vibrating.

Prior to do this, there is some work with calibration of the rig devices. We need the structure (linear) part of the system to be identified, ie. to measure its frequency response – vibration amplitude and phase shift for different excitation force frequencies. The natural frequency is set to 44 Hz. The force of the electromagnet is calibrated by piezo force sensor. This sensor is continuously discharging, but it is important for slow processes only, in addition it can be numerically fixed knowing an unit jump response.

The main part of measuring is following: to measure data at calm fluid, zero shifts, and then:

- set flow speed and measure self induced vibrations and noise of tube T_1, when other tubes are rigid
- set flow speed and measure vibrations y_1 of tube T_1, when one of the neighbouring is vibrating at certain frequency and amplitude.

Note: since it is not easy to excite big amplitudes at frequencies distant from natural frequency, we had to tune the second tube by adding of mass together with oscillator setting.

2.4 Data Treatment

Measured data are processed in Matlab environment. Helpful at programming was [5]. I have made several vibration spectra. The amplitudes have been determined by several methods: from sum of energy of spectrum lines according to peak shape; these lines are replaced by one with the same energy. When we know the investigated frequency, we can also set apropriate sample frequency and sample number so, that the record will contain an integer number of periods (or we can trim the measured record additionally). Finding function minimum can also be used, when searching dominant frequency, phase and amplitude of a signal.

Phase shifts of measured signals are mostly determined by cross correlation.

On the following page, there are some records of tube vibrations. All are done at flow speed 27 m/s (dynamic pressure 470 Pa). Quantities on x-axes are in s, Hz and m/s. Tube notation corresponds to Fig. 2 (upper tube, lower tube is T_1 in previous text)

2.5 Plots

In the Fig. 3. – upper tube - there is also peak at 57 Hz, but it disapears when the tube is excited at 18,7 Hz by an electromagnet (Fig. 5.).

Also peaks around 44 Hz in lower tube spectrum are lowering when other stronger frequency appears (compare Fig. 4. and Fig. 5.). There is also 44 Hz (structure natural frequency) with amplitude 15 μm in the frequency package.

The frequency dependence is not surprising, since the frequency goes closer to the natural frequency of the lower tube (44 Hz). The dependency on flow speed can be explained by

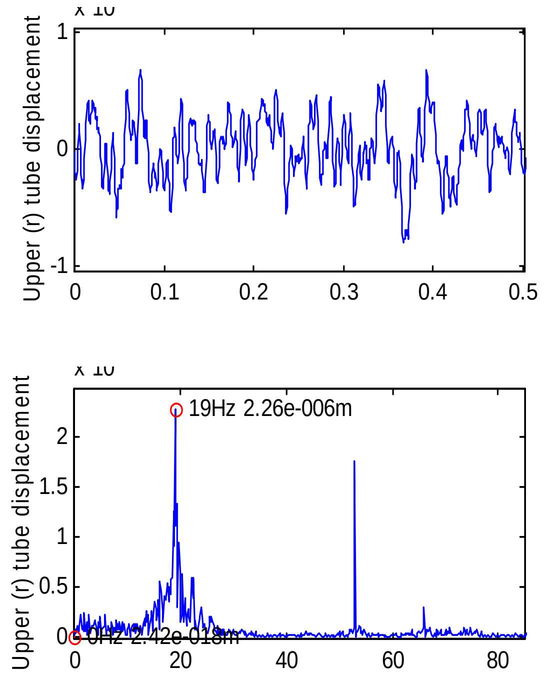

Fig. 3. Time history and frequency spectrum of self induced vibrations of upper tube (the lower tube is rigid), amplitudes around 5 μm, natural structure frequency was 17,6 Hz

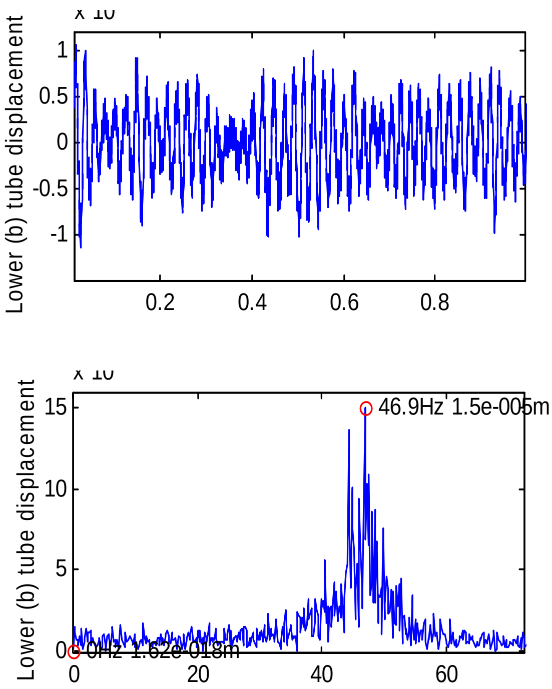

Fig. 4. Time history and frequency spectrum of self induced vibrations of lower tube (the upper tube is rigid), amplitudes around 10 μm, natural structure frequency was 44 Hz

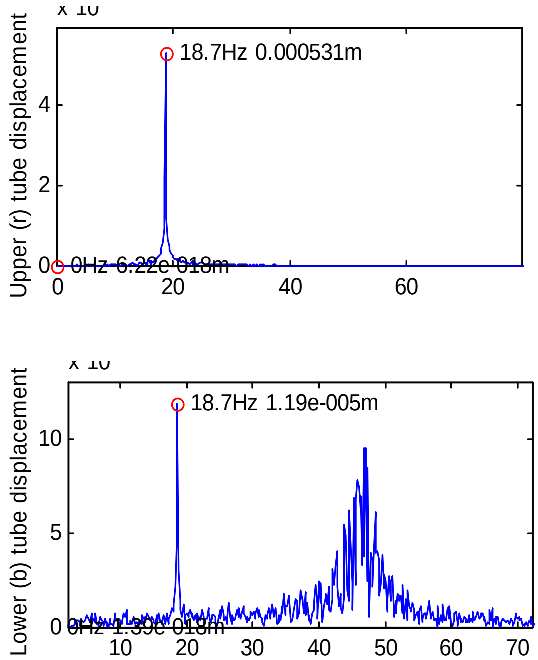

Fig. 5. Frequency spectra. Upper tube is excited at 18,7 Hz by an electromagnet, lower tube is responding to it.

2.6 Main Results, Transfer Function

According to Fig. 6, the vibration amplitude transfer from one tube to another is growing with flow speed and frequency.

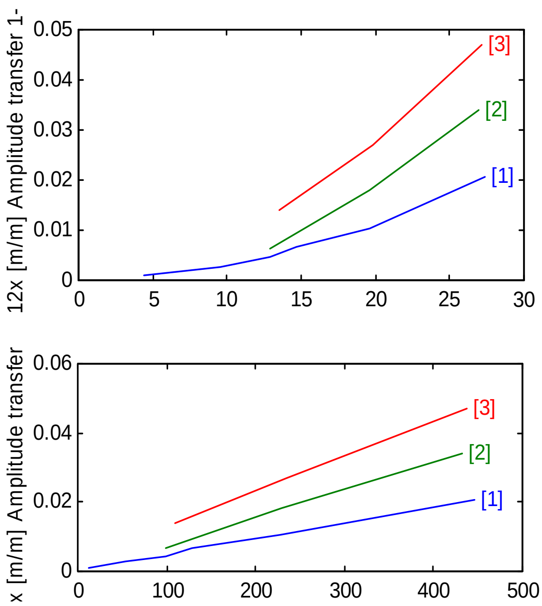

Fig. 6. Transfer function: lower / upper tube amplitude. X-axis on the first plot is flow speed in m/s, on the second one it is dynamic pressure in [Pa]. Line “1” is at 18,7 Hz, “2” at 25,9 Hz, and “3” at 33,9 Hz.

"hardening" of the flowing fluid, when it is faster.

More interresting is Fig. 7, where the amplitudes of the lower tube are converted to excitation forces by means of transfer function of the structure. It appears, that at higher flow speeds the vibration amplitude (Fig. 6, line "3") is smaller, than in case, when the force transfer (Fig. 7) would growing monotonously with frequency.

One of explanations is that the stiffness of the fluid-structure system S is not linear (the flowing fluid is "hardening") causing the amplitude is growing slower, when it is high – it is limited. But than probably would be line "3" bent.

Other explanation is, that there is a transfer maximum at certain frequency (and other conditions), but it will be proved by other experiment, where the tube is held at zero position by force sensors and the transfer function will be measured for different frequencies, flow speeds and amplitudes of the disturbing tube.

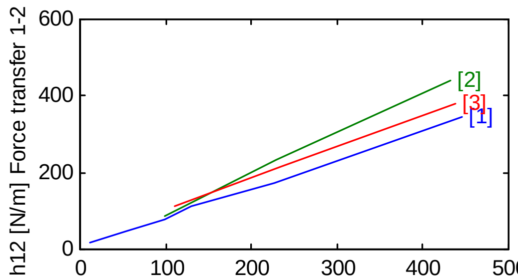

Fig. 7. Transfer function depending on dynamic pressure. Vibration amplitude of upper tube cause additional fluid force on lower tube, conditions are the same as in previous figure.

Phases of the transfers were also computed. They were fluctuating around 0 degrees within the measurement and computation error (10 degrees).

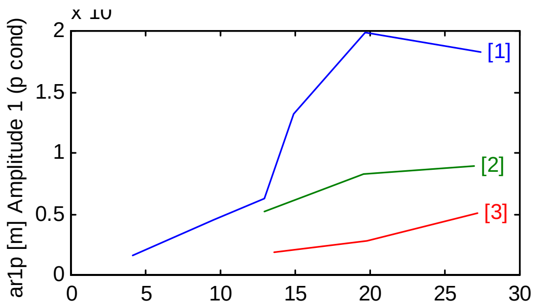

Fig. 8. self induced vibration amplitudes for different natural frequencies of the upper tube. "1" is at 17,6 Hz (but vibrated up to 19 Hz according to flow speed), "2" at 25,9 Hz, and "3" at 33,9 Hz. X-axis is onflow speed in m/s

For comparison: Forces inducing vibrations of a single vibrating tube (Fig. 8) are very small (growing with flow speed), maximum 0,08N (according to the amplitude). The additional fluid forces caused by vibrations of neighbouring tubes are up to 0,2 N. To be complete, the static drag force on the tube is up to 0,7 N.

3. CONCLUSION

Measurements which have been made for exploring of aeroelastic coupling between vibrating tubes show how the coupling is increasing with onflow speed. It is also changing with the transfer frequency, and it seems, there is an optimal frequency for maximum transfer depending on other conditions (flow speed, etc).

This will be clarified by the measurement with force sensors sustaining the tube T_1 at zero position. It is known, that there is a difference between fluid forces acting on a rigid tube and those acting on a vibrating tube, but when the vibration amplitudes are small, the difference is small as well.

Though the measurement conditions used in this work are closer to the reality than the experiment with one tube fastened by a force sensor, it does not show safely frequency dependence of the transfer in all cases, except for our geometry and structure T_1 with natural frequency of 44 Hz.

There is one more interresting thing to mention. Comparing frequency spectrum of self induced vibrations and the other one with a disturbing vibrations nearby we can see that previous amplitudes decreased and amplitudes at the new frequencies were assumed.

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