PHENOMENA IN STANDING WAVE IMPACT ON A HORIZONTAL PLATE

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Abstract

The paper deals with experimental and theoretical investigations of dynamics of a plate–fluid system. In experiments, a horizontal plate was suspended elastically in a wave flume and loaded with impact pressure forces resulting from growing water waves. The data obtained in experiments has revealed the essential role of the elasticity of the plate and its supports as well as the fluid compressibility in estimating the structure-fluid interactions. Therefore, in order to get a better insight into the problem considered, harmonic vibrations of an elastic band plate submerged in an infinite domain of compressible fluid have also been examined. The solution obtained and formulae derived enable to calculate the fluid pressure induced by the plate vibrations.

1. Introduction.

In offshore engineering we have a wide variety of problems associated with water wave forces acting on offshore structures. Among them, there are also cases of horizontal plates (or plate like elements of a structure) loaded with abrupt pressure forces resulting from growing sea waves. Examples are sea piers and suspended breakwaters under the action of water forces of short duration. A theoretical description of the mentioned problem is very difficult because of a complicated structure of the equations of the fluid motion together with the relevant boundary conditions, especially at moving boundaries of the fluid domain. Therefore, in describing the structure – fluid interaction, we are forced to resort to approximate methods, which, in principle, should be verified by experimental investigations. For this purpose and, to learn more about the phenomena, experimental investigations of dynamics of a horizontal plate in contact with water have been performed in the wave flume of the Institute of Hydro -Engineering of PAS in Gdańsk. The performed experiments allowed for collecting information important in creating approximate computational models which describe the structure-fluid interaction with an acceptable accuracy.

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2. Laboratory experiments.

The experimental set-up is shown schematically in Fig.1. It consists of the following main components: the model of a horizontal plate constructed in the form of a box with frame skeleton and casing made of aluminium alloy, the system of springs and strings, the piston type wavemaker and the system of pressure, wave and acceleration gauges together with a recording unit. The horizontal plate was suspended elastically in the wave flume over the still water level by means of a system of prestressed elastic springs at a chosen distance from the wavemaker. In order to obtain reliable results, we looked for a wave problem that could be controlled. Therefore, at a first step, we have chosen the case of standing water waves growing with time. In order to obtain these waves, additional rigid vertical plate was installed in the flume, just in the neighbourhood of the horizontal plate. In this way, the wavemaker together with the vertical plate formed a rectangular basin of water with its own set of eigenfrequencies.

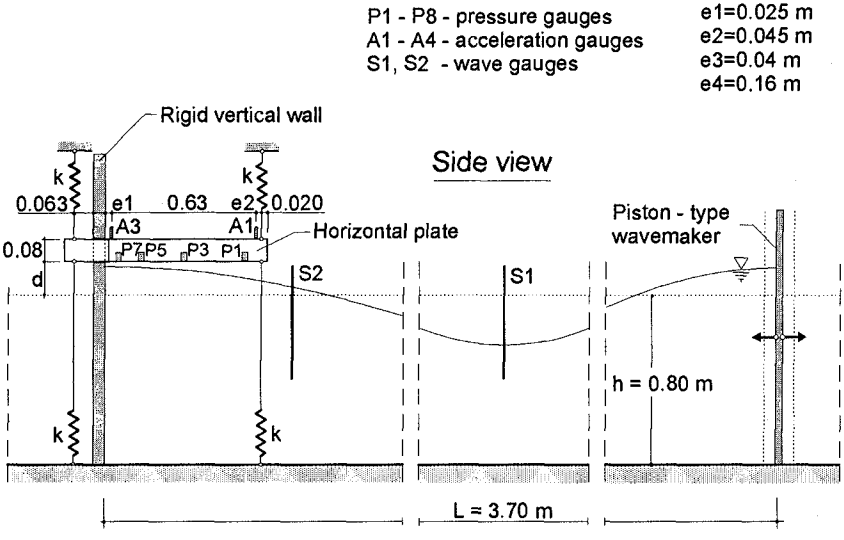

Fig. 1. The horizontal plate in the wave flume.

During experiments the wavemaker frequency was chosen to be equal to the first and the second lowest natural frequencies of the water test section and thus, the lengths of the generated waves were equal to the distance between the wavemaker and the vertical plate and, twice the distance, respectively. Due to the resonance, the harmonic motion of the wavemaker, starting from rest and moving with a relatively small amplitude, led to the standing surface wave with amplitude growing in time. The growing wave crest could reach the horizontal plate level at a certain moment of time and thus, the impact pressure phenomenon occurred. The generated waves were measured by means of two or three wave gauges, the vibrations of the plate - by four acceleration gauges and, the distribution of the impact pressure – by eight pressure gauges, respectively. The latter gauges were installed in two rows on the lower surface of the plate.

The data recorded in experiments has the form of a sequence of numbers corresponding to the assumed sampling frequency. The electronic devices used in

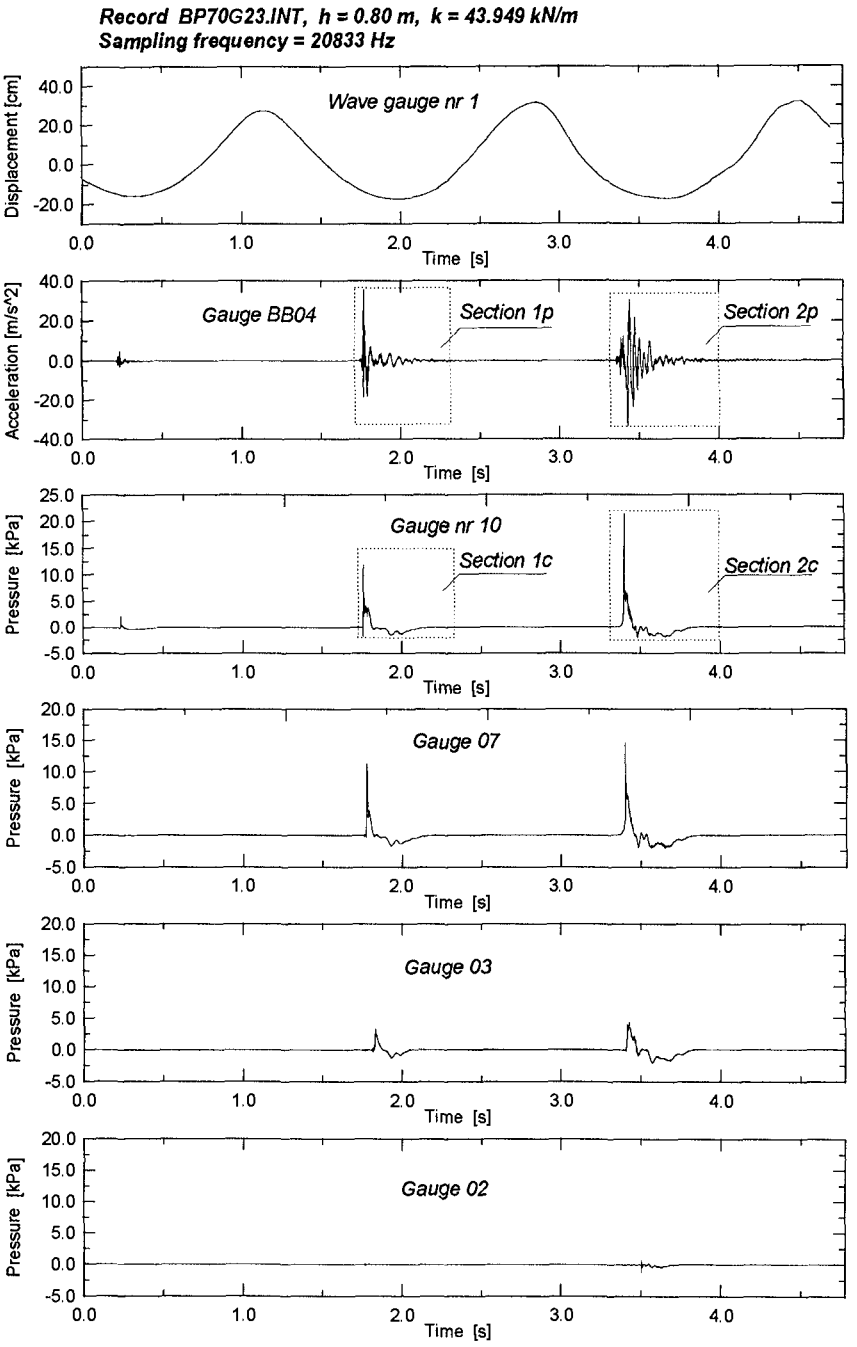

Fig. 2. The measured acceleration and pressures for standing waves.

experiments allowed to register the data numbers with the maximum sampling frequency equal to 20,833 Hz. These records were then processed with the help of the Kalman filter which enabled us to decompose the vibrations into components corresponding to dominant frequencies of the system mentioned.

The experiments started with the identification of the considered dynamical system in air. By applying an initial displacement of the plate, which was then released, the free vibrations of the plate were obtained. The spectral density of the acceleration record of the vibrations showed three eigenfrequencies: 24 Hz, 38Hz and 416 Hz corresponding to the vertical, rotational and flexural displacements of the plate,

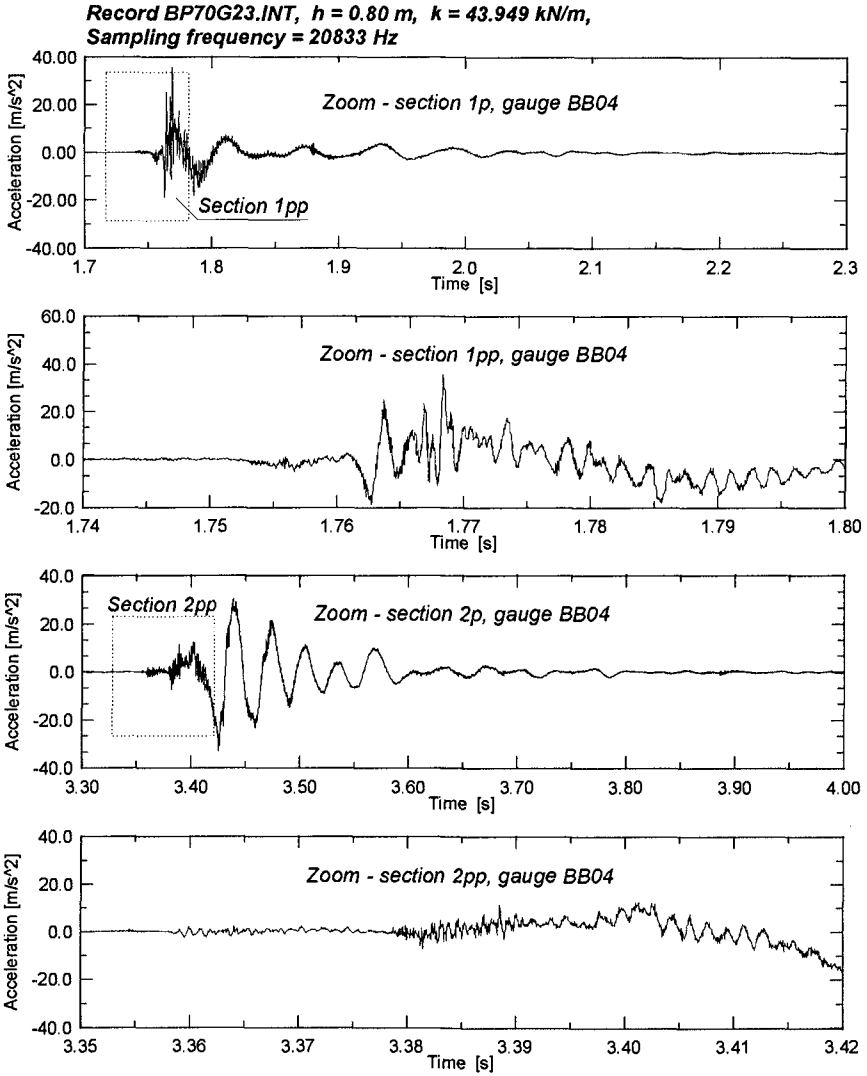

Fig. 3. The analysis of measured acceleration.

respectively. The two lowest frequencies detected correspond to the plane rigid body motion of the plate, while the third one is associated with a deformation of it. The plate as a box structure has many eigenfrequencies and the highest frequency detected is the lowest one of the plate.

The basic experiments of the plate loaded with water wave forces were performed for a relatively large number of particular cases corresponding to the chosen rigidity of the springs, the chosen gap width between the lower surface of the plate and the still water surface and, the assumed amplitude and length of the generated wave (the distance between the vertical plate and the wavemaker was a parameter in the experiments mentioned). With respect to the amount of data obtained, we attached here only few illustrative examples. Typical results of an experiment performed are shown in Fig.2 and in Fig.3, where the plots of the water wave, acceleration of the plate and the pressure acting on the plate surface are depicted. This experiment can be divided into a number of stages. The first one lasts from the outset of the generator motion to the moment of the maximum height of the surface wave, just before water

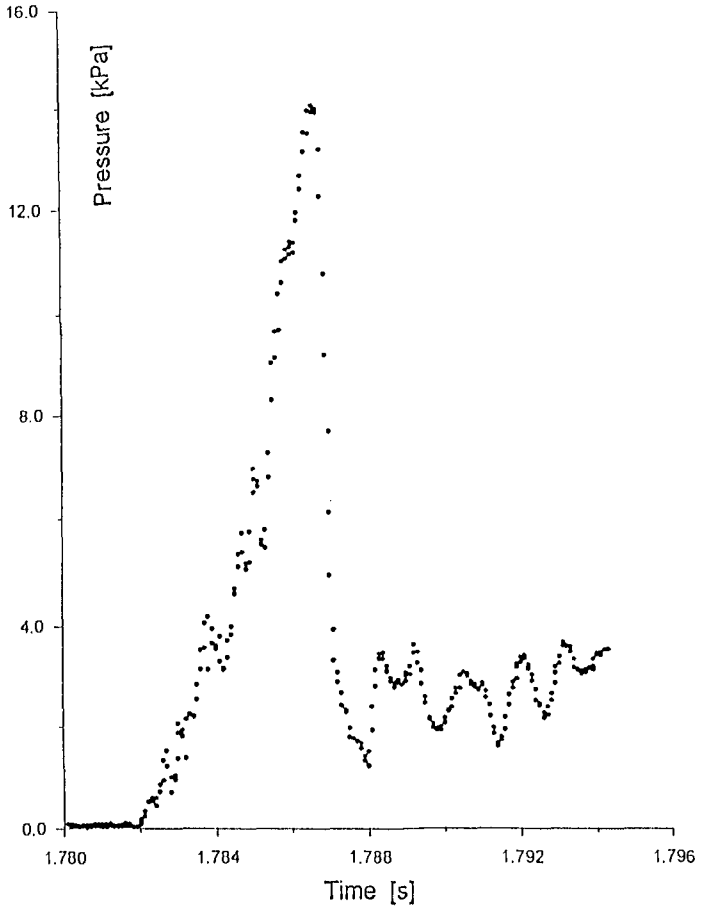

Fig. 4. The impact pressure of a standing wave.

strike at the plate. Then, we have a very short second stage during which the plate receives a finite impulse of the pressure forces. The registered measurements pointed the existence of acoustic waves propagating with sound velocity. With the end of this short stage the third – transitive stage begins during which the free damped vibrations of the plate take place. This third stage may be assumed to last till the next water strike at the plate. Since the water flow is not fully periodic in time, we cannot speak about periodic behaviour of the system at hand and thus, the second wave impact on the plate is assumed to be the beginning of the fourth stage and so on. From the plots in Fig.2. it may be seen that in addition to the range of frequency mentioned above we have now also the frequency of order 1 Hz relevant to the gravitational wave. Besides, the zoom sections shown in Fig.3. reveal the important feature of the impact pressure phenomenon, namely, a wide range of frequencies associated with the system as a whole. The frequencies vary from 1 Hz of the generation of water waves, through 10-30 Hz relevant to rigid body motion of the plate and approx. 200-400 Hz of the lowest eigenfrequency of the box structure. In addition to these frequencies, we have also higher frequencies corresponding to higher modes of vibrations of the box structure and dilatational waves propagating within the fluid. The higher frequencies of the system considered and thus, the influence of the dilatational waves on the system behaviour are of primary importance, especially in proper estimation of the impact pressure forces. This can also be seen in Fig.4. where the distribution of pressure recorded by pressure gauges installed on the plate is given. From the plot it follows, that the time range of the impulse pressure is very narrow and thus, in describing the impact pressure phenomenon, the small compressibility of the fluid as well as the elasticity of a structure must be taken into account. At the same time, because of the small interval of the impulse action on the plate, the higher modes of the system motion can be investigated independently from the lowest modes associated with the surface gravitational waves.

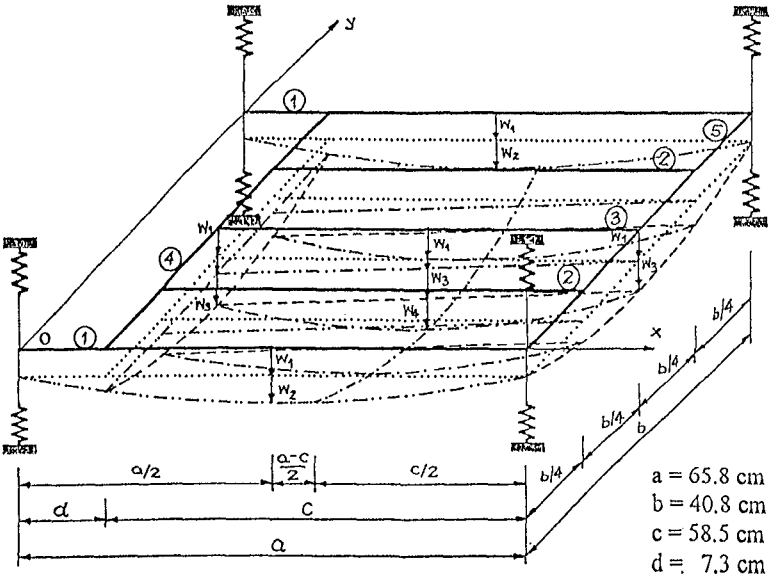

Fig. 5. The theoretical model of the plate.

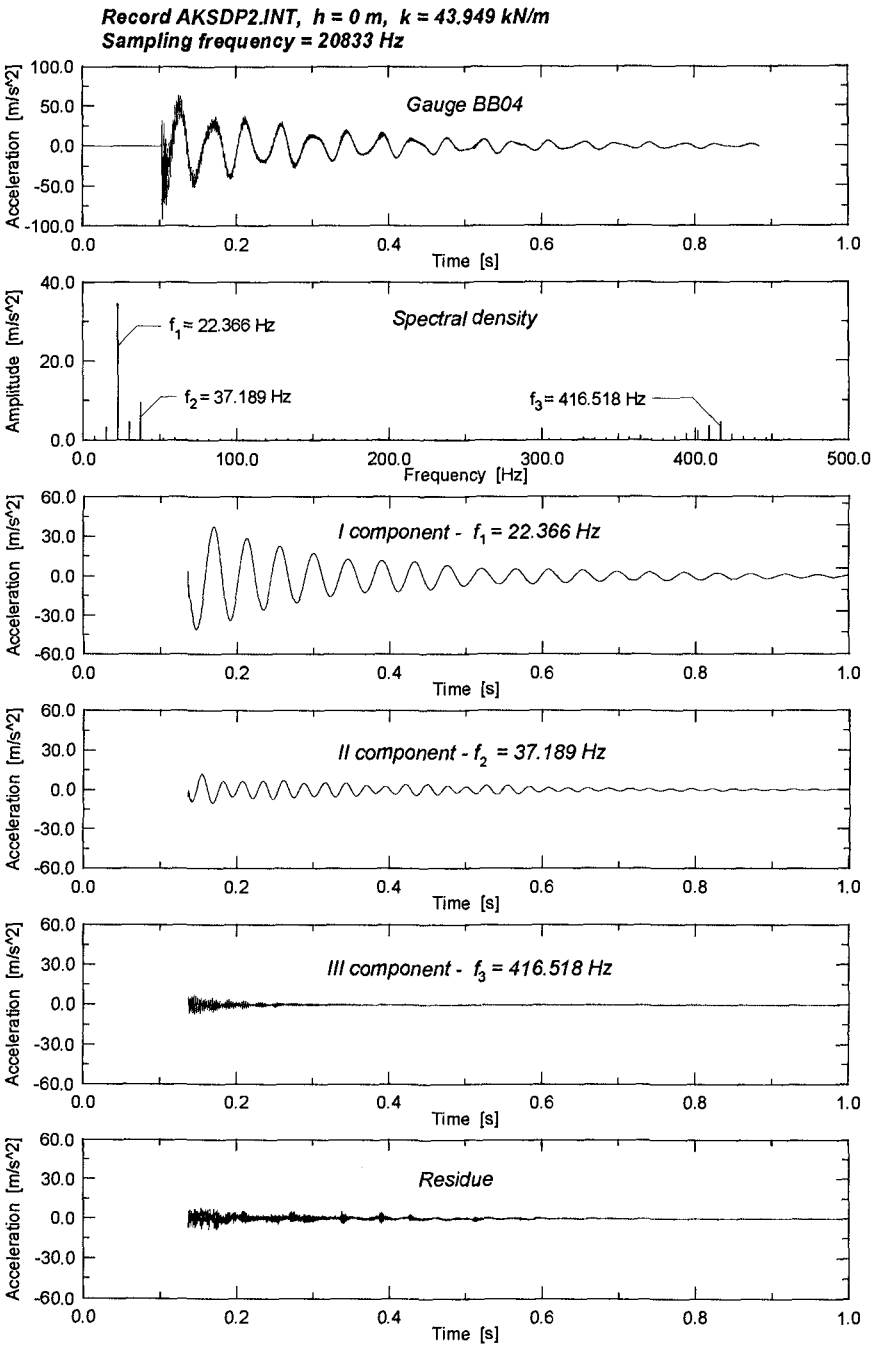

Fig. 6. The decomposition of acceleration in free vibration in air (initial displacement).

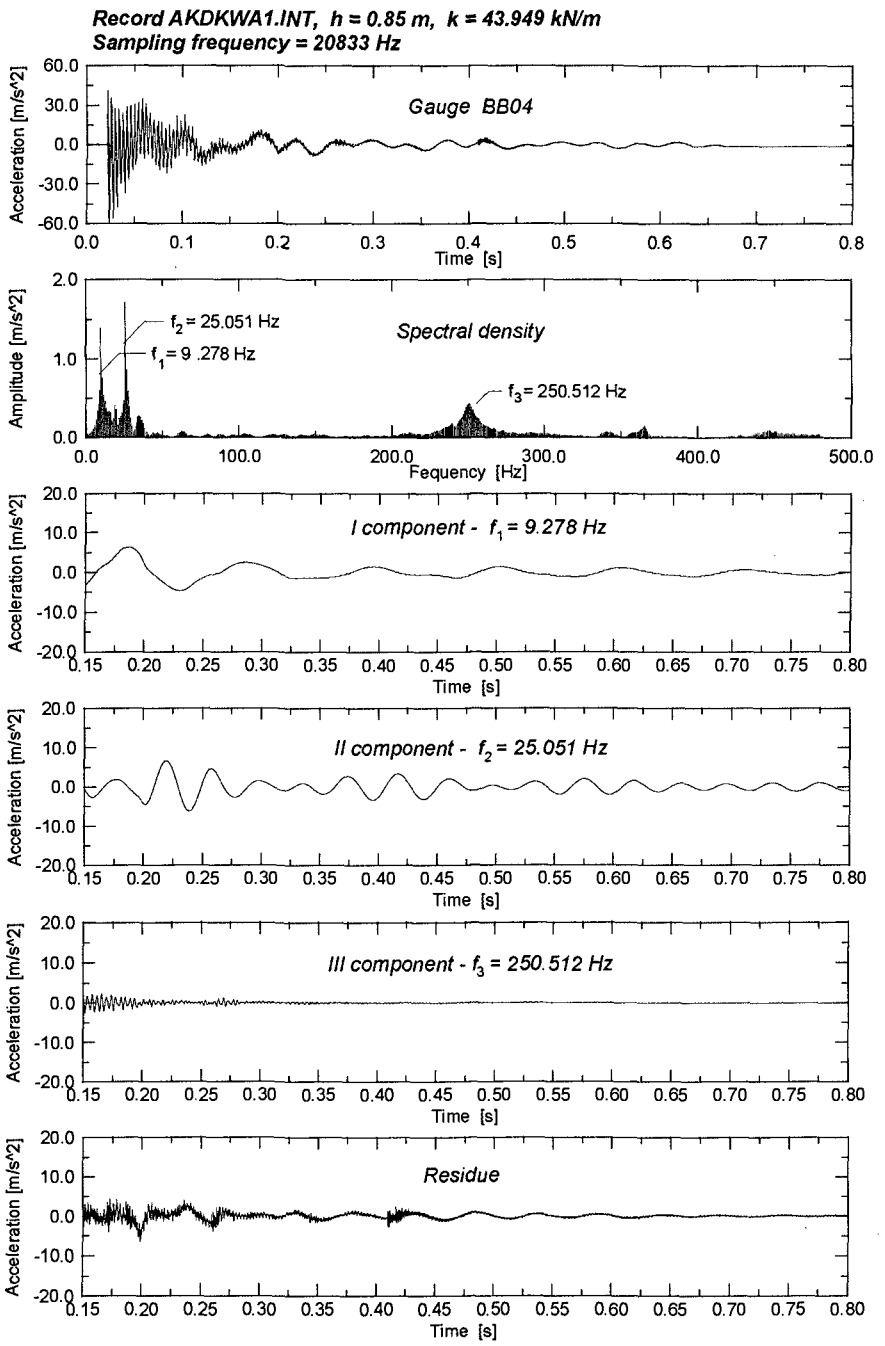

Fig. 7. The decomposition of vibrations in contact with water (initial displacement).

Therefore, the basic experiments mentioned so far were supplemented with experiments concerning vibrations of the plate initially resting on the surface of calm water (floating plate). The vibrations were induced by initial displacements of the plate or, by a hammer strike on it. In order to identify the lowest eigenmodes of the plate vibrations, the theoretical model of the plate shown in Fig.5. was constructed. The experiments started with vibrations of the plate in air. Some of the results obtained are illustrated in Fig.6, where the acceleration record is presented. The experimental results were confirmed in theoretical calculations based on a simplified

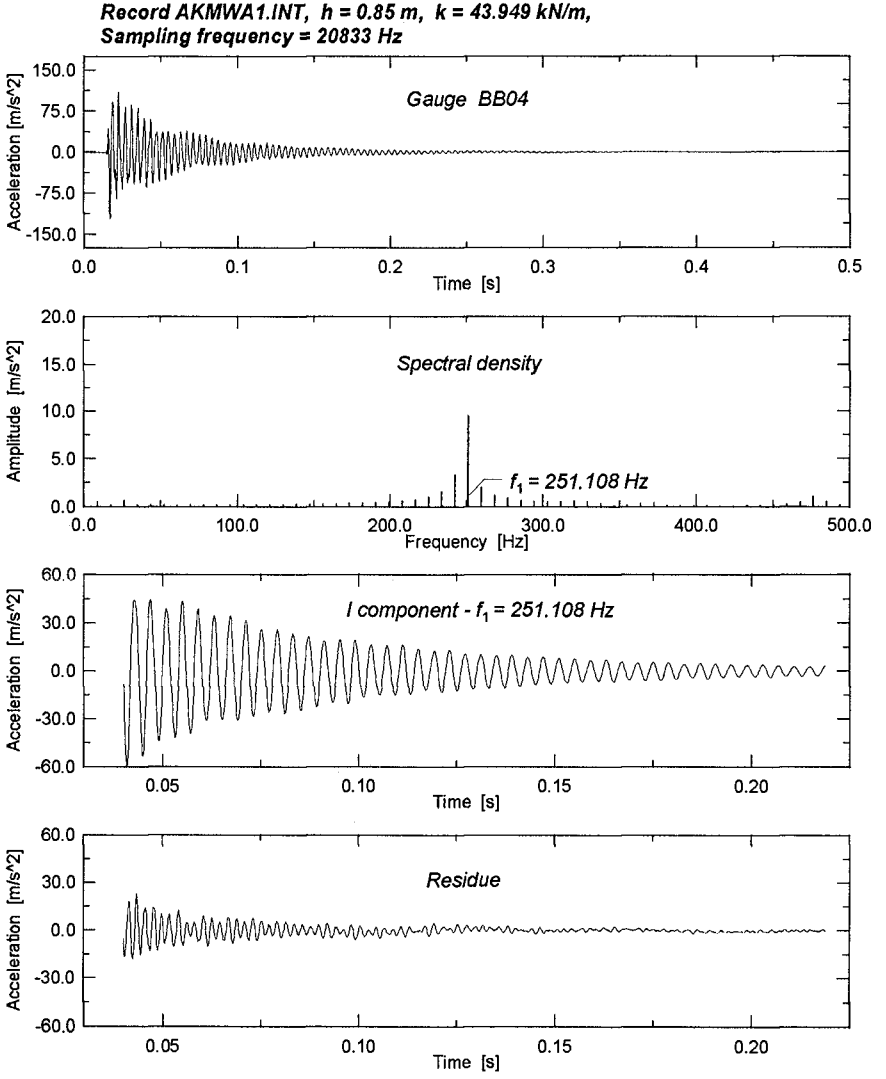

Fig. 8. The vibrations in contact with water induced by an impulse (hammer test).

model of the dynamical system shown in Fig.5. A similar test was performed for the plate having a contact with water. Like in the previous case, the vibrations of the plate were induced by an initial displacement of it. The results obtained in the experiments are shown in Fig.7. The spectral density of the plate vibrations in contact with water is shifted to the left (in the direction of lower values) as compared to the case of vibrations in air. The changes of eigenfrequencies are due to covibrating masses of fluid. The vibrations of the plate induced by a hammer strike are illustrated in Fig.8. where an acceleration record is shown. When compared to the afore-going cases we have here almost exclusively one component corresponding to flexural vibrations of the plate. This is a result of the method used to induce the vibrations of the system mentioned From the acceleration plots it is seen, that the vibrations of the system are damped. In the case of vibrations in air we have the so called structural damping resulting from energy dissipation within the material (the mechanical energy is transformed into heat and dissipated in cyclic deformations). In the case of vibrations of the plate – fluid system, the damping is a result of the dissipation of energy mentioned above and the transmission of energy outside the structure by dilatational waves. It is worth to add, that during reflections of the propagating waves from the flume boundaries, some energy is transmitted outside the fluid.

3. Fluid compressibility and a structure-fluid interaction.

From the experiments performed it follows, that in analysis of a structure loaded with impact pressure forces of fluid and, or vibrating in contact with fluid, the elastic deformation of the structure and the small compressibility of the fluid must be taken into account. Accordingly, for higher frequencies of the vibrations, the dilatational waves generated play an important role in proper estimation of the structure – fluid dynamical interactions. In order to get a better insight into the phenomena considered, the problem of harmonic vibrations of a structure submerged in an infinite domain of compressible fluid has been investigated. In particular, we have confined our attention to the plane problem of harmonic vibrations of an infinite elliptical cylinder immersed in the compressible fluid domain. The solution derived corresponds to the vibrations of the cylinder in the direction of the smaller axis of the ellipse. In the limit, the smaller axis of the ellipse was assumed to decrease to zero and, the solution for the ellipse approached the solution for an elastic infinite plate vibrating in the fluid. In this way, the solution for the ellipse was converted into the solution for the plate. For comparison, a similar problem for an infinite circular cylinder was also considered. The solutions obtained enable us to calculate the resultant force R of the fluid pressure acting on the cylinder or thin plates vibrating in fluid:

$$R = \ddot{w}(t)\cdot\rho\cdot\pi\cdot b_x^2\cdot F_M(h) + \dot{w}(t)\cdot\omega\cdot\rho\cdot\pi\cdot b_x^2\cdot F_T(h), \quad h = \frac{\omega\cdot a}{c}, \tag{1}$$

where: ρ is the fluid density, ω is the angular frequency of vibrations , a is the radius of the cylinder, c is the velocity of sound in fluid, $\dot{w}$ and $\ddot{w}$ are the velocity and the acceleration of the cylinder (or the plate). In the case of the cylinder $b_x = a$ and, in the case of the plate $2b_x = 2a$ is the plate width. The resultant force has two components: the first one corresponding to the covibrating mass of fluid, and the second – describing the damping of vibrations. The plots of the resultant components for the rigid body vertical motion of the circular cylinder and a band plate are shown in Fig.9. Similar plots of the resultant components for the flexural and rotational vibrations of the plate are presented in Fig.10. From the plots it is seen, that with

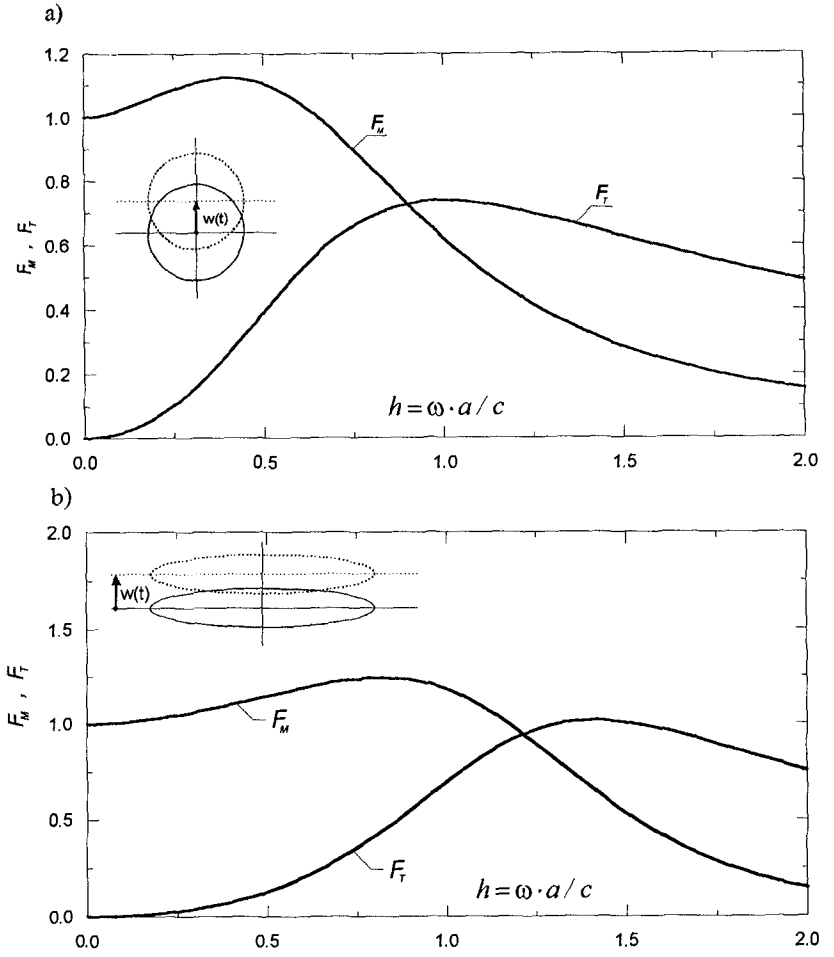

Fig. 9. The influence of compressibility. The coefficients $F_M(h)$ and $F_T(h)$ for vertical vibrations of a circular cylinder (a) and, a band plate (b).

neglecting the fluid compressibility in description of the problem considered , no information about damping of structure vibrations can be obtained. In other words, the fluid compressibility is important in proper estimation of the covibrating mass of fluid and is essential in calculating damping of vibrations.

4. Conclusions.

The phenomenon of impact pressure forces induced by water waves has been examined experimentally by means of a horizontal plate supported elastically in a hydraulic flume. The pressure, wave and acceleration gauges allowed for recording the relevant parameters in the time domain. With respect to the results of the experiments, a theoretical solution to the problem of harmonic vibrations of an elastic band plate submerged in an infinite domain of compressible fluid has also been

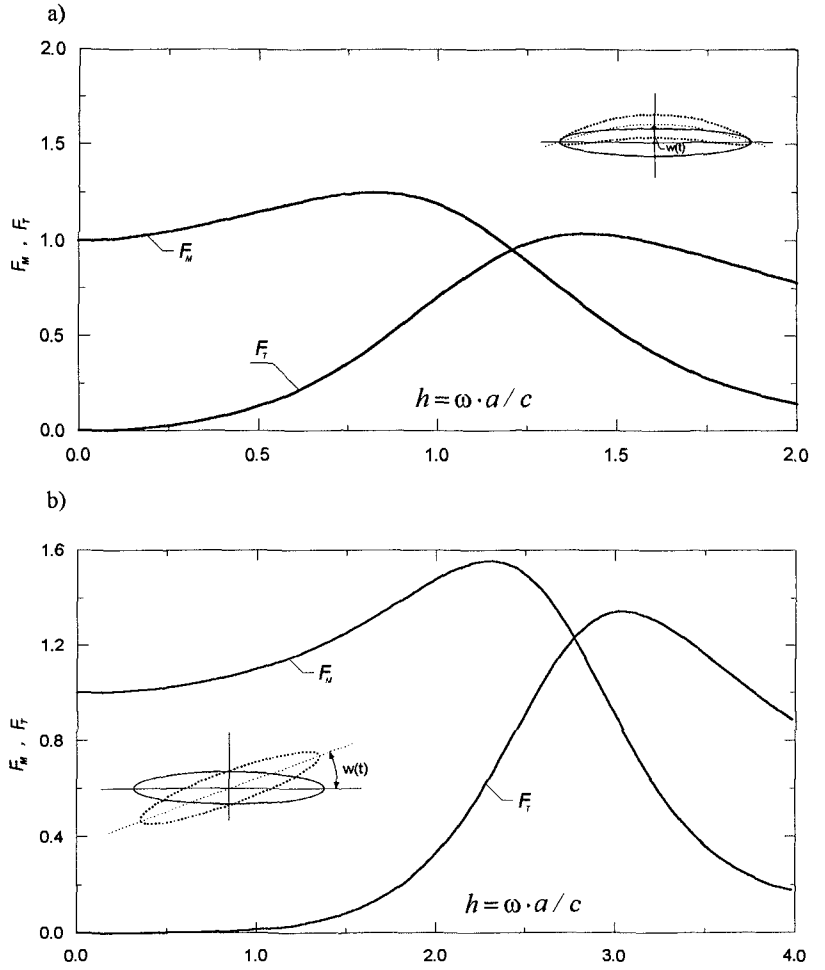

Fig. 10. The influence of compressibility. The coefficients $F_M(h)$ and $F_T(h)$ for flexular (a) and, rotational (b) vibrations of a band plate.

derived. From the results of experimental and theoretical investigations performed, the following conclusions may be withdrawn:

a) The value of the impulse strongly depends upon the elasticity of the supports of the plate. Thus, the problem has to be studied as a problem in hydro-elasticity.
b) In the first stage, due to the impact, progressive dilatational waves appear in water and a lot of eigenfrequencies of the structure are initiated. This stage is difficult to be described by a theoretical model.
c) In the next stage damped vibrations appear. In our experiments we observed not only damped rigid body motions, but also damped vibrations due to bending of the plate

d) For higher eigenfrequencies, the compressibility of the fluid and the propagation of dilatational waves have to be taken into account. To get reliable results we had to measure and register the data with 20,000 Hz frequency for each gauge.
e) The experiments with vibrations of the structure placed on the surface of the water due to initial displacement or impulse show that the calculated covibrating mass is in good agreement with experimental values and, the theoretical dissipation of energy due to the propagation of dilatational waves is a reasonable estimate for damping for high frequencies.
f) In our experiments the impact was repeated, but the consecutive presure impulses were random.

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