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AN EXPERIMENTAL METHOD FOR IMPULSIVELY LOADING RING STRUCTURES[†]

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Abstract—An experimental method for impulsively loading structural rings with a simultaneously applied, short-duration pressure pulse is presented. The loading is produced by magnetic pressure between two parallel current-carrying conductors. A fast discharge capacitor bank and a current pulse shaping technique are utilized to provide a pressure pulse with a duration of about 2 μsec, a duration sufficiently short that loading can be considered impulsive for most structural ring experiments. Applicability of the method was demonstrated with an experiment where the impulse was cosinusoidally distributed over half the circumference of a thin aluminum ring. Measured strain–time histories were in close agreement with theoretical predictions.

INTRODUCTION

FOR many applications, the goal of impulse simulation is to impart a simultaneous short-duration pressure pulse to the surface of a structure. Most existing experimental information on the response of impulsively loaded structures has been obtained by testing with sheet explosives [1–4], light-sensitive explosives [5, 6], magnetic induction [7–9] or magnetically propelled flyer plates [10–14]. Each of these techniques has advantages and limitations which should be considered together with the objectives of an experiment or test. Detailed discussions of the limitations and advantages of testing with these methods appear in the cited reference. This paper presents a new method which is similar to, but offers some important advantages over, the magnetic flyer plate method.

For the flyer plate technique, energy from a fast discharge capacitor bank is used to propel a thin metallic plate onto a structure. The circuit consists of a capacitor bank, a switch and the flyer plate–load coil combination as shown in Fig. 1. When the switch is closed, a magnetic pressure is generated in the insulated region between the flyer plate and the load coil. The pressure is proportional to the square of the damped sinusoidal current from the capacitor discharge and the flyer plate is accelerated to terminal velocity by a sequence of pressure pulses with exponentially decreasing magnitude. After crossing a properly dimensioned gap, the flyer plate impacts the structure and imparts a pressure pulse whose duration is short compared with the capacitor bank discharge time.

The new method also uses the energy from a fast-discharge capacitor bank to develop pressure between a thin metallic plate and a load coil. However, the structural ring is placed in direct contact with an electrical insulator which is all that separates it from the thin metallic plate. Since the structure is loaded as soon as current flows in the circuit, the current pulse must be shaped to produce an impulsive loading. The current pulse is shaped by adding a large resistance in the circuit after the current reaches its first maximum and starts to descend; this overdamps the circuit and causes the current to exponentially

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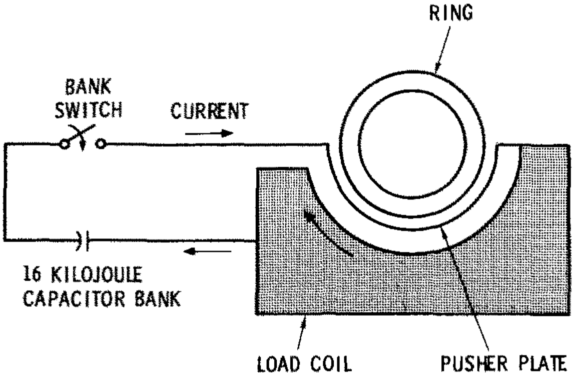

FIG. 1. Experimental arrangement.

approach zero. Then the current which flows in the load is a single pulse and the resulting pressure has the form of a single pulse. Since the thin metallic plate simply pushes on the surface of the structure, the authors have termed the new method the magnetic push impulse simulation technique.

The new method utilizes much of the technology developed for the magnetically propelled flyer plate technique; however, several disadvantages of that method are eliminated; specifically, flyer plate wrinkling before impact, asimultaneity of the arrival of the flyer plate onto the surface of the structure,† interaction of the flyer plate with the air before impact and detachment of strain gages. The first three disadvantages are eliminated because the pusher plate is in contact with the structure, and gage detachment is eliminated because the pressure pulse is continuous and spread over 2 μsec.

In the next section the theory for pressure pulse shaping and ring response will be discussed. Then, the magnetic push simulation method is demonstrated with a ring experiment. Finally, results and summary of the simulation technique are presented.

THEORY

Magnetic pressure

Detailed discussions on the generation of a magnetic pressure between two parallel current-carrying conductors were presented in Refs. [11, 12]. Briefly, the pressure exerted between two closely spaced parallel conductors is given by

$$p = \frac{B^2}{2\mu}, \qquad B = \frac{\mu i}{w} \tag{1}$$

where B is the magnetic flux density, i is the current, μ is the permeability of space and w is the width of the conductor. As explained in Ref. [12], the spatial distribution of the pressure can be shaped by varying the width of the conductor.‡

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† Arrival of a flyer plate onto a structural ring is shown by several frames from a high-speed framing camera in Ref. [12].

‡ Shaping of the conductor to obtain various spatial distributions of pressure is subject to certain limitations; these limitations are discussed in Ref. [12].

Current pulse shaping

The circuit for the magnetic push method is shown in Fig. 2. A single current pulse is produced by placing an aluminum foil in series with the load. At a designated time after the capacitor bank is switched, the current which flows through the foil causes it to explode by rapid joule heating. When the foil explodes, the resistance in the circuit greatly increases; this overdamps the circuit and the current exponentially approaches zero. For this application the foil is timed to explode after the current reaches its first maximum and starts to descend. With this technique the current is a single pulse and resulting magnetic pressure is a single pulse.†

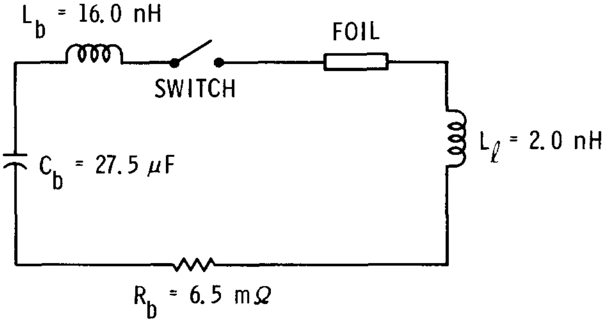

FIG. 2. Circuit diagram and bank parameters.

The pressure pulse which loads the structural ring is determined by the current which flows in the pusher plate and the pusher plate width w. This pulse duration is sufficiently short that the load can be considered impulsive and the integral of the pressure–time pulse is taken as the distributed impulse $I(\theta)$. From equations (1)

$$I(\theta) = \frac{\mu}{2}\int_0^{t_d} [i(t)/w(\theta)]^2\,dt \tag{2}$$

where t_d is the duration of the current pulse.

In order to achieve the desired impulse delivered to the structure, the capacitor bank voltage must be determined. This voltage is calculated by considering the energies required to explode the foil and deliver the impulse given by equation (2). Procedures for the foil design and formulas which relate capacitor bank voltages to impulse levels are given in Ref. [16].

Ring response

The response of ring structures to impulsive loads has been the subject of several recent analytical investigations. Solutions for the membrane stresses from a point impulse and a cosinusoidally distributed impulsive load over half the ring circumference are presented in Ref. [17]. These solutions are traveling wave solutions, rather than modal

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† A single current pulse can also be obtained by shorting the capacitor bank from the load; e.g. see Refs. [8, 15].

solutions and the usual problems of summation and convergence were avoided. The shell response to the cosinusoidally distributed impulse was reinvestigated in Ref. [18]. This analysis included the shell bending terms and demonstrated that bending effects are small for the early time response. Comparison of a modal solution and the exact traveling-wave solution for the membrane stress produced by the cosinusoidally distributed impulse indicated that a three-term modal solution is extremely accurate. This modal solution is given by

$$\frac{\sigma h}{cI_0} = -\frac{1}{\pi}\sin\tau - \frac{1}{2(2)^{\frac{1}{2}}}\cos\theta\sin[(2)^{\frac{1}{2}}\tau] - \frac{2}{3\pi(5)^{\frac{1}{2}}}\cos 2\theta\sin[(5)^{\frac{1}{2}}\tau] \tag{3a}$$

$$\varepsilon = \sigma/E \tag{3b}$$

$$\tau = ct/a, \qquad c^2 = E/\rho. \tag{3c}$$

The angular position θ and ring geometry are shown in Fig. 3; E, ρ and c are Young's modulus, density and bar velocity; σ and ε are the circumferential membrane stress and strain; t is time; I_0 is the peak intensity of the impulsive load which is cosinusoidally distributed over $|\theta| < \pi/2$.

One of the objectives of the present experiment is to demonstrate the ability to record strains shortly after switching the capacitor bank. This objective is achieved by measuring the early time ring response and, as was shown in Ref. [18], the shell bending effects can be neglected. A comparison of measured strain–time histories and the response predicted by equation (3a) will be presented.

RING EXPERIMENT

Applicability of the method was demonstrated with an experiment where the impulse was cosinusoidally distributed over half the circumference of a thin aluminum ring.

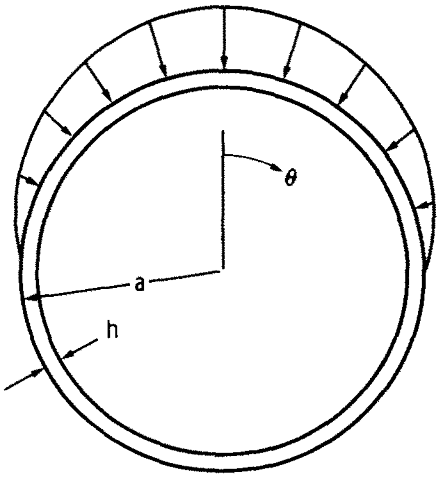


FIG. 3. Ring geometry.

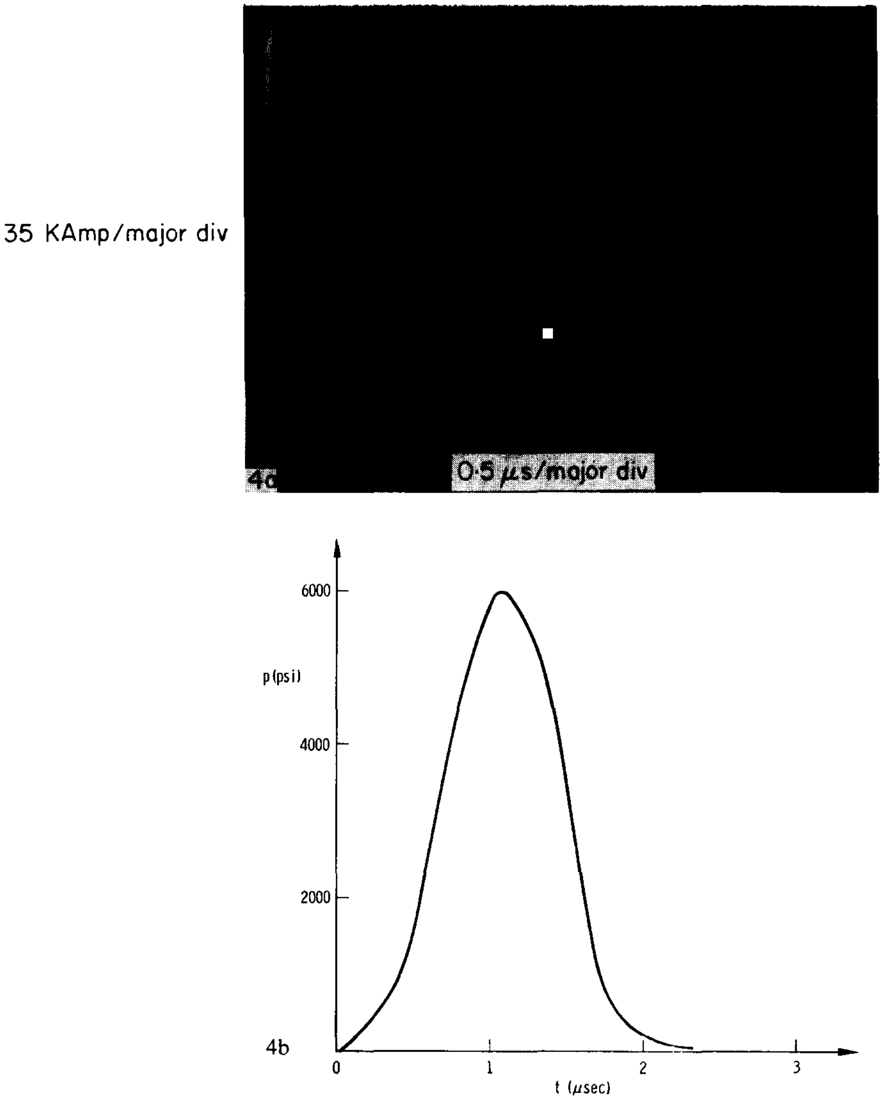
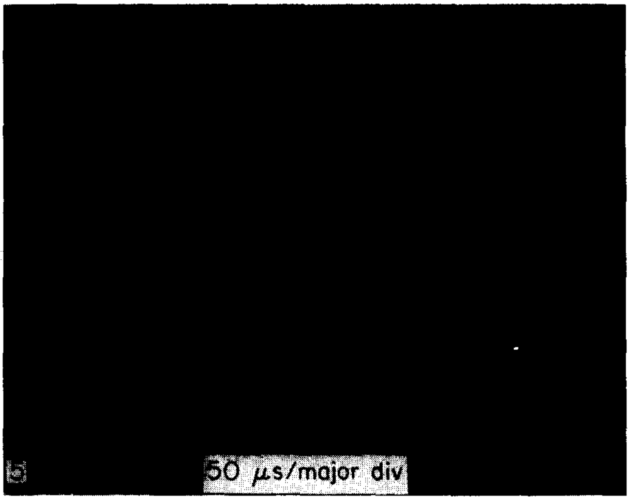


Fig. (a). Current–time in the pusher plate.
(b). Pressure–time at $\theta = 0$.



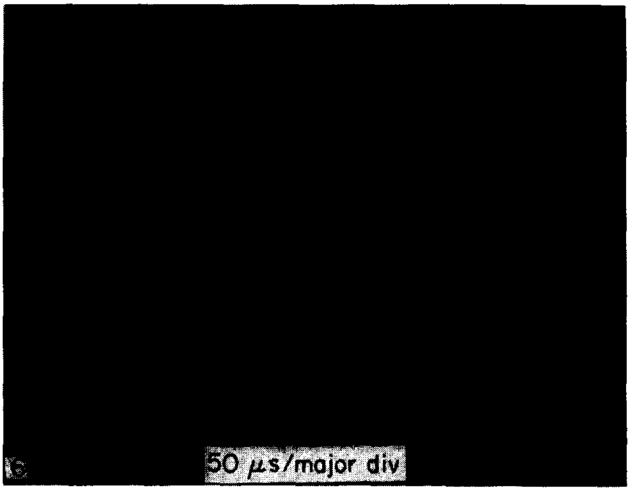


FIG. 5. Strain–time at $\theta = 0$.
FIG. 6. Strain–time at $\theta = \pi$ (upper trace from inside ring surface).

Measured strain–time histories were found to be in close agreement with theoretical predictions.

Loading technique

A schematic of the experimental arrangement is shown in Fig. 1. The pusher plate is 2 ml of dead soft aluminum and the load coil is a machined block of aluminum. These elements form the two parallel, current carrying conductors. They are electrically insulated with 10 ml of mylar and the structural ring is insulated from the pusher plate with 2 ml of mylar. The capacitor bank is a single ES-108 unit manufactured by British Insulated Callendar's Cables, Limited and the circuit parameters are listed in Fig. 2.

For this experiment, the bank was charged to 8·0 kV which produced a peak current in the pusher plate of 150 kA. The current was measured by integrating the signal from a Rogowski loop, displayed and then photographed on a Tektronix 454 oscilloscope. This current trace is shown in Fig. 4(a) and the corresponding pressure pulse is shown in Fig. 4(b).

The magnitude of the distributed impulse was $I(\theta) = I_0 \cos\theta$ over $|\theta| < \pi/2$. This distribution was achieved by increasing the width of the pusher plate at $\theta = 0$ by $(\cos\theta)^{-\frac{1}{2}}$. As indicated by equation (2), this plate shaping produces a cosine distribution of impulse.

Ring specimen

The ring specimen was 2024 aluminum which was machined from a plate to an outer diameter of 6·00 in. and a thickness of 0·10 in.; the width of the ring was 0·50 in. The bar velocity of the ring was $c = 0{\cdot}20$ in./μsec.

Strain measurement

The impulse–induced strain waves were measured with Kulite dual element type M(12)DGP-350-500 semiconductor strain gages. The gages were composed of two elements of opposite gage factor. Each element forms an active arm in a standard wheatstone bridge. The signal from the bridge circuit was displayed and photographed on a Tektronix 556 oscilloscope, using Tektronix 1A6 signal amplifiers.

Strain–time data are presented in Figs. 5 and 6. The peak intensity of the impulse was 382 taps† which produced peak strain in the neighborhood of 550 $\mu\varepsilon$. Strain–time data at $\theta = 0$ are presented in Fig. 5; this record demonstrates that measurements can be obtained on the loaded portion of the ring. Strain–time data on the inside and outside of the ring at $\theta = \pi$ are presented in Fig. 6; these traces are extremely similar in shape and amplitude which demonstrates that the early time response is extensional.

Comparison with theoretical predictions

A comparison of the measured strain–time data and the response predicted by equations (3) is shown in Fig. 7 for $\theta = 0$ and in Fig. 8 for $\theta = \pi$. These comparisons indicate that the measured strain–time histories are in excellent agreement with theoretical predictions.

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† 1 tap = 1 dyne-sec/cm^2.

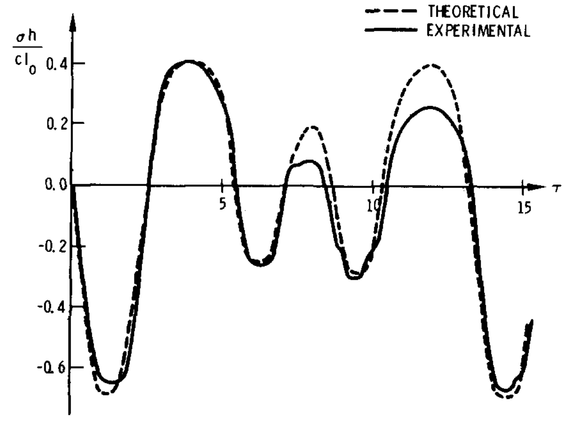

FIG. 7. Experimental and theoretical comparison at $\theta = 0$.

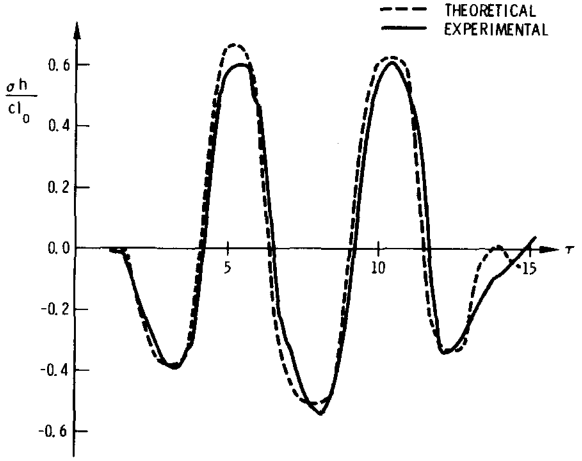

FIG. 8. Experimental and theoretical comparison at $\theta = \pi$.

SUMMARY

An experimental method for impulsively loading structural rings with a simultaneously applied, short-duration pressure pulse has been presented. The new method utilizes much of the technology developed for the magnetically propelled flyer plate technique; however, as discussed in the Introduction, several disadvantages of the flyer plate technique are eliminated. Applicability of the method was demonstrated with an experiment on impulse–induced stress waves. The data demonstrate that the higher frequency structural modes, the membrane modes, can be measured in the presence of the electrical noise created by capacitor bank switching and the exploding foil.

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Абстракт—Дается экспериментальный метод расчета внезапно нагруженных конструкционных колец, с одновременным действием импульса давления, действующим в короткое время. Нагрузка вызвана магнитным давлением между двумя параллельными проводниками под током. Используется быстрая батерия разрядного конденсатора и метод формирования тока импульсов, для получения импульса давления, срок которого равняется приблизительно 2 μсек. Это действие является достаточно коротким для того, чтобы можно рассматривать нагрузку, в смысле импульсов, для большинства экспериментов с конструкционными кольцами. Показано применимости метода на эксперименте, в котором импульс косинусоидально расположен на половине окружности тонкого алюминиего кольйа. Измеренные результаты для деформаций во времени хорошо согласовуются с теоретическими предсказаниями.