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THE RESPONSE OF A SIMPLY SUPPORTED PLATE TO TRANSIENT FORCES

Part II - The Effect of N-Waves
at Oblique Incidence

by Anthony Craggs

Prepared by
UNIVERSITY OF SOUTHAMPTON
Southampton, England
for Langley Research Center

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THE RESPONSE OF A SIMPLY SUPPORTED PLATE TO TRANSIENT FORCES

PART II: THE EFFECT OF N-WAVES AT OBLIQUE INCIDENCE

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SUMMARY

A numerical method is used to compute the response of a simply supported plate to an 'N' wave arriving at oblique incidence. The factors influencing the response under these conditions are: (i) the ratio of the pulse duration to the fundamental period of the plate and (ii) the convection forcing terms which are different for each mode. Also, asymmetric modes are excited, which do not make any contribution when the wave is at normal incidence to the plate. The computed results show that both the convection terms and the asymmetrical modes make a significant contribution to the form of the response for the displacements, velocities and accelerations, though their effects are more dominant in the accelerations than for any other parameter.

INTRODUCTION

In the first part of this study the response of a plate to a normally incident transient pressure loading was computed. This work is now extended by considering the response of a structure to a travelling wave, which is more representative of the general case of sonic boom excitation, than the normal incidence case. In particular, the report considers the response of a simply supported plate to travelling 'N' waves and the related loading of 'N' waves arriving at oblique incidence.

Even for this elementary system the problem is a complex one to solve by conventional analytical techniques. When a normal mode approach is adopted the problem is complicated by the nature of the generalised forces. For travelling waves these forces are functions, not only of the pressure time history that would be measured at a single point, but also of the convection velocity and plate dimensions in the direction of traverse. Because there is a time delay in the loading of each point on the structure the shape of the normal modes influences the magnitude of the generalised forces and, consequently, the time dependence of each of the generalised forces is different. In this situation it is more convenient to use numerical techniques rather than to look for

analytical solutions. There is then the added advantage that arbitrary transient wave forms can be used if required. The method is a simple extension to that of part 1, ref. 1.

An analytical solution has already been made by CHENG*. However his final analysis was considerably simplified by resorting only to the fundamental mode and a single speed of traverse corresponding to a convection frequency term equal to the fundamental frequency of the plate. In this report the first four modes which are excited are used and a range of trace velocities are considered, although the duration of the pulse is kept constant such that it is equal to the period of the fundamental mode. Three response parameters are computed for each normal mode: (i) the generalised displacement, (ii) velocity and (iii) acceleration. Thus a clear estimate of the contribution of each mode may be made for the various loading conditions.

Although the convection velocity parameters considered are at the lower end of the scale which occur in practice, they are used in this analysis since above this range the plate would effectively respond as though the loading was at normal incidence.

SYMBOLS

m, n	integer mode suffices
ψ_{mn}	normal mode
q_{mn}	generalised displacement
$\{q\}$	generalised displacement array
ρ	plate density
h	plate thickness
μ	Poisson's ratio
ν	critical damping ratio
ω_{mn}	natural frequency of (m,n)th mode
$\bar{\omega}_{mn}$	$= \frac{\rho h \omega_{11}^2 \pi^2}{16} q_{mn}$

*Unpublished work submitted by D. H. Cheng, City College of the City University of New York, prepared during temporary assignment at NASA Langley Research Center.

$w(x,y)$	displacement
$\{w\}$	displacement array
t	time
$\bar{w}(x,y)$	$(\frac{\rho h \omega_{11}^2 \pi^2}{16}) \frac{w(x,y)}{\psi_{11}(x,y)}$
$p(x,y,t)$	pressure
$\{r\}$	impulse response array
$[R]$	integrating matrix
a,b	overall plate dimensions
β	b/a
L	maximum structural dimension in directions of traverse
τ	duration of wave
T_1	period of fundamental mode
v	velocity of wave
λ	wavelength
Δt	time increment
d	width of segment
Ω_{mn}	convection frequency
N	number of plate segments
θ	angle of inclination of the plate
S	convection frequency ratio for fundamental mode
σ_x, σ_y	stresses in x and y-direction

THEORY

When a plane wave travels over a plate, the total time that the wave is on the structure is given by:

$$\frac{1}{v} (\lambda + L)$$

where λ is the wavelength, L is the maximum dimension of the structure in the direction of traverse and v is the velocity of traverse. The manner in which the plate responds depends whether λ is greater than L , or vice versa, and how the terms (λ/v) and L/v are related to the fundamental period of the structure T_1 . If λ is much greater than L and λ/v is of the same order as T_1 , the structure will effectively respond as though the wave was at normal incidence. If L is much greater than λ the plate will then respond as though the wave was a moving line force.

In practice, although λ is probably greater than L , the convection term L/v is of the same order as the fundamental period and the travelling effect is then important. In what follows these conditions are considered for an 'N' wave moving over a simply supported plate.

For a plate loaded by a forcing function $p(x, y, t)$ the equation of motion for the transverse displacement, w , may be written in terms of the normal modes ψ_i and the generalised coordinates q_i as

$$w = \sum_i^{\infty} q_i(t) \psi_i(x, y) \quad (1)$$

The equation of motion of each generalised coordinate is that of a single degree of freedom system:

$$\ddot{q}_i + 2\omega_i v \dot{q}_i + \omega_i^2 q_i = \frac{1}{\rho h} Q_i(t) \quad (2)$$

When the plate is simply-supported the normal modes have the form:

$$\psi_{mn} = \sin \frac{m\pi x}{a} \cdot \sin \frac{n\pi y}{b}$$

therefore

$$Q_{mn}(t) = \frac{4}{a \cdot b} \int_0^b \int_0^a p(x, y, t) \sin \frac{m\pi x}{a} \cdot \sin \frac{n\pi y}{b} dx dy \quad (3)$$

Thus, having found Q , the solution is found by solving a set of equations of the type (2), and then substituting for q in (1). In ref. (1) it was shown that when Q was a complicated function it was convenient to break it up into a finite number, n_s , of rectangular

impulses of equal width, Δt , and store the values of the ordinates in an array $\{Q\}$. When this has been done the response array, $\{q\}$ given at the same time intervals may be written down in the matrix form:

$$\{q\} = \Delta t [R] \{Q\} \quad (4)$$

where $[R]$ is a square, lower triangular matrix of order $n_s \times n_s$, the non zero elements of the n_r^{th} column containing the first $(n_s - n_r + 1)$ terms of the unit impulse response array $\{r\}$, which is computed from the equation:

$$r_{mn}(t) = \frac{e^{-\omega_{mn} vt}}{\omega_{mn} \sqrt{1 - v^2}} \sin(\omega_{mn} \sqrt{1 - v^2} t)$$

The Approximation of the Forcing Array $\{Q\}$ for a Simply Supported Plate due to a Wave Travelling in a Direction Parallel to One Edge

The details of the plate loaded by a pressure wave on one face only are shown in Fig. 1. To idealise the forcing function the plate is first divided into a number of equal rectangular segments which are normal to the convection direction. If the width of each segment is small compared with the overall length of the wave, then, for each segment, the forcing function may be assumed to be as if at normal incidence. Under these conditions the generalised force for a mode $\psi_i(x, y)$ is given by:

$$Q_i(t) = d.p(t) \left\{ \int_0^a \psi_i(x, \frac{d}{2}) dx + d.p(t) H(t - \frac{d}{v}) \int_0^a \psi_i(x, \frac{3d}{2}) dx + \dots \right. \\ \left. + d.p(t) H(t - \frac{id}{v}) \int_0^a \psi_i(x, (\frac{2i+1}{2})d) dx \right\} + \int_0^b \int_0^a \psi_i^2 . dx dy$$

where $H(t - t_1)$ is the Heaviside shift term which means that the function p is zero until $t \geq t_1$; it then has the form as though t was starting from zero. For a single mode the generalised force is given by:

$$Q_i(t) = d.p(t) \left\{ \sum_{i=0}^{N-1} H(t - \frac{id}{v}) \int_0^a \psi_i(x, (\frac{2i+1}{2})d) dx \right\} + \int_0^b \int_0^a \psi_i^2 . dx dy$$

where N is the number of segments. Substituting for ψ_{mn} for a simply supported plate gives:

$$Q_{mn}(t) = \frac{8d}{bmn\pi} p(t) \sum_{i=0}^{N-1} H(t - \frac{id}{v}) \sin\left(\frac{n\pi}{b} \left(\frac{2i+1}{2}\right)d\right) \quad (5)$$

The generalised force array $\{Q_{mn}\}$ can then be evaluated at equal intervals of time and the nett response built up by summing the contributions from all the modes. Thus, at a point (x, y) on the plate:

$$\begin{aligned} \{w\} = & \Delta t (\psi_{11}(x, y) [R_{11}] \{Q_{11}\} + \psi_{12}(x, y) [R_{12}] \{Q_{12}\} \\ & + \psi_{13}(x, y) [R_{13}] \{Q_{13}\} + \dots) \quad (6) \end{aligned}$$

The main difference between the normal incidence and a travelling wave may be deduced from equation (5). At normal incidence the shift term t_1 is zero and

$$Q_{mn} = \frac{8d}{bmn\pi} p(t) \sum_{i=0}^{N-1} \sin\left(\frac{n\pi}{b} \left(\frac{2i+1}{2}\right)d\right) \doteq p(t) \frac{8}{bmn\pi} \int_0^b \sin \frac{n\pi y}{b} dy$$

When the wave travels over the plate, the shift term causes the mode shape to have some influence on the time history of the forcing function.

The force acting on the i^{th} segment is multiplied by a harmonic term $\sin \frac{n\pi}{b} \left(\frac{2i+1}{2}\right)v\left(\frac{d}{v}\right)$. The convection frequency for the (m,n) th mode is then:

$$\begin{aligned} \omega_{mn} = \frac{n\pi v}{b} \quad \text{or} \quad f_{mn} = \frac{nv}{2b} \\ (\text{rads/s}) \quad \quad \quad (\text{c/s}) \end{aligned}$$

The convection frequency ratio is defined by

$$S = \Omega_{11} / \omega_{11}$$

For a simply supported plate the convection frequency term is deduced naturally because the mode shapes are sine functions. It should be noted, however, that a similar term will exist for other boundary conditions and the frequency may be defined as $\Omega_c = \pi v/L$.

Oblique Incidence

The solutions of the travelling wave and oblique incidence problems are virtually the same. The difference lies solely in the interpretation of the results. In this analysis the wave is specified by its duration rather

than its wavelength; so that for a travelling wave the effects of different speeds would involve altering the duration as well as the speed of traverse. At oblique incidence the duration of the pulse remains constant but the trace velocity is increased to $v \sec \theta$, where θ is the angle of incidence of the plate (see Fig. 1).

DETAILS OF THE COMPUTATIONS

The theory of the previous sections has been used to compute the response of a simply-supported plate with aspect ratio, $\beta = 1.5$. The description of the loading term measured at a point in space was given by

$$p(t) = (1 - 2t/\tau) \quad \text{for } 0 < t < \tau$$

$$p(t) = 0 \quad \text{for } 0 > t > \tau$$

The duration of the wave, τ , was kept constant and equal to the period of the fundamental mode and the wave travelled in the y-direction. In making an accurate estimate of the response a sufficient number of modes should be used. The number of modes depends upon the rate of convergence for the generalised coordinates. This convergence is dependent on the spatial distribution and the frequency content of the forcing pressure $p(x, y, t)$. In part 1, it was shown that for normal incidence the displacements and stresses were dominated by the fundamental mode, but this was mainly because some of the modes with frequencies close to the fundamental were not excited. The accelerations, however, were significantly influenced by the higher modes. As a general rule, with transient loads, it is the lower modes which contribute most to the response. For this work a fixed number of modes were used with the object of studying the contributions from each one under various loading conditions rather than evaluating an accurate estimate of the response at a point on the plate. For the particular plate considered, the order in which the first 9 modes occur in the frequency scale is (1, 1), (1, 2), (2, 1), (1, 3), (2, 2), (2, 3), (1, 4), (3, 1), (2, 4). However, the generalised forces for the (2, 1), (2, 2), (2, 3) and (2, 4) modes are zero when the wave moves in the y-direction. Here only the first 4 active modes were used, i.e. the (1, 1), (1, 2), (1, 3) and (1, 4). Of these the (1, 2) and (1, 4) modes are not excited under normal incidence conditions.

For good accuracy the number of segments that the plate is broken into should be large and the step size, Δt , should be small. In this work the plate was divided into 20 strips, so that there were five strips per half wave of the (1, 4) mode. The step size was such that there were 320 steps in the duration of the fundamental period.

The application of equation (4) gives the displacement response

array only. The velocity and acceleration arrays were found by a numerical differentiation procedure which was based on a 5 point difference formula, the details of which are given by HILDEBRAND, ref. (2). This was much more economical on computer time than the superposition method used in ref. (1).

A range of the convection frequency parameters which occur in practice are given in TABLE 1 below. These were for a velocity of traverse of 1100 ft/sec. and glass windows that were simply supported. The convection frequency, Ω_{11} , was evaluated relative to the largest dimension.

TABLE 1 - RANGE FOR CONVECTION FREQUENCIES

	f_{11} c/s	Ω_{11} c/s	S
Large Glass Window 240" x 84" x $\frac{1}{2}$ "	8	27	3.5
Medium Window 36" x 24" x $\frac{1}{4}$ "	22	184	8.5
Small Window 10" x 8" x $\frac{1}{8}$ "	210	610	2.9

For this study S was varied from 1 to 8 and the period ratio τ/T was kept constant at unity, corresponding to the worst possible condition. Maintaining the period ratio constant and increasing S corresponds to a single 'N' wave striking the plate at different angles of incidence. It is convenient to make S = 1 equivalent to $\theta = 0^\circ$, then the other values computed S = 2, 4 and 8 are equivalent to $\theta = 60^\circ, 75^\circ$ and 83° respectively.

RESULTS

As it was difficult to make a clear estimate of the effect of each mode from overall response curves the generalised forces and responses were evaluated separately. Fig. 2 shows the generalised forces for the first 4 modes. Fig. 3 shows the generalised displacement which has been normalised by dividing by the maximum displacement for the (1, 1) mode only under a uniform unit static pressure.

i.e.
$$\bar{q} = q / \left(\frac{16}{\rho h \omega_{11}^2 \pi^2} \right)$$

The corresponding normalised velocities and accelerations are shown in Figs. 4 and 5. Here the first 3 modes are shown as the response in the 4th mode was usually too small. The overall responses at a point on the plate, which is susceptible to the first three modes, are shown on a

phase plane diagram in Fig. 6.

The variations of the generalised forces, with angle of incidence, for the respective modes are shown in Fig. 2. It appears to be at the lower values of S (or small angles of incidence) that the convection term will be of most importance as its duration is larger and consequently more energy will be imparted to the mode. It is interesting to note the manner in which the generalised forces for the (1, 2) and (1, 4) modes behave. The oscillating convection terms show up clearly at the beginning and end of the forcing function corresponding to the pulse moving on and off the plate. At the intermediate stage there is a constant negative term. As the angle of incidence increases the convection effects become shorter and the magnitude of the constant term diminishes.

Figs. 3, 4 and 5 compare each of the generalised displacements, velocities and accelerations with varying angles of incidence. As expected the contributions from the (1, 2) and (1, 3) modes for the velocities and accelerations are larger than they are for the displacements because of the lower rates of convergence.

A summary of the maximum values of the generalised coordinates is given in Table 2 below for $S = 2$ and $\nu = 0.02$. Although none of the stress time histories were computed the maximum generalised stress coefficients were estimated from the maximum generalised displacements using:-

$$\sigma_{x(m,n)} = (m^2 + \frac{\mu n^2}{\beta^2}) q_{(m,n)}$$

$$\sigma_{y(m,n)} = (\frac{n^2}{\beta^2} + \mu m^2) q_{(m,n)}$$

The maximum values for each of the modal parameters do not all occur at the same time, and the overall maximum at a point on the plate will only be obtained by summing the responses from all of the modes. Some overall response diagrams are shown on the phase plane ($x \sim \dot{x}$) and ($\dot{x} \sim \ddot{x}$) in Fig. 6. The effects of the higher modes are shown by a comparison with similar plots obtained by using only the fundamental mode.

The overall maximum values for different angles of incidence and damping factors are shown in Table 3. These converge to the values for normal incidence as θ increases.

TABLE 2 - MAX. VALUES $S = 2.0$, $\nu = 0.02$, $\tau/T = 1.0$

Parameter	Mode						
	(1,1)	(1,2)	% of (1,1)	(1,3)	% of (1,1)	(1,4)	% of (1,1)
\bar{q}	1.804	.306	17	.047	2.2	.015	.8
$\dot{\bar{q}}$	1.720	.571	33	.113	6.6	.072	4.2
$\ddot{\bar{q}}$	1.504	1.134	75	.463	31	.499	33
σ_x	2.000	.442	22	.094	4.7	.042	2.1
σ_y	1.253	.621	49.6	.200	16	.110	8.1

DISCUSSION

In the preceding sections it has been pointed out that the principal effects of travelling waves are that the generalised forces for the excited modes each have different time histories, and further asymmetric modes are brought into action which are not excited under normal incidence conditions. The computed results show that the asymmetric modes make a significant contribution to the overall response and therefore they will need to be considered when making similar response calculations, i.e. a single degree of freedom model involving the first mode only is insufficient. It is important to note that the effects of the convection frequencies considered are independent of the period ratio τ/T_1 ; and the results quoted here, primarily interpreted to understand the effect of an 'N' wave at oblique incidence, can be interpreted in their own right. Their importance would then depend upon whether or not the range of S used was significant for practical purposes. However, the range does cover the estimated values for plate glass windows shown in Table 1.

The influence of the oscillating convection forces for a particular mode may be important if a condition occurs where the frequency matches up with the natural frequency of the mode. It should be noted that as the convection frequencies are different it is possible for this isochronous condition to exist in more than one mode at the same time; and because of the larger number of cycles of the convection terms for the higher modes (c.f. Fig. 2a and Fig. 2d) their contributions will become increasingly important.

The trend of the maximum values shown in Table 3 differ somewhat

from those given in CHENG*, who assumed that the worst travelling condition occurred when S was equal to one, and only used the fundamental mode when evaluating the response. The worst possible case then occurred when the 'N' wave was at normal incidence. Table 3 shows that for a lightly damped system ($\nu \leq .02$) there is a maximum between $\theta = 0^\circ$ on $\pi/2$ (normal incidence) corresponding to $S = 2$. Apart from the contributions from the (1, 2) and (1, 3) modes there is possibly another reason for this. In ref. 1 it was shown that when the period ratio was about 1 then the amplification factor was strongly dependent upon the rise time, and the maximum occurred when the rise time was $\frac{1}{4}$ of the fundamental period. For the travelling wave although the peak value of the generalised force for $S = 2$ is less than it is for normal incidence when $S = \infty$ (Fig. 2a) the rise time is about $\frac{1}{4}$ of the fundamental period, and this is probably the dominant effect.

CONCLUSIONS

A simple computer orientated method has been presented for determining the response of plates to travelling waves. The method has been applied to evaluating the effects of 'N' waves at oblique incidence on a simply-supported plate and the contributions made by the asymmetric modes. The results show that the generalised forces are considerably modified by oblique incidence loading. The contributions from the asymmetric modes vary with the response parameter, i.e. displacement, velocity or acceleration and a convection frequency term given by $\frac{\pi V}{L}$ and in the range of convection frequencies considered, which were practical values, the contributions were significant especially for the accelerations.

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2. HILDEBRAND, F.B. Introduction to Numerical Analysis (p. 82) McGraw Hill 1956.

*Unpublished work submitted by D. H. Cheng, City College of the City University of New York, prepared during temporary assignment at NASA Langley Research Center.

TABLE 3 - VARIATION OF MAXIMUM VALUES OF RESPONSE WITH S AND DAMPING FACTOR ν at $(\frac{x}{a} = 0.25)$ $(\frac{y}{b} = 0.5)$

parameter \ S	1	2	4	8
\bar{w}	.9991	1.166	1.215	1.232
$\dot{\bar{w}}$.7835	.8373	.8319	.99356
$\ddot{\bar{w}}$.9840	1.26	1.439	1.570
	$\nu = 0.2$			

parameter \ S	1	2	4	8
\bar{w}	1.773	1.992	1.961	1.925
$\dot{\bar{w}}$	1.508	1.577	1.477	1.760
$\ddot{\bar{w}}$	2.131	2.578	2.258	2.134
	$\nu = 0.02$			

parameter \ S	1	2	4	8
\bar{w}	1.910	2.138	2.087	2.036
$\dot{\bar{w}}$	1.635	1.706	1.591	1.910
$\ddot{\bar{w}}$	2.438	2.900	2.407	2.191
	$\nu = 0.002$			

parameter \ S	1	2	4	8
\bar{w}	1.925	2.153	2.101	2.048
$\dot{\bar{w}}$	1.649	1.720	1.603	1.927
$\ddot{\bar{w}}$	2.472	2.941	2.423	2.196
	$\nu = 0.0002$			

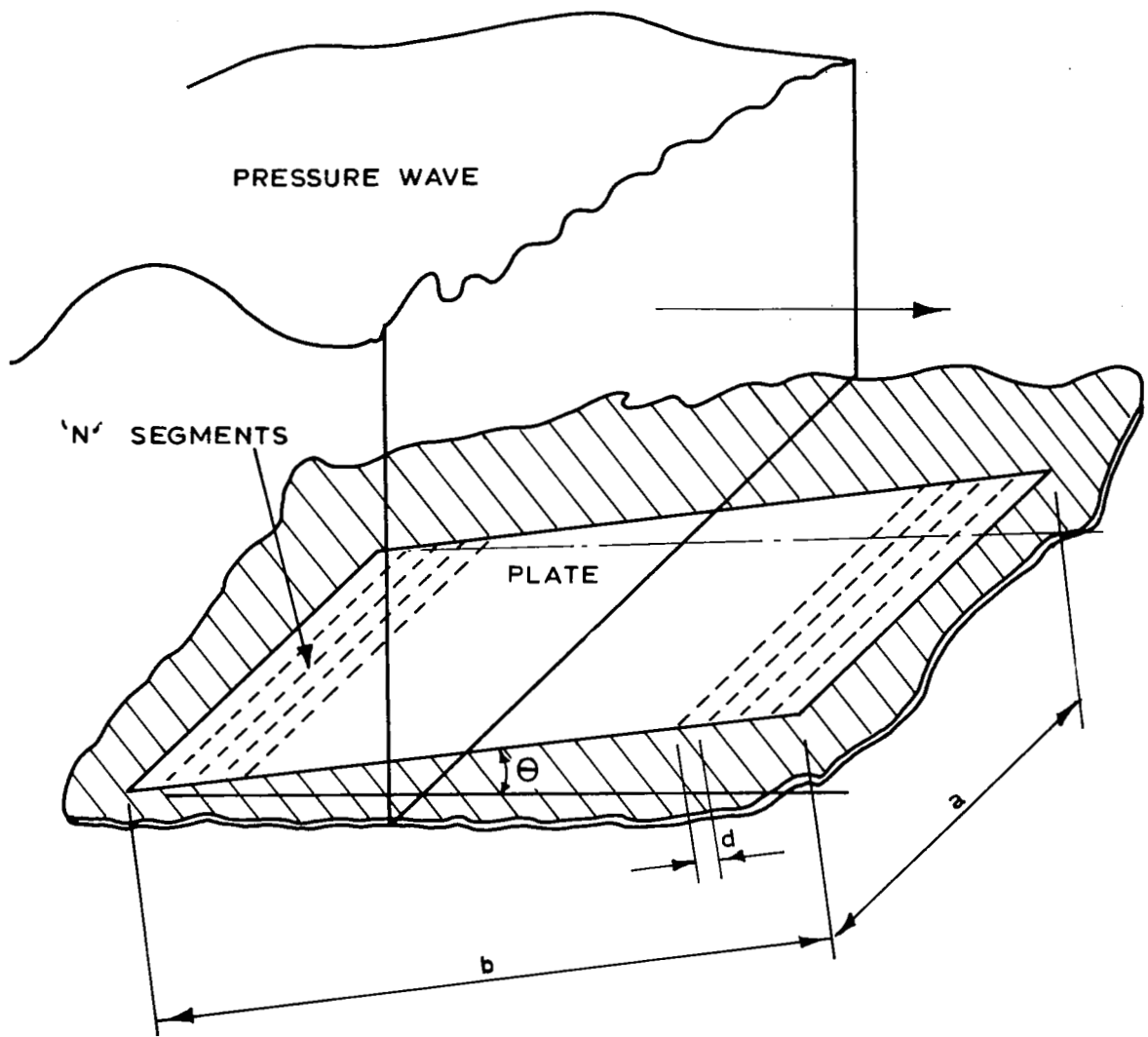


Fig.1 Plate loaded by travelling wave

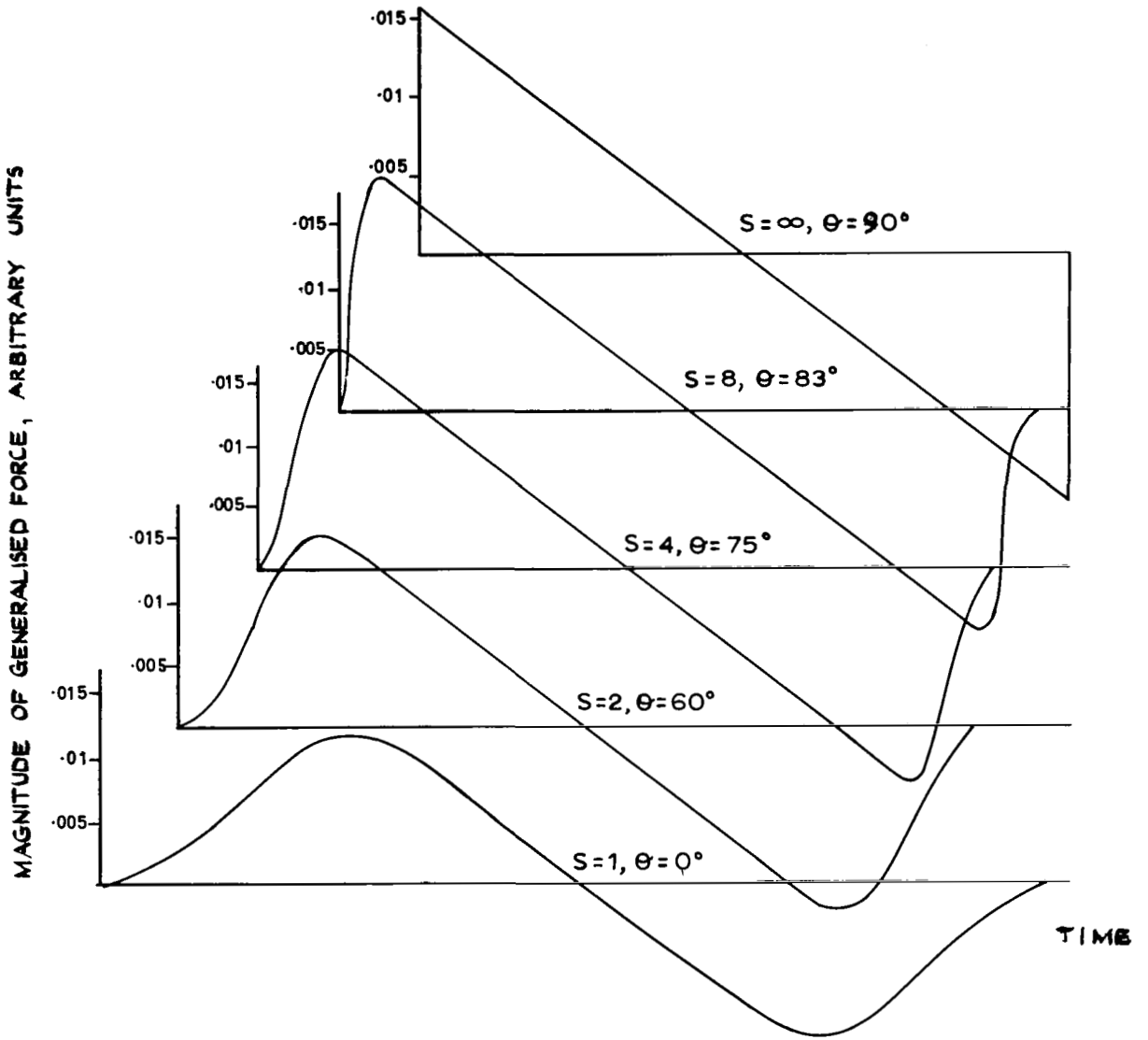


Fig. 2a Variation of generalised force for (1,1) mode with different angles of incidence.

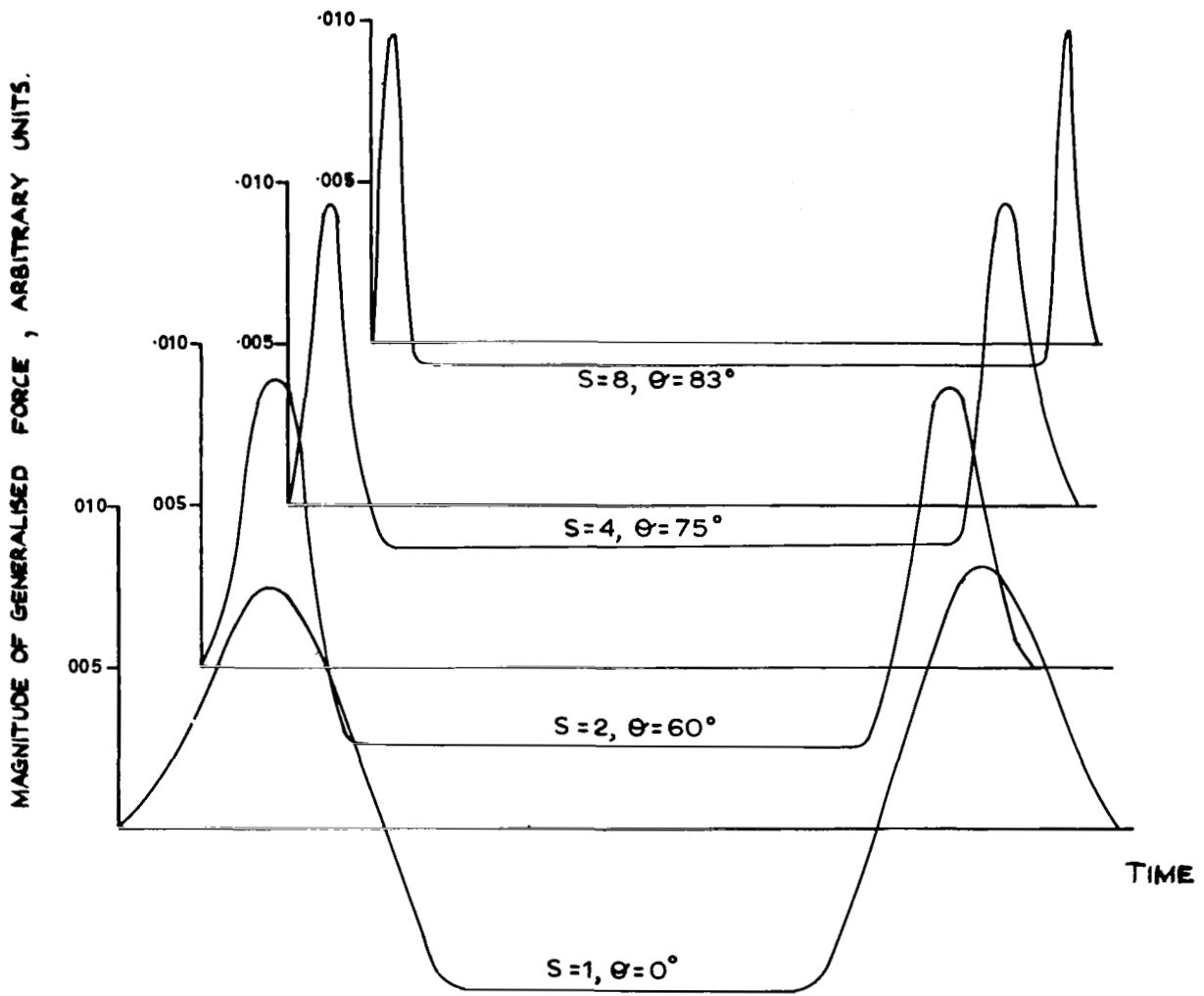


Fig. 2b Variation of generalised force for (1,2) mode with different angles of incidence.

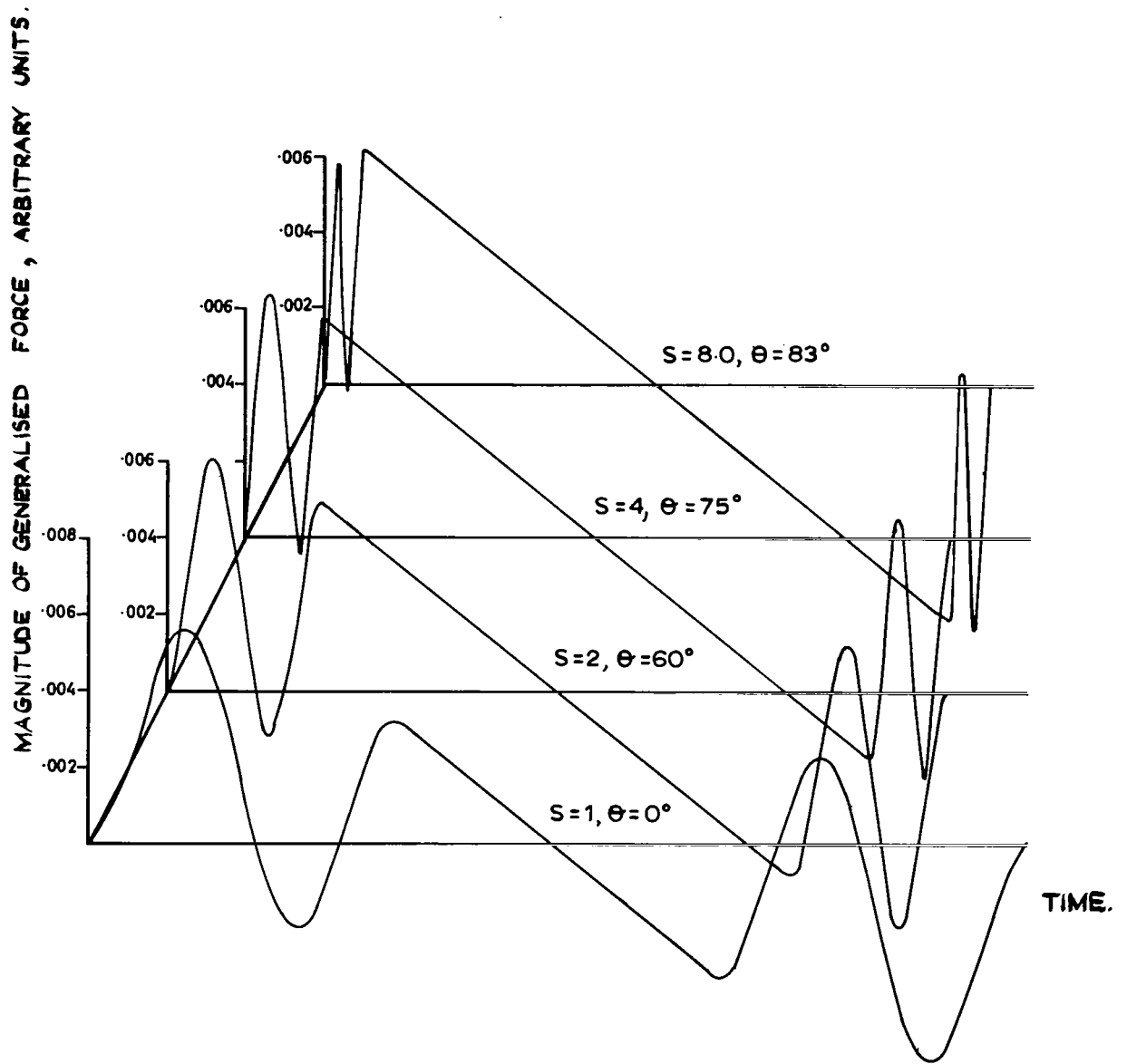


Fig. 2c. Variation of the generalised force for the (1,3) mode, with angle of incidence.

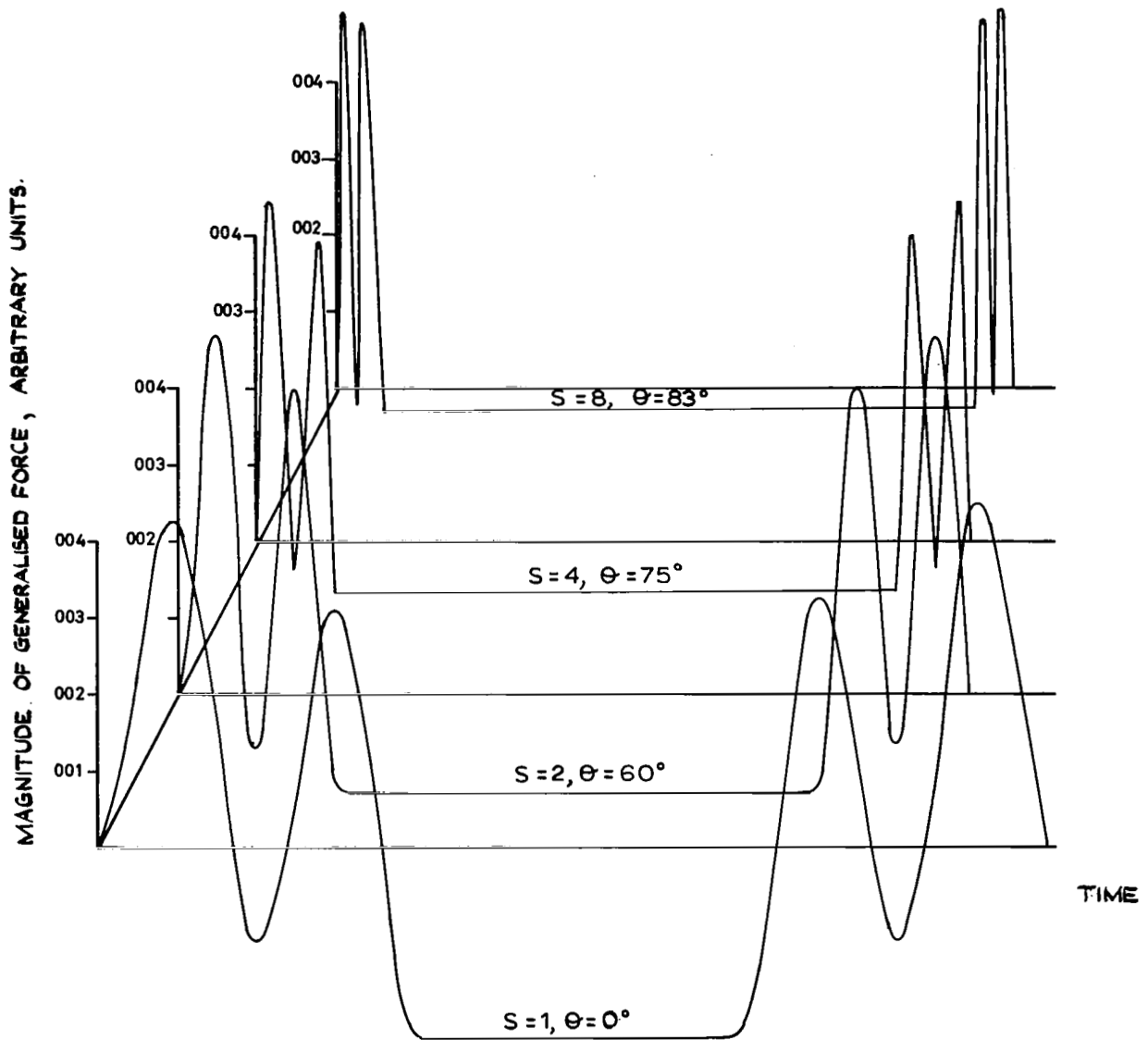


Fig. 2d. Variation of the generalised force for the (1,4) mode with angle of incidence.

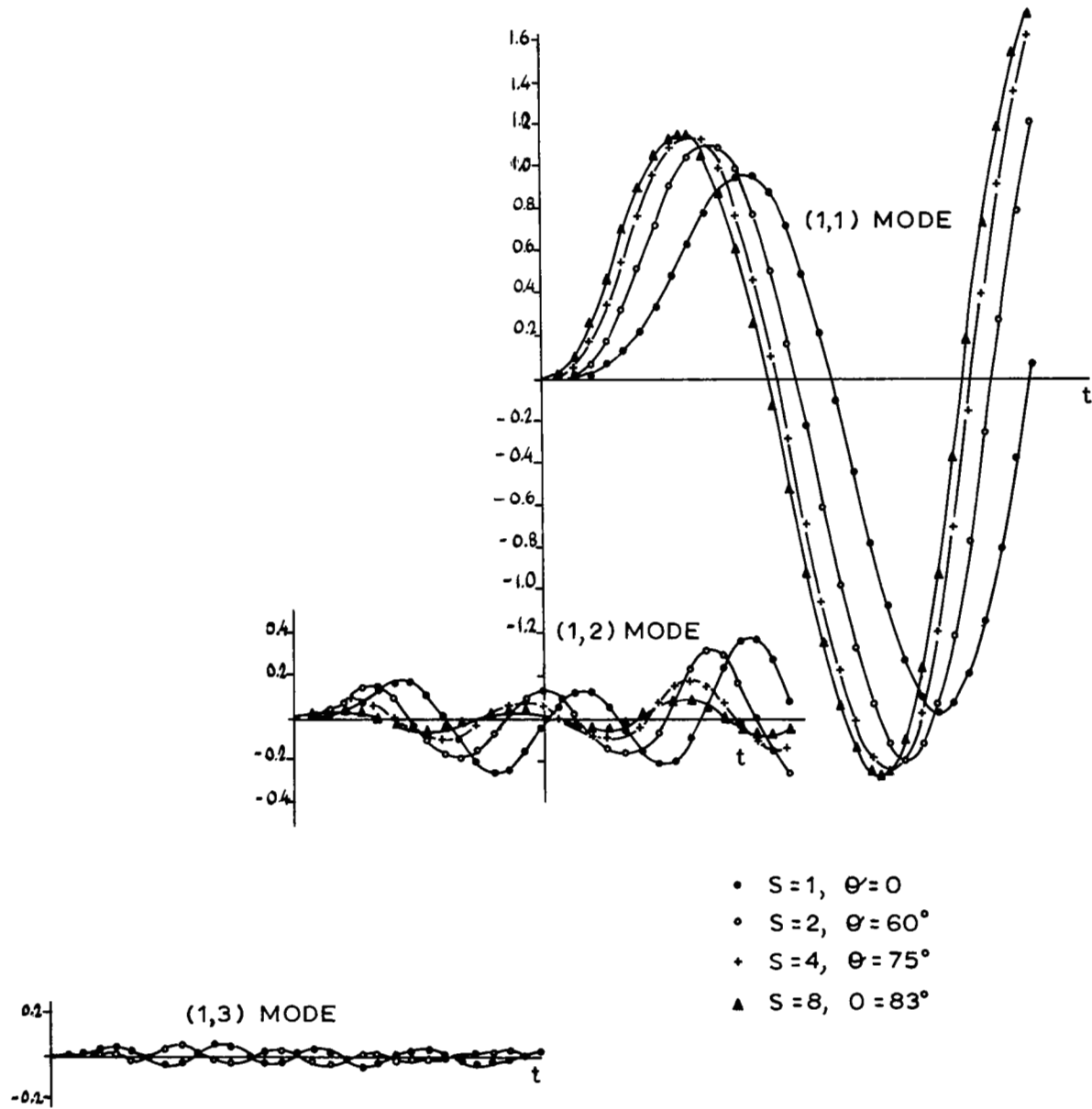


Fig. 3 Generalised displacements, \bar{q}

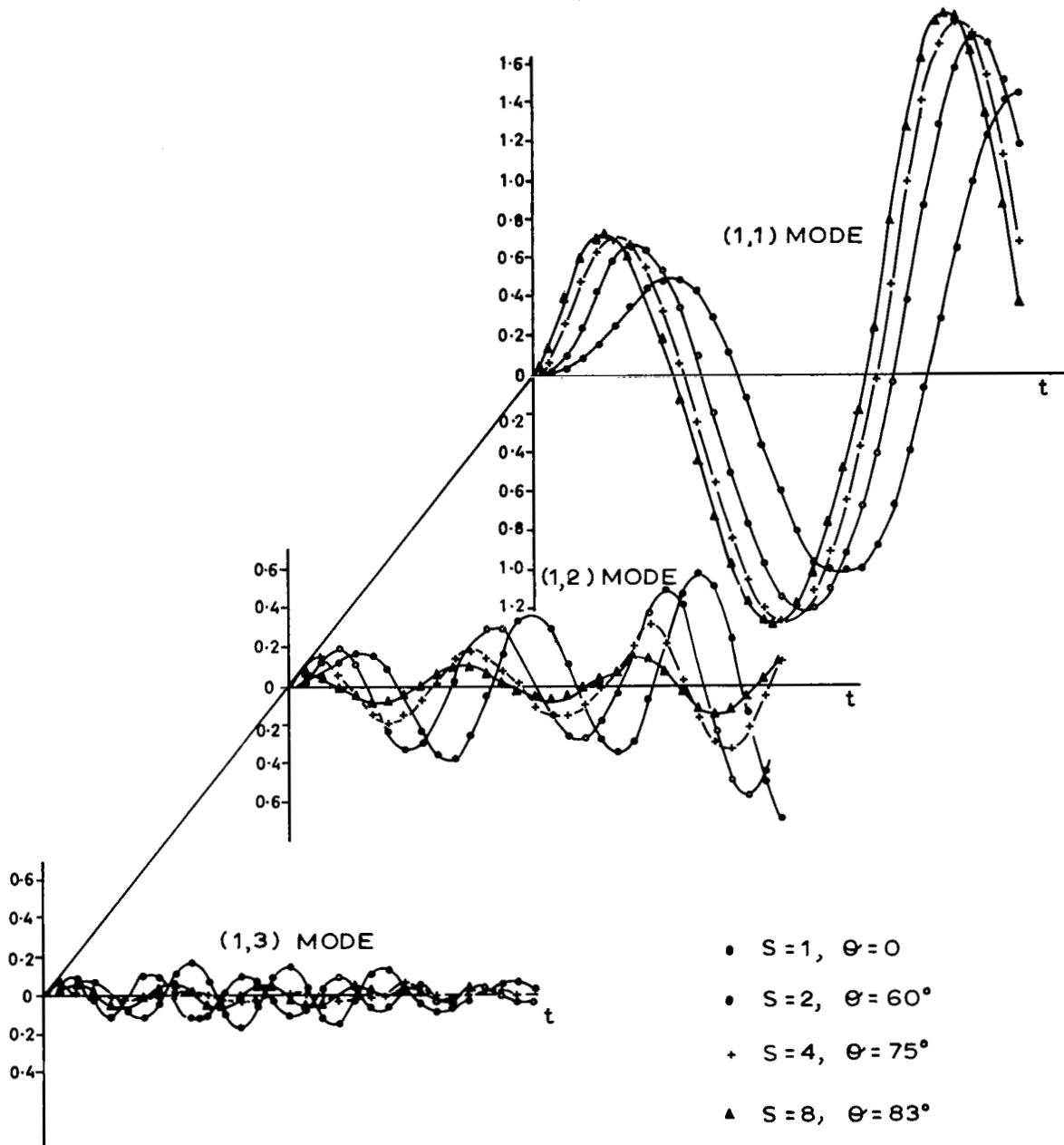


Fig.4 Generalised velocities, \bar{q}_j

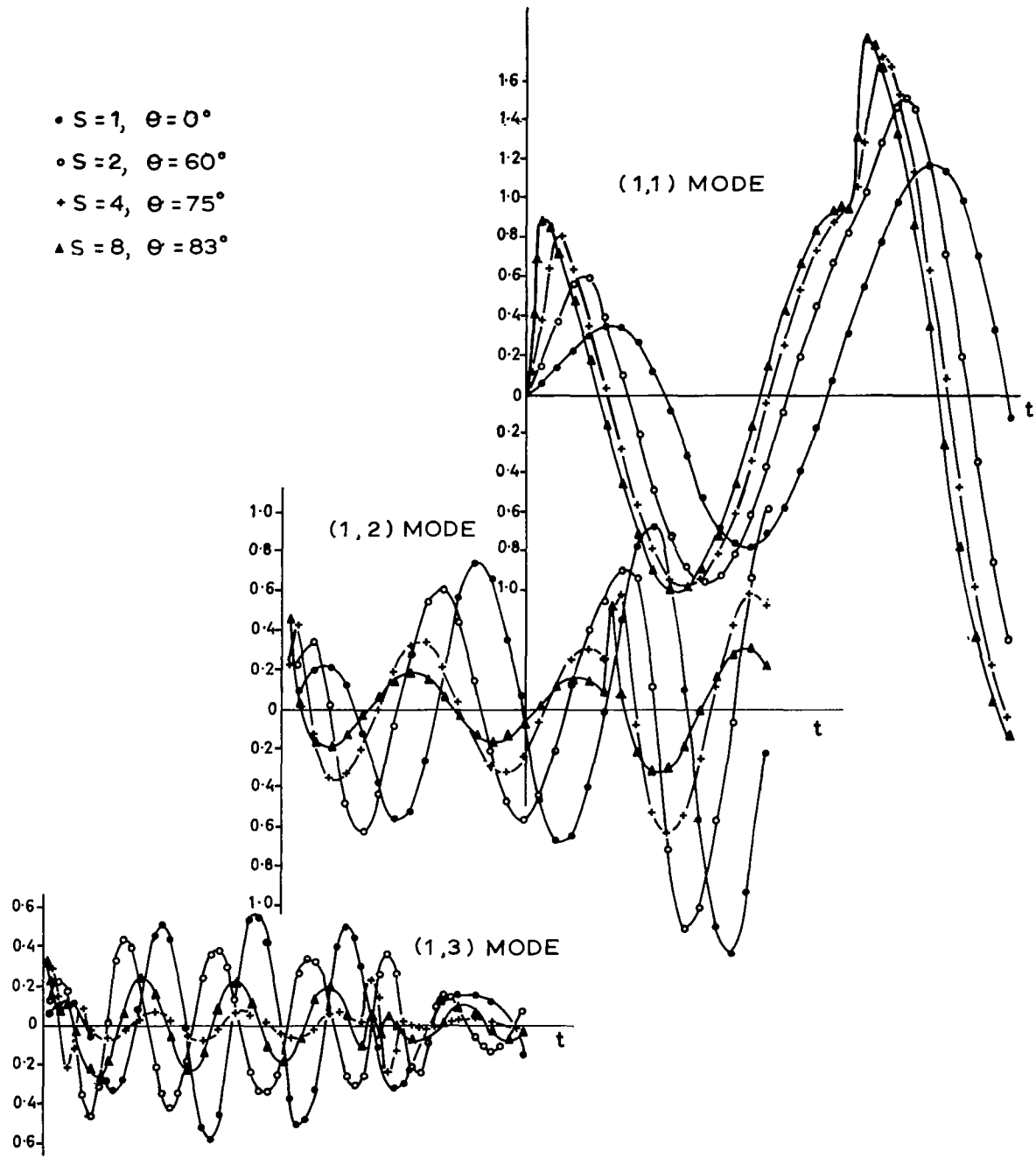


Fig.5 Generalised accelerations. \ddot{q}

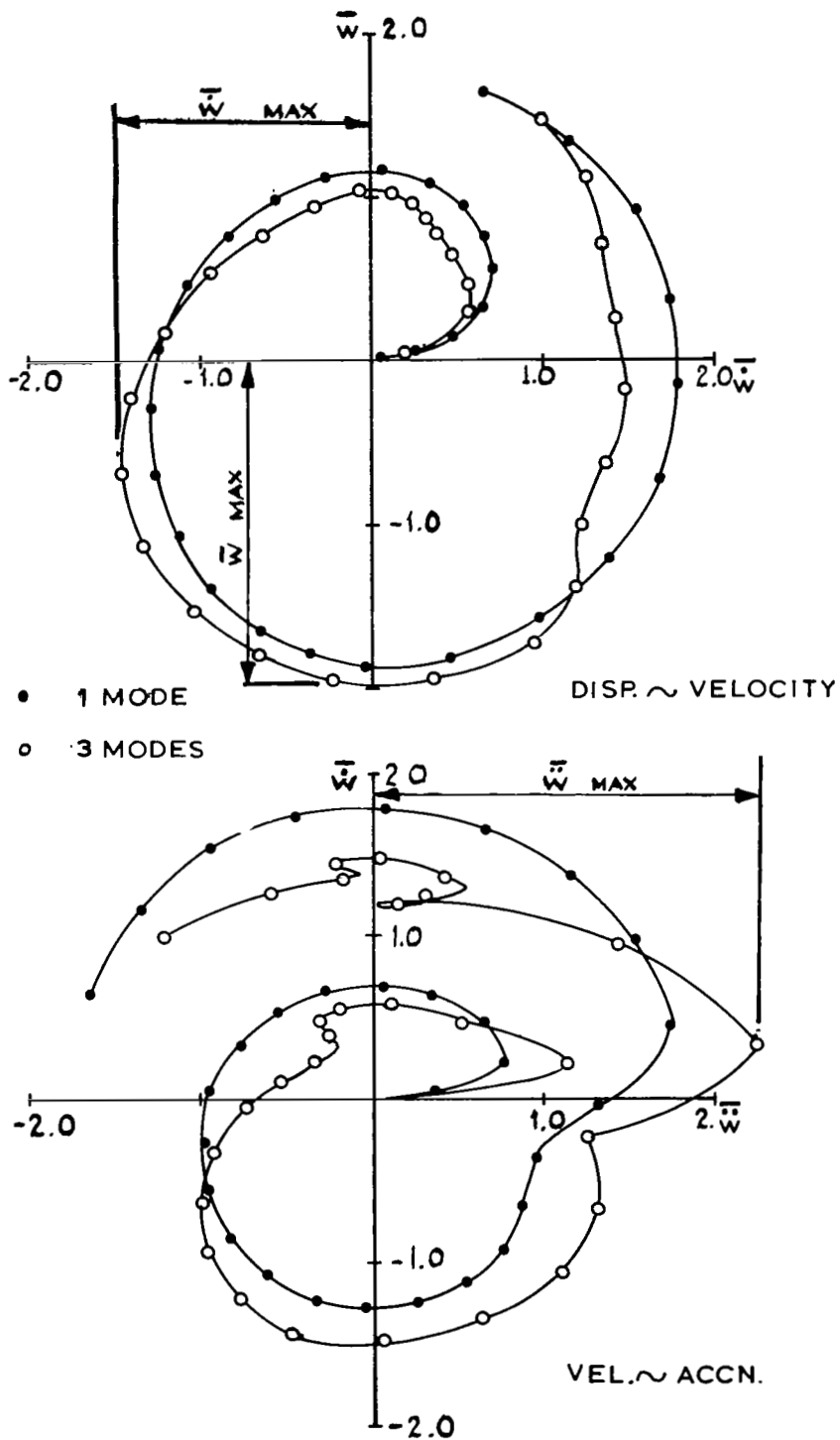


Fig.6 Phase plane diagrams. Response to 'N' wave at $x/a = 0.5$ $y/b = 0.25$ $c/t = 1.0$ $S = 4.0$

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