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DYNAMICS AND COMPUTER AIDED DESIGN OF TENNIS RACKET

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ABSTRACT

As a step toward the goal, i.e., the establishment of racket dynamics and the proposal of an improved evaluation system for optimum design, the effects of the support conditions of grip and the gut strings on the dynamic characteristics of the two different type of rackets are investigated using experimental modal analysis. The results show that the damping ratio and the decay rate of each mode are much greater and the damping of each mode scatteres wider under the grip constraint condition than those of free-support, and also show that the gut strings contribute very little to the modal parameters within the frequency ranges of 600 Hz, in which no membrain modes appear, but the damping is very small relative to the time during the ball/racket impact and the acceleration is large even in high-frequency modes. Accordingly, it may be safely assumed that the higher modes and the magnitude of acceleration are responsible for the stability of hitting surface.

INTRODUCTION

There are a number of unclarified points regarding optimum design of tennis racket, although some sophisticated books(1) on science of tennis have been published and several studies(2)(3) on modal analysis of tennis racket have been reported. The present study aims at the more realistic dynamic identification of the racket on the basis of the idea that the dynamics of racket is consisted of the dynamics of structure with frame and gut strings, the kinetics of rigid body by an arm swing given at a grip as a boundary condition, and an ball/racket impact as an input force. In this report, the effects of the support conditions of grip and the gut strings on the dynamic characteristics of the racket are investigated, and dynamic behavior of the two different type of rackets which have appeared lately in the market, is compared with each other using experimental modal analysis, as a first step toward the goal, i.e., the establishment of racket dynamics and the proposal of an improved evaluation system for optimum design.

EXPERIMENTAL MODAL ANALYSIS SYSTEM

Figure 1 shows a schematic diagram of the measuring and analysing system, where the transmitted transfer function data from a personal computer are processed in a host computer using modal analysis(4), the curve-fitted data being transmitted to the personal computer again for the evaluation of racket characteristics .

SPESIFICATIONS OF TENNIS RACKETS AND DYNAMICS AS A RIGID BODY

The two representative rackets used in this study are illustrated in Fig.2(a). On the left is a standard mid-size racket(RACKET A, 3.53 N weight) made of fiberglass, graphite, celamic and kevlar, while on the right is a racket(RACKET B, 3.63 N weight) made of carbon graphite with a frame thickness 1.5 times that of the standard (RACKET A) in the hitting direction, which is

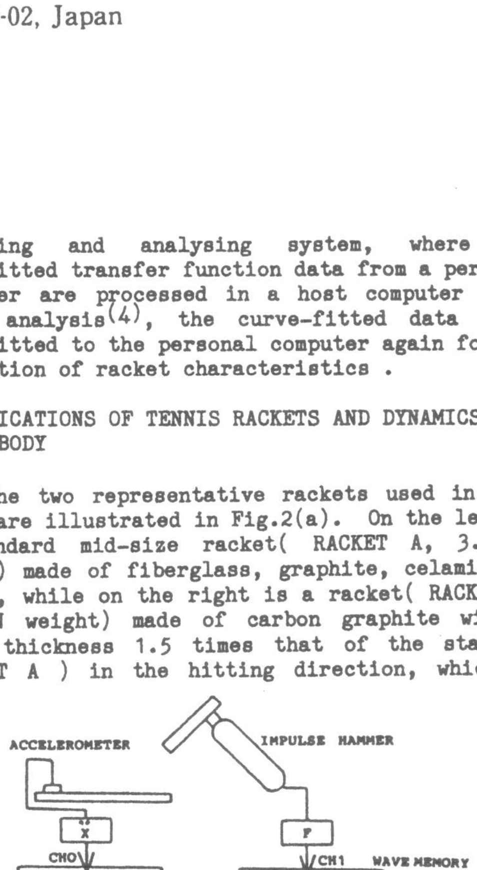


Fig.1 Schematic diagram of the measuring and analysing system used in the study.

called a thick racket. Both rackets are of 680 mm in total length and 626 cm^2 in head size and 246 N(55 lb) in strings tension. The figure in the midst shows the location of the center of mass and the measured dynamic characteristics of each racket as a rigid body, i.e., the center of purcussion of the body for a fixed point on the grip , for which there will be no reaction at the fixed point in the direction of impact force. This presents a relationship between the support position on the grip and the center of purcussion in the gut face (an optimum impact point for a grip position as a rigid body). Fig.2(b) demonstrates the gut face of RACKET B after a play, which was painted with ink previously to observe the player's hitting area in practice. It is seen that this hitting area coincides with the above optimum impact area which is slightly down from the geometrical center of the gut face.

EXPERIMENTAL MODAL ANALYSIS OF TENNIS RACKET

Experimental Methods

A free condition is achieved by supporting the racket on soft sponges, while a constraint condition is achieved by fixing a grip wrapped with a soft sponge around at a position(56 - 84 mm from the grip end) with a vice. An accelerometer is located at one of the divides of racket throat. The frequency resolution of the analysis is 4.8 Hz.

Results of Modal Test

Figs.3 show the natural frequency and its simplified mode shape, the average damping ratio of each mode and its decay rate when the gut strings have been hitted under the various test conditions. The detailed mode shape and the amount of scatter of damping ratio are illustrated in Fig.4 and Fig.5, respectively. In Figs.6 are shown the comparison of magnitude of each mode with respect to the displacement(a) and the acceleration(b). The node line and the magnitude of each mode could be investigated from Fig.4 and Fig.6, and the damping characteristics from Fig.3 and Fig.5.

The Effects of Grip Support Condition on Modal Parameters

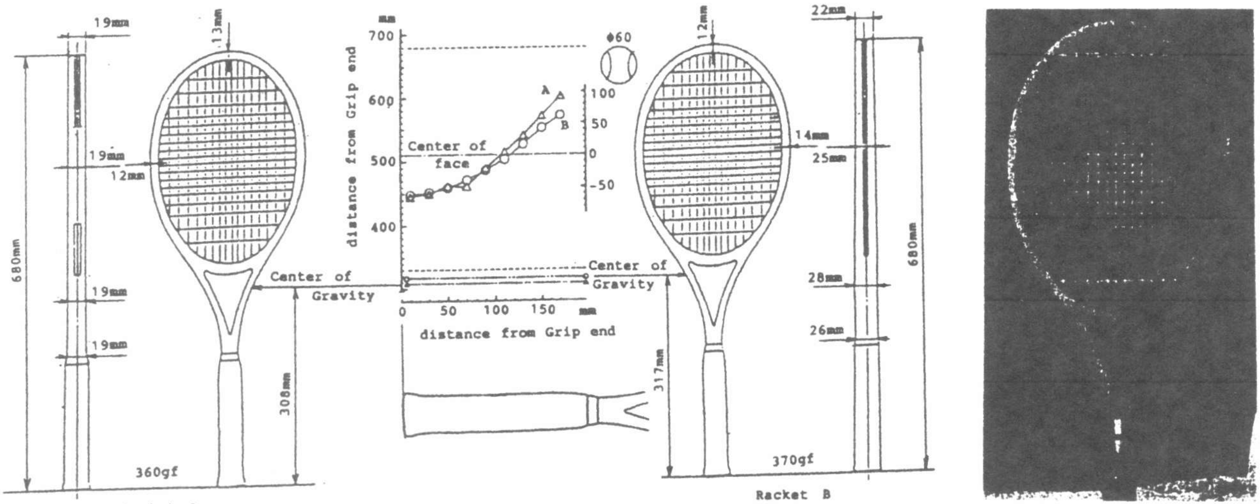
Let us briefly examine some of the features of the results of freely-supported rackets compareing with those of grip constraint. The 1st resonance frequency 122 Hz of RACKET A is a bending mode with two nodes, one at 0.20L(136 mm, L=680 mm) from the grip end and the other on the head face, resembling to the 3rd mode 122 Hz of grip constraint. The damping ratio 0.007, however,is under 30 % of grip constraint. The 2nd frequency 337 Hz is the 2nd bending mode with three nodes, one at 0.13L(88 mm) and the other two on the head face, resembling to the 4th mode 347 Hz of grip constraint. The damping ratio 0.006 is about 30 % of grip constraint. The 3rd frequency 366 Hz is the tortional mode with two nodes, resembling to the 5th mode 396 Hz of grip constraint. The damping ratio 0.009 is about 30 %. The 4th frequency 576 Hz is the 1st membrane mode. The 5th mode is a bending with 4 nodes, and the 6th mode is a combination of tortional and bending.

The node on the grip of the 1st resonance 215 Hz of freely-supported RACKET B is located at 0.30L(204 mm) from grip end, and the displacement of the grip end is large. The damping ratio 0.002 is about 10 % of grip constraint. The 2nd frequency 508 Hz is a tortional mode with two nodes. The damping ratio 0.006 is 50 % of grip constraint. The 3rd frequency 562 Hz is the 2nd bending mode with 3 nodes, one at 0.19L(129 mm) on the grip and the other two on the head face. The damping ratio 0.002 is 10 % of grip constraint. The damping ratio of the 4th mode 635 Hz(membrane mode)is also 0.002, which is very small.

Figure 5 shows that the damping ratio of each mode under the grip constraint varies more widely than that of free-support, and the scatter of tortional modes is larger than that of bending.

The Effects of Gut Strings on Modal Parameters

It is shown from the comparison of the modal parameters of a racket frame without strings to



(a)

(b)

Fig.2 Rackets used in the study.

(a) Specifications and dynamic characteristics as a rigid body.

(b) Gut face showing a hitting area after a play.

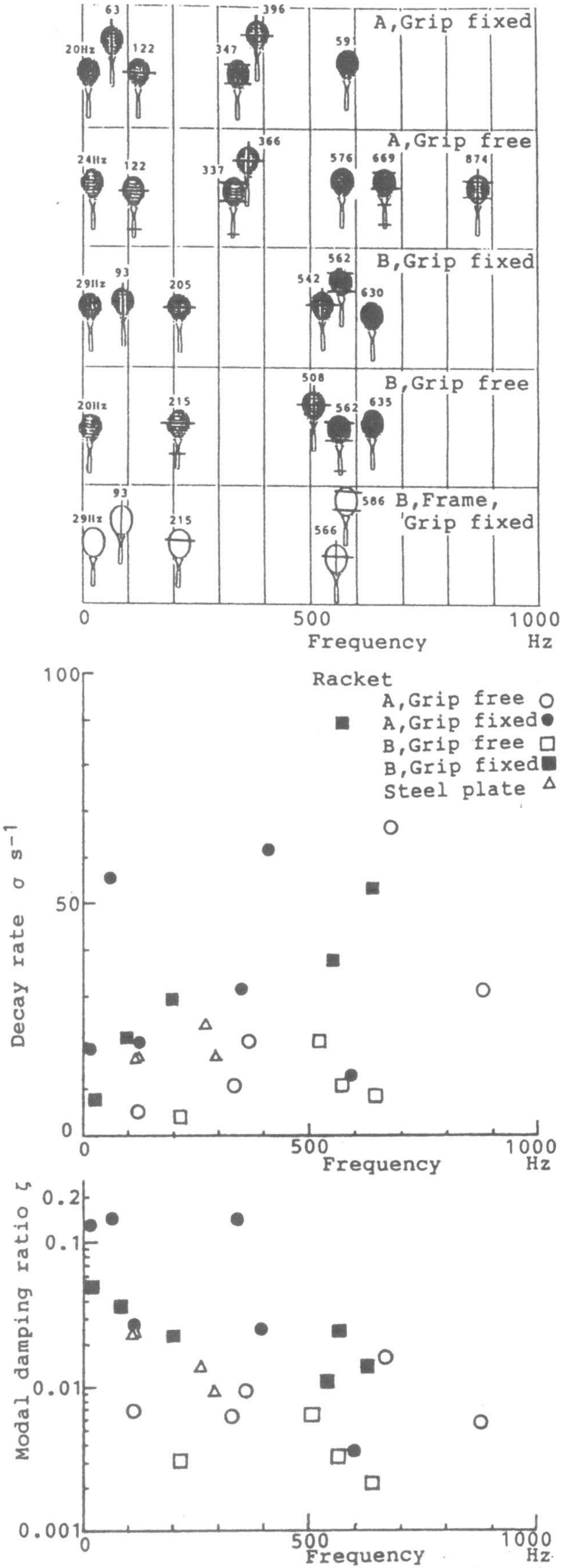


Fig.3 Simplified mode shape corresponding to each natural frequency, the average damping ratio, and the average decay rate of each mode under the various test conditions.

those of one with gut strings under the constraint condition of RACKET B (Fig.3 and Fig.6) that each mode without strings is almost the same as that with strings, and each frequency without strings is slightly higher than that with strings. Figs. 5(d) and 5(e) show that when the frame is hitted, the gut strings has a minor influence on the damping ratio of each mode .

Dynamic Behavior of the Two Different Type of Rackets

It is seen from the comparison that each mode shape of RACKET B is almost the same as that of RACKET A, but the frequency of each mode is 1.4(tortional mode) to 1.8 times (bending mode) that of RACKET A. Although the displacement of RACKET B is smaller, the acceleration is larger than that of RACKET A (Fig.6). Further, RACKET B and RACKET A are reversed in order of modes concerning the 2nd and the 3rd.

According to the manufacturer's catalogue, it seems that the thick racket(RACKET B) has increased its frequency and decay rate up to about double those of standard racket with respect to the 3rd mode of grip constraint in order to make the frequency coincide with the period during the ball/racket impact. Nevertheless, according to Fig.3, the damping ratio of each mode of RACKET B compared to RACKET A is 0.002 to 0.007 with 1st mode, 0.006 with 2nd(tortional mode, the same), and 0.002 to 0.009, indicating that the damping of RACKET B is far less than that of RACKET A. Interestingly enough, however, the decay rates of the same mode of the two quite different type of rackets are the same. The decay rates of the 1st through 3rd mode are 5, 10, and 20 1/s, respectively, which are very small relative to the contact time during the ball/racket impact (about 0.004 s with a high speed video). Accordingly, it may be safely assumed that even the higher modes do not die down during impact.

Figs.7 are the prediction of excited modes of RACKET A and RACKET B when a player hits the ball, on the left being the displacement mode and on the right the acceleration mode. Fig.7(a) is the summation of amplitude of the modes which have no nodal lines around the center of the gut face. This would presumably indicate the mode when the ball hits nearly the center of the face, so to speak the experienced player's mode, while Fig.7 (b) is the summation of amplitude of the modes which have nodal lines near the center, presumably indicating the mode when the ball misses the center of the face, so to speak the beginner's mode.

As is commonly believed, if the definition of sweet area would be the area where the displacement is very small, RACKET B surely gives a quite wider area. However, RACKET B gives a larger acceleration. In addition to this, from the author's feeling, it would seem that the acceleration modes are also responsible for the stable hitting surface area or sweet area.

Key to Optimum Design of Tennis Racket

In addition to the dynamic balance as a rigid body, i.e., the relationship between the support position and the center of purcussion of the body, the magnitudes of displacement and accleration and the decay rate relative to the time during the impact with a freely-supported racket should be evaluated. It is hoped that the

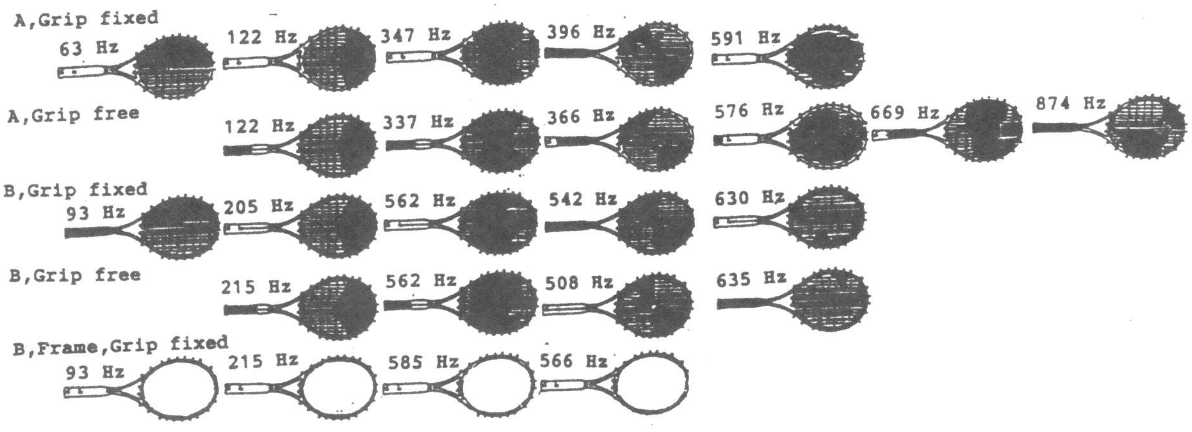
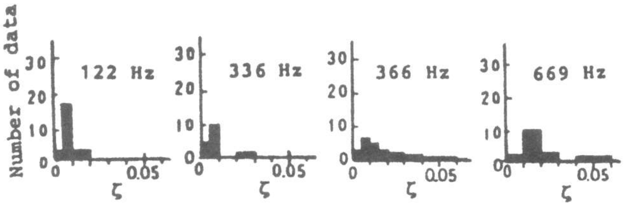
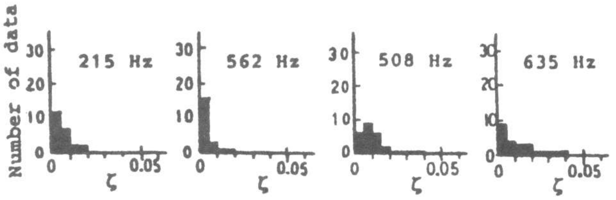


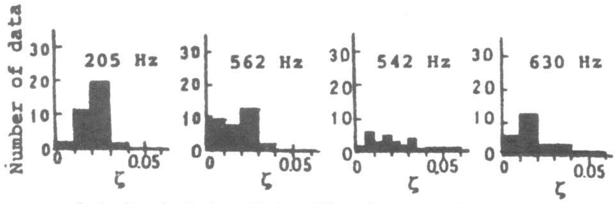
Fig.4 Detailed mode shape under the various test conditions.



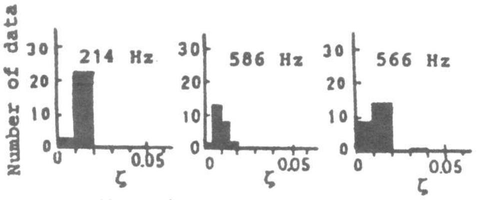
(a) Racket A, Grip free, Gut impact



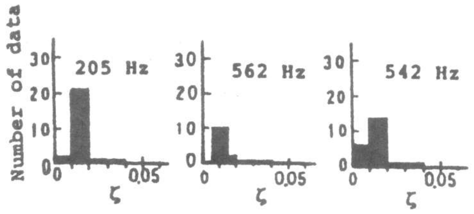
(b) Racket B, Grip free, Gut impact



(c) Racket B, Grip fixed, Gut impact



(d) Racket B Frame, Grip fixed



(e) Racket B, Grip fixed, Frame impact

Fig.5 Scatter of damping ratio of each mode under the various test conditions.

optimum design method for structural dynamic modification of racket might be established on the basis of the idea that the target vibration mode could be reduced by making its node coincide with the hitting area.

This study will lead to developing techniques to evaluate accurately the dynamics of tennis racket.

CONCLUSIONS

As a step toward the goal, i.e., the establishment of racket dynamics and the proposal of an improved evaluation system for optimum design, the effects of the support conditions of grip and the gut strings on the dynamic characteristics of the rackets are investigated using experimental modal analysis. The results show that the damping ratio and the decay rate of each mode are much greater and the damping of each mode scatteres wider under the grip constraint condition than those of free-support, and also show that the gut strings contribute very little to the modal parameters within the frequency ranges of 600 Hz, in which no membrain modes appear, but the damping is very small relative to the time during the ball/racket impact and the acceleration is large even in high-frequency modes. Accordingly, it may be safely assumed that the higher modes and the magnitude of acceleration are responsible for the stability of hitting surface.

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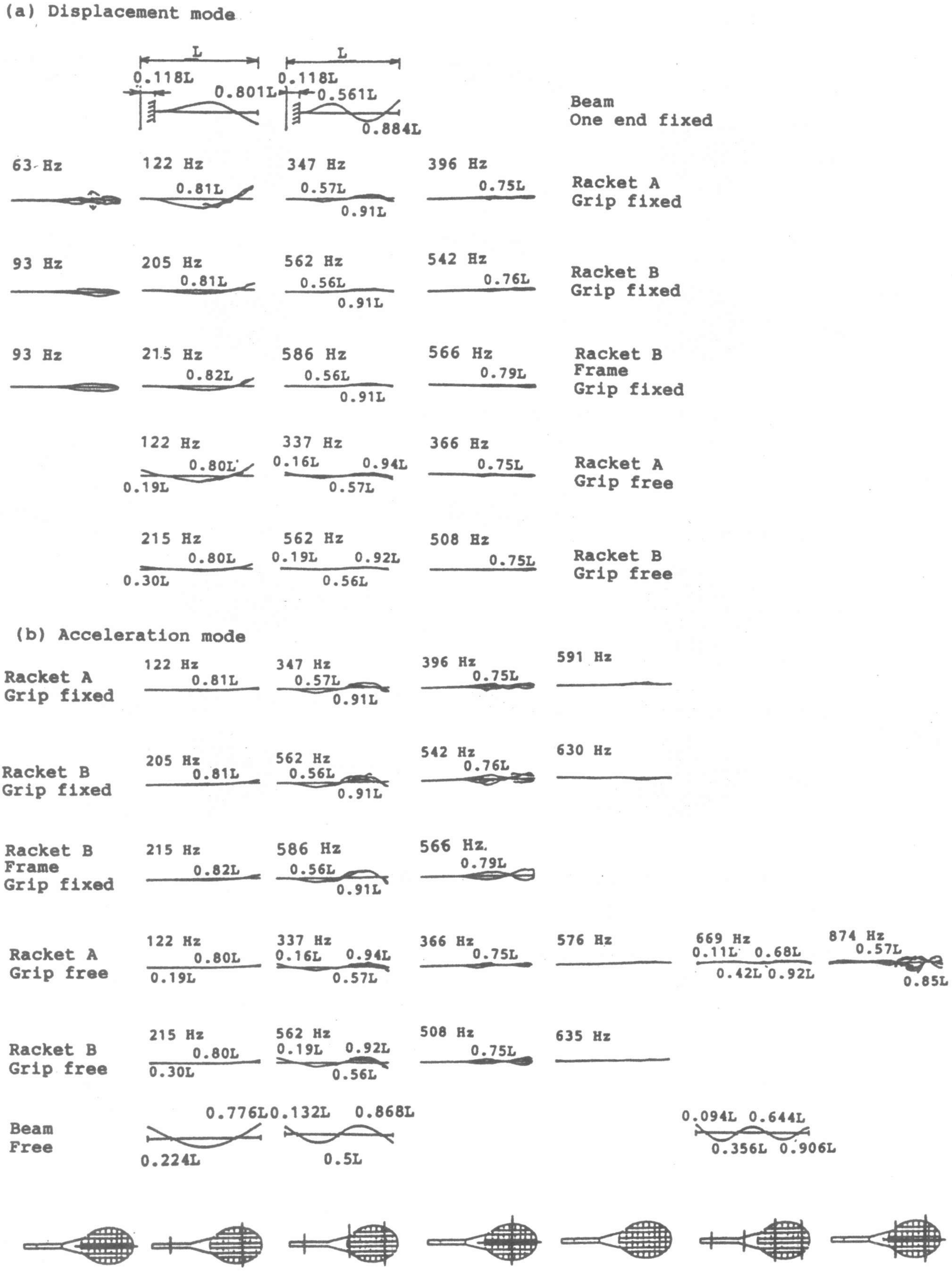
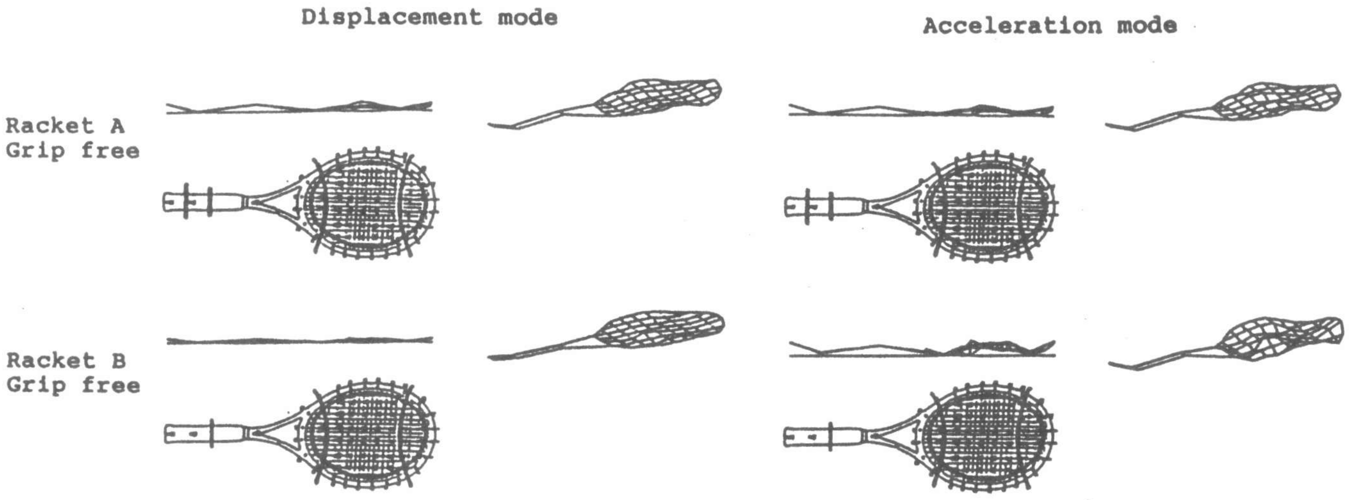
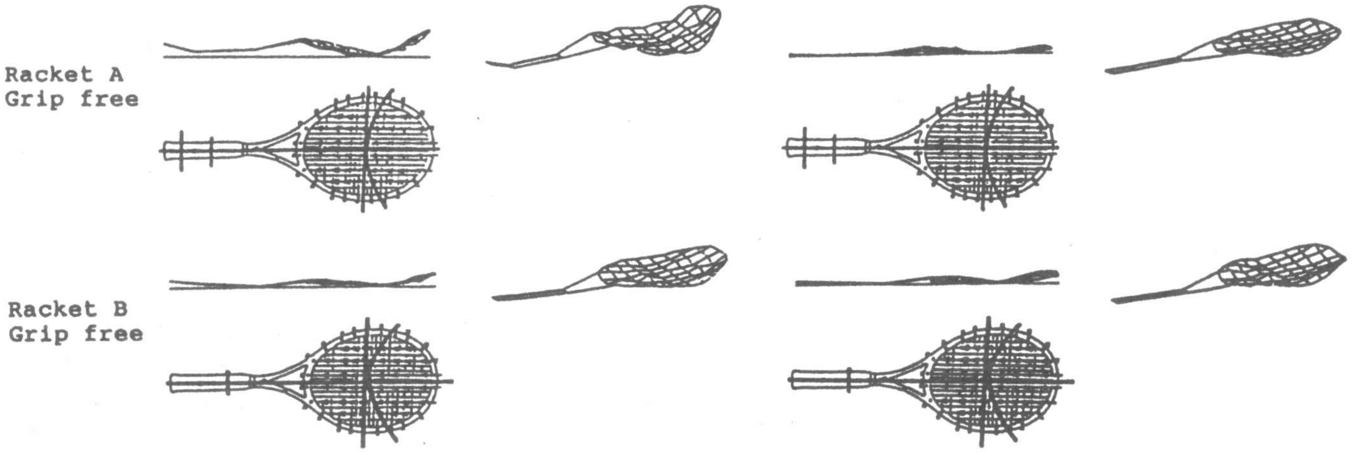


Fig.6 Magnitude and node point of mode shape under the various test conditions.
(a):displacement, (b):acceleration.



(a) when the ball hits nearly the center of the gut face



(b) when the ball misses the center of the gut face

Fig.7 Prediction of excited modes when a player hits a ball.