SOME NEW METHODS OF DAMPING IMPACT-INDUCED VIBRATIONS IN BADMINTON RACQUETS

V Kralovic Department of Aeronautical and Automotive Engineering
VV Krylov Loughborough University,
Loughborough, Leicestershire, LE11 3TU, UK

1 INTRODUCTION

Resonant vibrations of tennis and badminton racquets induced by impact forces in the course of the game have a profound effect on the performance of players[1-3]. According to the investigations of Brody et al[1], most of the impact energy is absorbed by the handle. It is further transmitted to the arm, which can cause permanent arm problems. Therefore the need to attenuate resonant vibrations raised the interest in various damping treatments in manufacturing of modern tennis and badminton racquets in order to lessen the handle's task. A badminton racquet, in particular, is a complex dynamic system that involves a whole range of innovations. Most of them have been first applied in the production of modern tennis racquets.

In the present paper we introduce and examine experimentally some new methods of suppression of resonant flexural vibrations in badminton racquets. Generally, the reduction of vibrations in a badminton racquet can be achieved via modifications of the elastic and damping properties of the racquet head (e.g. stiffer materials), net (e.g. lowering string tension), and shaft and handle (e.g. the so-called "smart grip")[2]. In this paper we focus on the modifications of the shaft only. The paper is divided into sections according to the methods used.

It is well known that applications of additional damping materials may have a significant effect on the behaviour of vibrating structures. They can be either attached to the surface or inserted (injected) into cavities. In order to decrease weight the shafts of badminton racquets are usually manufactured as hollow tubes. A narrow space inside tubes can be easily filled with granular materials (e.g. sand), bitumen-like materials or even reologic liquids. Indeed, all these substances have a significant impact on the frequency responses, as it will be shown in Section 3.1.

Moreover, adhesive bitumen-like materials or elastic tapes of various loss factors can be attached to the external surface of the shaft. Partial and full coverage of the shaft by such damping layers has been studied as well. A noticeable suppression of resonant peaks has been obtained in the case of full coverage, whereas a partial coverage had a minor effect.

On a design stage, a new badminton racquet could be modified also according to some special principles of vibration damping. One of such recently proposed methods is based on the acoustic 'black hole' effect that can take place for flexural waves propagating in plates or rods of power-law profile[4-9]. In this regard, shafts of various profiles have been manufactured and their response to dynamic loading investigated. The measured cross mobilities show a significant damping in racquets having the shaft tapered according to a power-law relationship between the local radius of the shaft $r(x)$ and the distance from the end x. In this case the sharp end of a shaft represents a one-dimensional acoustic black hole for flexural waves. Ideally, such ends provide zero reflections.

From the point of view of using different materials, a badminton racquet implements many types of materials. In particular, soft wood used in the handles has a partial damping effect[10]. Aluminium racquets are still in production. They are light and easy to manufacture. Graphite / epoxy frames have absorbing materials already fabricated into them[1]. Carbon composite materials, such as carbon nanotubes[11], are currently used in production of high-end racquets, stiffening the shaft and the head. Although the size and shape of badminton racquets have not changed much over the last years, some modern racquets implement the techniques adapted from tennis technology: smart grip, vibration filters, etc. Such methods are not examined in this paper. Attention is paid only to the application of the aforementioned novel treatments that are applied to the existing badminton racquets.

2 EXPERIMENTAL SET-UP

In order to quantify the effect of various damping treatments, measurements of cross mobility have been carried out in a wide frequency range (0- 6 kHz or sometimes 0-12 kHz) for the most important impact and perception areas. These areas of interest are the sweet, the throat, the side, the tip in the net zone, plus the throat and tip areas in the frame of the head of the badminton racquet. For simplicity, all of the measured Frequency Response Functions (FRFs) in this paper relate to the case of impact in the throat area of the frame (this also eliminates the noise from the net to make the measured cross mobilities more reliable).

The experimental set-up used for the investigation of damping of flexural vibrations in badminton racquets (Figure 1) consisted of an electromagnetic shaker, accelerometer, force transducer, spectrum analyser, power amplifier and various supports. Experiments were carried out within the Noise and Vibration Laboratory of the Aeronautical and Automotive Engineering Department at Loughborough University.

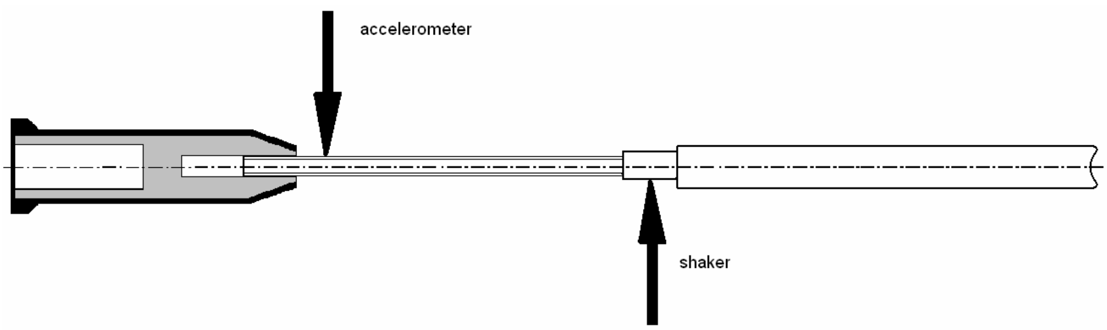

Figure 1. Measurement set-up. The position of the accelerometer was at 70 mm from the end of the shaft.

The excitation input to the shaft / net was provided by an electromagnetic shaker Ling Dynamic Systems 200 series which was connected to the force transducer (B&K type 8200). The force transducer was pasted to the bottom surface of the shaft via a super glue or screwed to the net, respectively. Sets of foam block supports formed a base with nearly free boundary conditions. They were placed on a massive steel frame to improve mechanical stability. A broad band accelerometer (B&K type 4371) was attached to the upper surface of the shaft, also via super glue. A random signal was generated by the HP 3566 FFT analyser. The actual signal from the analyzer was then processed. Other equipment included an ENDEVCO charge amplifier model 27218.

Commercially produced badminton racquet were used - with the unchanged profile (hollow shaft) and with the profile designed according to a power-law relationship. Several types of absorbing materials were used, such as sand, duct tape (with thickness δ = 0.2 mm and loss factor η_{dt} = 0.1), elastic tape (δ= 0.08 mm, η_{et} = 0.04), foam and a bitumen-like absorbing material (δ= 1.2 mm, η_b = 0.14). Frequency response analysis was performed on the force transducer and accelerometer measurements.

3 EXPERIMENTAL STUDIES

In this section we present the results of the cross mobility measurements carried out for various modifications of a typical mass-produced badminton racquet. The resulting frequency response functions show how these techniques influence the suppression of resonant peaks.

3.1 Injection of Absorbing Materials into the Shaft

3.1.1 Granular Materials

A well-established damping technique involves using granular materials. Their wide application possibilities (e.g. foundation isolation for machines, buildings, etc.) together with some unique properties represent a strong and broadband damping treatment. Non-cohesive granular materials, such as sand, are used also in some acoustic applications, for example to fill the cavities of speaker stands. The appropriate granular damping material is bonded to the structure which is vibrating primarily in the flexural mode. Unlike traditional damping materials, the primary mechanisms of energy dissipation in granular materials are related to shear friction and impact phenomena. These are highly non-linear. To quantify the effect of this damping treatment on damping of filled shafts one has to take into account the nature of grain material, grain size, cavity shape, dimensions of cavity, and pressure[12]. Also, resonances in the granular material do, indeed, influence the damping process.

In our experiments the granular material (sand) has been injected into the shaft of the racquet, and the end has been closed with a small piece of bitumen-like material. Figure 2 shows the comparison of the FRFs of a free badminton racquet and the same one with the cavity of the shaft filled with sand. As one can see, noticeable damping of up to 20 dB has been achieved for some of the resonant peaks. Generally, this effect is more pronounced in the mid and high frequency range.

Note that this method of damping stiffens the structure and increases its weight by about 10%. The associated shift of the mass centre towards the handle is negligible and thus does not play any important role in the resulting performance.

According to the recent research into general particle damping[13], a more significant suppression can achieved when a multiple chambers design is used. Applying this concept to the present work, one would suggest for the shaft to be divided into a set of shorter cavities to increase the effect of the impact, friction and shear mechanisms. Also, with the rapid innovations in material processing, new cohesive and more efficient granular materials could have found wider applications. Another possible variation in the application of granular materials is to fill in pre-drilled longitudinal holes in the shaft, instead of filling the whole tube with sand.

3.1.2 Inserting of Bitumen-like Materials

The same principle can be applied by filling the cavity of the shaft with such absorbing materials as bitumen-like materials. In our experiments the material was pressed into the tube in order to completely cover the inner space.

Figure 3 represents the measured cross mobilities for a free badminton racquet and for the same racquet with its shaft filled with bitumen-like material. Again, a significant attenuation of up to 20 dB has been observed.

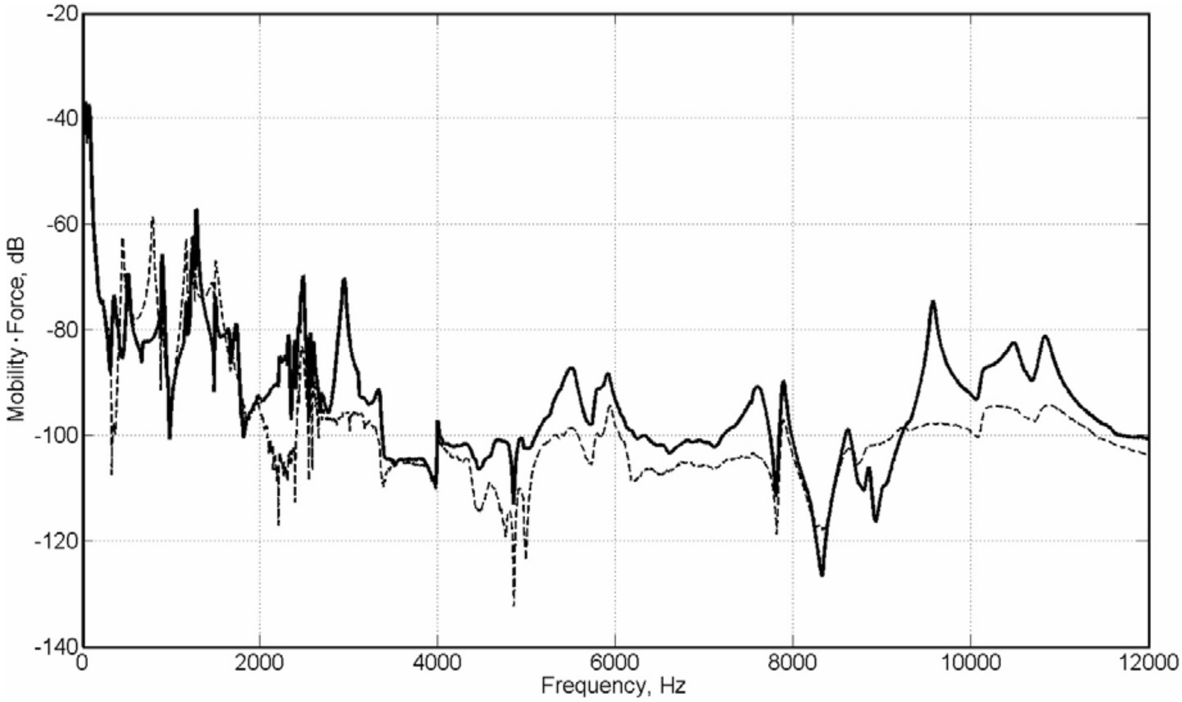

Figure 2. Comparison of cross mobility of a free badminton racquet (solid line) and racquet with shaft filled with sand (dashed line).

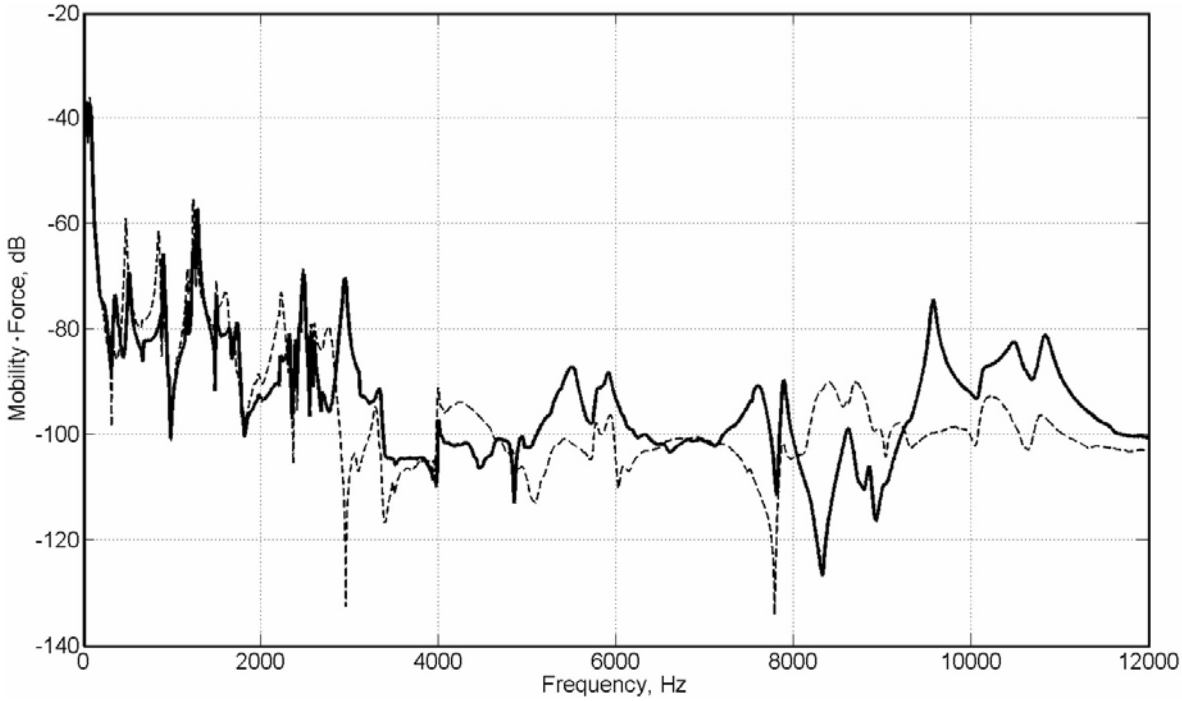

Figure 3. Comparison of cross mobility of a free badminton racquet (solid line) and racquet with shaft filled with bitumen-like material (dashed line).

The above-mentioned experimental results for the cross mobilities of the modified badminton racquets make these two techniques good candidates for future applications. In both cases attenuation of up to 20 dB has been reached. The behaviour of the racquet filled with sand is more stable, and from the practical point of view it may be preferred to bitumen-like material because of its lower weight and being more environmentally friendly. This methodology offers a wide field of variations. Further possible modifications of the same principle, such as application of reologic liquids, are not discussed in this paper.

3.2 Attachments of Layers of Absorbing Materials

Another method of damping successfully applied in engineering is to attach layers of absorbing materials with high values of loss factor. In our measurements we used elastic (parcel) tape, duct tape and bitumen-like material attached to the exterior surface of the shaft. In this section we also compare the measured cross mobilities for a partial coverage with those for a full coverage of the shaft.

According to the measurements, for the original racquet with a handle no visible suppression has been achieved. To make the comparison of partial and full coverage more visible we present the resulting FRFs for a racquet with the original handle being removed. Figure 4 includes the plots of cross mobilities of a free badminton racquet and of the same racquet with the shaft covered by 8 layers of elastic tape. In the lower frequency range the difference between partial and full coverage is hardly noticeable, whereas with the increasing frequency the full coverage shows a minor benefit for the vibrating structure.

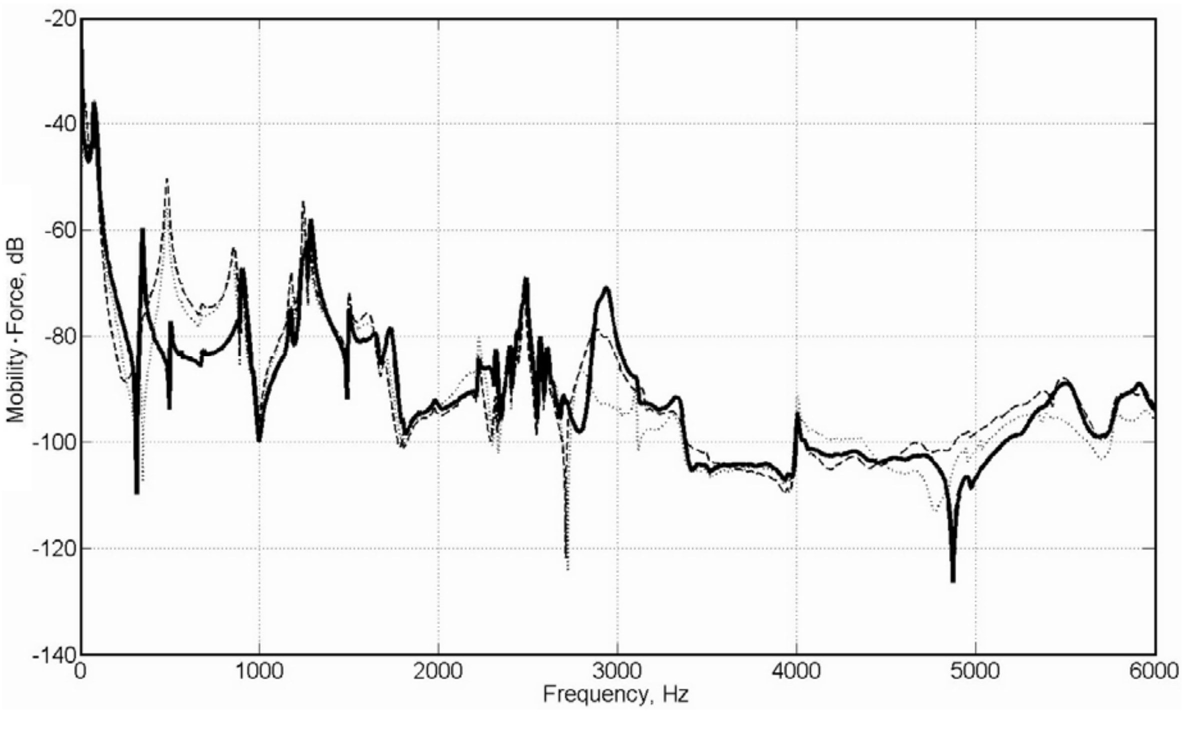

Figure 4. Comparison of cross mobilities for a free badminton racquet without the original handle (solid line) and for the same racquet with shaft covered by 8 layers of 50 mm long strips of duct tape (dashed line) and shaft fully covered by 8 layers of duct tape (doted line).

3.3 Shafts with Profiles Tapered According to a Power-Law Relationship

In the quest to achieve maximum damping one has to keep in mind that the increase in mass of the racquet may have a negative effect on the player's performance[1-3]. Hence, the ultimate method of suppression is to be efficient, broadband and light-weight. One of such methods can be the method based on the principle of acoustic 'black holes'. In this section we describe the results of cross mobility measurements that show a significant damping effect in shafts having the ends tapered according to a power-law relationship between the local radius $r(x)$ of the shaft and the distance x from the end: $r(x) = \varepsilon x^m$. In this regard, shafts of various cross-sections and profiles have been manufactured and their response to the dynamic loading investigated.

According to the recent theoretical studies[6], an ideal circular rod of power-law profile with the exponent $m \geq 2$ provides zero reflection from the sharp ends and thus represents a one-dimensional acoustic black hole for flexural waves. Due to the ever-present imperfections and truncations though, the production of ideal power-law profiles is not possible. Additional strips of narrow layers of absorbing materials dissipate the elastic wave energy concentrated near the sharp ends and thus improve the situation significantly[4-8].

3.3.1 Solid Shaft Tapered According to a Quadratic Law

Keeping in mind the above discussion, one can suggest to use tapered rods in badminton racquets instead of hollow shafts. Two such rods with a known truncation of 0.4 mm have been manufactured for the values of the quadratic coefficient $\varepsilon = 3.3\ 10^{-4}\ mm^{-1}$ and $\varepsilon = 1.65\ 10^{-4}\ mm^{-1}$, respectively. Measurements of cross mobilities have been carried out for racquets with free rods and with rods covered by very short and narrow strips of bitumen-like material (see Figure 5). One can see that some resonances in the case of covered tapered rods are damped quite substantially.

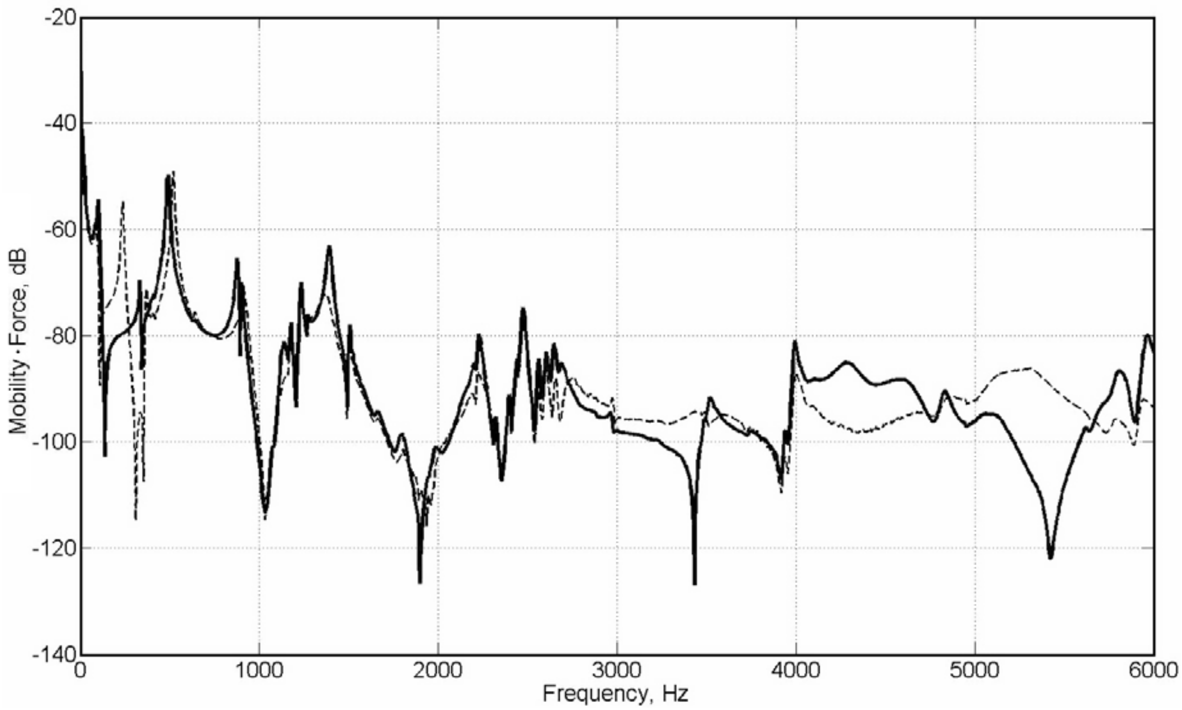

Figure 5. Cross mobility of a badminton racquet with a free rod tapered according to a quadratic law with $\varepsilon = 3.3\ 10^{-4}\ mm^{-1}$ (solid line) and the same racquet with the tip of the rod covered by a 10 mm long strip of bitumen-like material (dashed curve).

3.3.2 Linear Tapering of Hollow Shafts

One could expect that the method of vibration damping based on the acoustic black holes effect successfully applied to solid wedges and tapered rods[4,8] can be developed also for hollow structures such as shafts of badminton racquets. In particular, these shafts can be easily deformed in the workshop, so that the initial circular cross-section changes into ellipse with the height of the minor axis gradually decreasing to zero. This results in gradual decrease of the corresponding flexural wave velocity with the distance towards the end of the deformed shaft. Figure 6 displays some preliminary results for cross mobility measured for a badminton racquet with a shaft which profile decreases linearly towards the end, with a truncation of 0.6 mm.

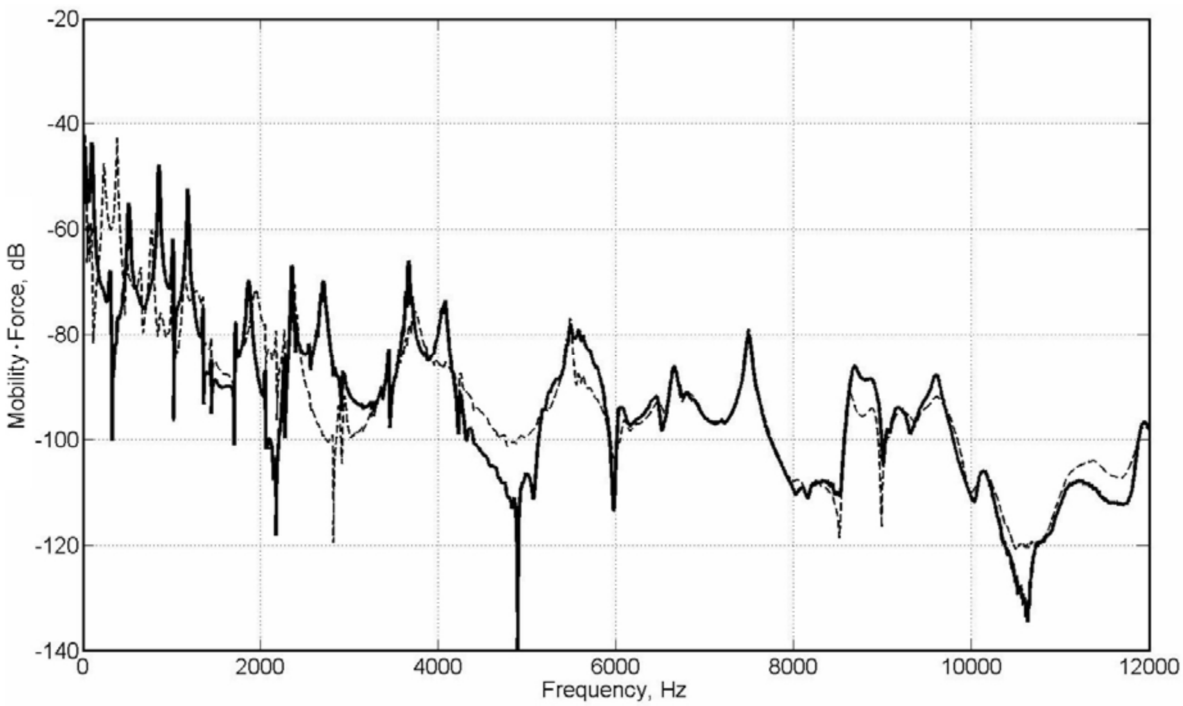

Figure 6. Cross mobility of a badminton racquet with the hollow shaft deformed according to a linear law; free shaft (solid line) and the same shaft covered by a 10 mm long strip of bitumen-like material (dashed curve). Note a suppression of up to 15 dB.

Thus, even though the above-mentioned linearly deformed hollow shaft does not provide the acoustic black hole effect for flexural waves of suitable polarisation, a noticeable damping of resonant peaks indeed takes place. Generally, one would expect that hollow and non-hollow shafts of power-law profile could be used in badminton racquets for damping impact-induced resonant vibrations. Further research is needed in this area to confirm these expectations.

4 CONCLUSIONS

Experimental studies of impact-induced vibrations in badminton racquets have shown several possible modifications to the shaft of the racquet that would reduce levels of vibrations at resonances.

Granular materials and bitumen-like materials inserted into the cavity of the hollow shaft provide suppression of up to 20 dB. The associated increase in weight by 5 - 10 % can be acceptable.

Attachment of absorbing layers to the external surface of the shaft was not of a great benefit for reduction of vibrations. Some resonant peaks have been even amplified instead of being damped. On the other hand, some peaks have been damped by up to 10 dB when fully covered by a duct tape, in comparison with a free or partly covered shaft, where this treatment had a negligible effect.

Cross mobility measurements carried out for racquets with non-hollow shafts tapered according to a quadratic law have shown significant reduction of resonant vibrations when covered by a short narrow adhesive film of absorbing material. This can be attributed to a reduction of reflections of flexural waves from the sharp tip of the shaft due to the acoustic black hole effect. The advantage of this new technique is noticeable even in the mid frequency range. Tapered shafts used in the experiments provided damping of about 10 -15 dB. It is expected that even more significant suppression can be achieved with the increasing ε - factor and decreasing truncation. Such a light-weight damping treatment can be applied at the design stage in mass-production, especially, in conjunction with carbon composites which can be formed very precisely.

It is expected that hollow shafts of power-law profile can be used in badminton racquets as well for damping impact-induced resonant vibrations. Preliminary experiments with a deformed hollow shaft of linear profile have demonstrated the reduction of some resonant vibration peaks up to 10 dB. Further experimental and theoretical research is needed in this area.

5 REFERENCES

1. H. Brody, Tennis science for tennis players, University of Pennsylvania Press (1987).
2. H. Brody, The physics and technology of tennis, Solana Beach, California, Racquet Tech Pub. (2002).
3. J. Haake, Tennis science and technology, Backwell Science (2000).
4. V.V. Krylov and R.E.T.B Winward, Experimental investigation of the acoustic black hole effect for flexural waves in tapered plates, Journal of Sound and Vibration 300, 43-39 (2007).
5. V.V. Krylov and F.J.B.S. Tilman, Acoustic ‘black holes’ for flexural waves as effective vibration dampers, Journal of Sound and Vibration 274, 605–619 (2004).
6. V.V. Krylov, Propagation of plate bending waves in the vicinity of one- and two-dimensional acoustic ‘black holes’, Proceedings of the ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rethymno, Crete, Greece, 13-16 June 2007 (on CD).
7. V.V. Krylov, New type of vibration dampers utilising the effect of acoustic ‘black holes’, Acta Acustica united with Acustica 90(5), 830–837 (2004).
8. V. Kralovic and V.V. Krylov, Damping of flexural waves in tapered rods of power-law profile: Experimental studies, Proceedings of the Institute of Acoustics, 29, Pt 5, 66-73 (2007).
9. M.A. Mironov, Propagation of a flexural wave in a plate whose thickness decreases smoothly to zero in a finite interval, Soviet Physics - Acoustics 34, 318–319 (1988).
10. S.C. Sims, Vibration damping, US Patent 5362046 (1994).
11. N. Grobert, Carbon nanotubes – becoming clear, Materials Today, 10 (1-2), 28-35 (2007).
12. A. Lenzi, The use of damping material in industrial machines, PhD thesis, University of Southampton (1982).
13. Z. Xu. M.Y. Wang and T. Chen, Particle damping for passive vibration suppression: numerical modelling and experimental investigation, Journal of Sound and Vibration, 279(3-5), 1097-1120 (2005).