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Enhanced vibration performance of ultrasonic block horns

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Abstract

Block horns are tuned components designed to vibrate in a longitudinal mode at a low ultrasonic frequency. Reliable performance of such horns is normally associated with the amplitude of vibration, uniformity of vibration amplitude at the working surface and the avoidance of modal participation by non-tuned modes at the operating frequency. In order to maximise vibration amplitude uniformity, standard slotting configurations are included in the horn design. However, defining a slotted block geometry which guarantees sufficient tuned frequency isolation from nearby modes as well as high amplitude and amplitude uniformity, is not straightforward. This paper discusses horn configurations which satisfy these criteria and investigates the design requirements of block horns which operate as intermediate components in ultrasonic systems, where the block horn dominates the vibration behaviour of the system. The importance of mode shape characterisation is discussed and modes are classified using experimental data from 3D laser Doppler vibrometer measurements and finite element analysis. In particular, the role of additional fine slots and castellations are studied with reference to two distinct ultrasonic applications involving a similar block horn. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: High power ultrasonics; Block horns; Modal analysis; Finite element analysis

1. Introduction

Block horns are used in many high power ultrasonic systems, such as welding and cutting, where they either operate as a tool directly acting on the work surface [1], or as an intermediate component acting as a transmission element between the transducer and tool [2]. Generally, block horns are tuned to the first longitudinal mode of vibration at an operating frequency in the low ultrasonic range of 20–40 kHz. For reliable operation of the block horn, the longitudinal mode frequency has to be isolated from other close modes which can participate in the response at the operating frequency or can cause mode switching to occur during operation [3]. Block design for operating mode isolation can be achieved by finite element (FE) analysis, where models are validated by experimental modal analysis (EMA). The advent of the 3D laser Doppler vibrometer (LDV) has resulted in accurate identification of modes and significant improvement in data correlation, which allows both in-plane and out-of-plane responses to be characterised. The combination of FE modelling and 3D LDV has enabled a greater depth of understanding of block horn behaviour to be gained and therefore improved strategies for enhanced block horn performance.

2. Performance of a block horn used as a working tool

The design of ultrasonic block horns is focused on satisfying three main performance criteria: isolation of the operating frequency from close non-tuned modes, uniformity of amplitude at the working surface and high amplitude of the operating mode. Studies have shown that uniformity and frequency separation can be achieved by the inclusion of slots in the horn configuration [3–5], whereas high vibration amplitudes are obtainable in block horns with tapered profiles. However, simultaneous application of all the design guidelines is often problematic, with the result that all performance criteria cannot be satisfied in every ultrasonic operation.

2.1. Standard slotting configurations

A FE model of the longitudinal mode at 35 kHz of a block horn without slots is presented in Fig. 1(a). Poor

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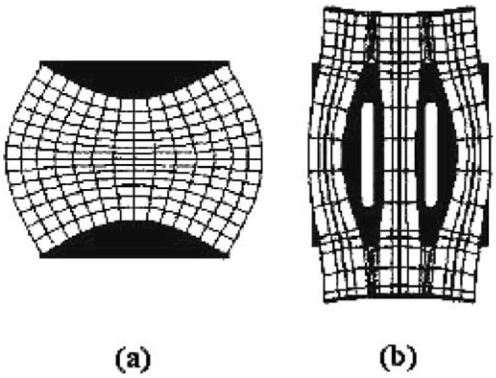

Fig. 1. Longitudinal mode of block horn, (a) no slots (b) double-slotted.

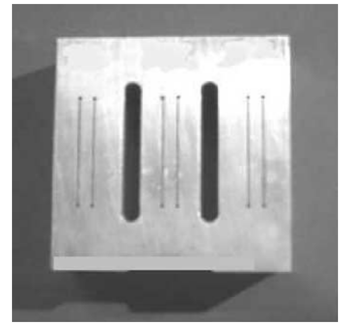

Fig. 2. Double-slotted block horn with six fine slots.

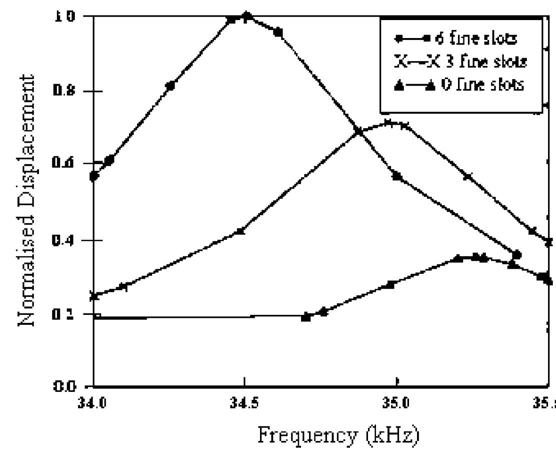

Fig. 3. Block horn amplitude for different fine slot configurations.

uniformity of vibration amplitude due to Poisson's effect in the longitudinal mode and poor frequency separation (640 Hz) are as expected for this horn configuration. The uniformity requirement for a block horn, measured as the ratio of minimum to maximum response amplitude on the output surface, $U_{\min}/U_{\max}$, is estimated to be 80% [3]. The frequency separation should be at least 1 kHz from the longitudinal mode frequency. A block incorporating two standard slots, as shown in Fig. 1(b), having length, width and slot spacing of 1/3, 1/24 and 1/4 wavelength respectively, results in a high horn amplitude uniformity and good frequency separation (2590 Hz).

2.2. Incorporating fine slots to improve longitudinal mode amplitude

For block applications requiring high amplitude of vibration as well as high amplitude uniformity, slotted block horns with tapered profiles are used, but these are very prone to modal coupling at the operating frequency such that problems of multiple-frequency excitation are common [1,6]. An alternative approach to improving vibration amplitude is therefore investigated.

The modal behaviour of a double-slotted block horn, and in particular the longitudinal mode characteristics, can be approximated to the vibration characteristics of its three internal columns. The modal frequency of a column uniquely depends on its length, while longitudinal amplitude is also sensitive to width variation. It is possible to reduce the column widths whilst maintaining the horn global dimensions by incorporating a number of very fine slots in addition to the standard slots in the horn.

A double-slotted block horn incorporating six fine slots is shown in Fig. 2. FE predictions of amplitude sensitivity to the number of fine slots is shown in Fig. 3, which highlights the improved response of horn configurations with fine slots. Although including fine slots improves vibration amplitude, it also enriches the block horn spectrum such that numerous modes are excited in the many additional columns of the structure, with mode families being characterised by spatial phase variations between adjacent thin columns. Identification and classification of these horn modes is necessary to assess the feasibility of a fine slotted block horn geometry and therefore EMA using a 3D LDV has been conducted to validate FE model predictions. Table 1 shows how the 3D LDV data, which allows one out-of-plane and two in-plane components of vibration response to be measured, enables accurate identification of all the responsive modes in the measured frequency range and straightforward validation of FE models. Despite the predicted density of modes for the block with fine slots, the EMA data indicate that the modes related to the thin columns created by the fine slots excite a very low response compared with the whole block modes. Consequently, modal participation by these modes in the operating mode does not significantly affect block horn performance. The addition of fine slots to a slotted block horn is demonstrated to offer a practical design solution, allowing amplitude on the working surface to be increased without the problems of modal coupling, associated with tapered blocks.

Table 1
Block horn modal frequencies in 28–40 kHz range

FEA (Hz)	EMA using 3D LDV (Hz)	Error (%)
28 155	28 396	0.8
28 642	27 922	−2.6
28 824	28 135	−2.4
30 071	29 071	−3.4
30 474	30 192	−0.9
31 151	30 415	−2.4
32 522	32 893	1.1
34 921	35 024	0.3
35 404	35 468	0.1
36 249	35 944	0.9
36 596	35 172	−4.0
36 618	35 214	−4.0
37 000	38 039	2.7
37 002	35 320	−4.7
38 672	Not found	
39 786	37 470	−6.0
39 824	38 716	−2.8

3. Block horn used as an intermediate component

Many ultrasonic systems utilise block horns to transfer vibration energy from a transducer to a series of tuned components attached to the horn output surface. The advantage of this use of block horns is that several tools can be driven by one transducer and generator. Fig. 4 shows a 35 kHz ultrasonic cutting system, where the block horn drives three equally spaced tuned cutting blades.

In this case, amplitude uniformity of the block horn is not the most critical design parameter for the system. Initially, a castellated geometry of the input face of the block horn proved to result in very high uniformity. Such castellations produce horn columns of different lengths resulting in the existence of two longitudinal modes. One, at 35.3 kHz, is due to motion of the outer columns, the other, at 36.4 kHz, is due to motion of the central column. High amplitude uniformity is achieved by tuning the block to the longitudinal mode associated with the length of its outer columns. The length of the castellations is predicted by a sensitivity analysis of uniformity and frequency separation parameters, using FE models.

However, despite the high block amplitude uniformity, the FE and EMA data in Fig. 5 reveal that the two outer blades of the cutting head operate with a significant flexural response in the longitudinal mode.

Fig. 4. Ultrasonic cutting device.

3.1. Redesign of block horn to improve frequency separation

The predicted and measured natural frequencies in the range 29.5–42 kHz are presented in Table 2, which highlights the presence of two modes occurring close to the longitudinal mode frequency and these are presented in Fig. 5. Modal coupling exists between the longitudinal mode of the system and two modes exciting bending and torsional responses of the blades, which prevents the system running in its operating mode and gives rise to increased dynamic stresses. In the cutting system, the vibration behaviour of the block horn dominates the behaviour of the system and is therefore modified to improve isolation of the longitudinal mode frequency. Block horn modes in a frequency range of 8 kHz around 35 kHz have been classified in two main categories: (a) in-plane modes whose frequencies are highly dependent on block width and/or length, but independent of block thickness; (b) out-of-plane modes (including flexural and torsional modes), which are highly sensitive to block

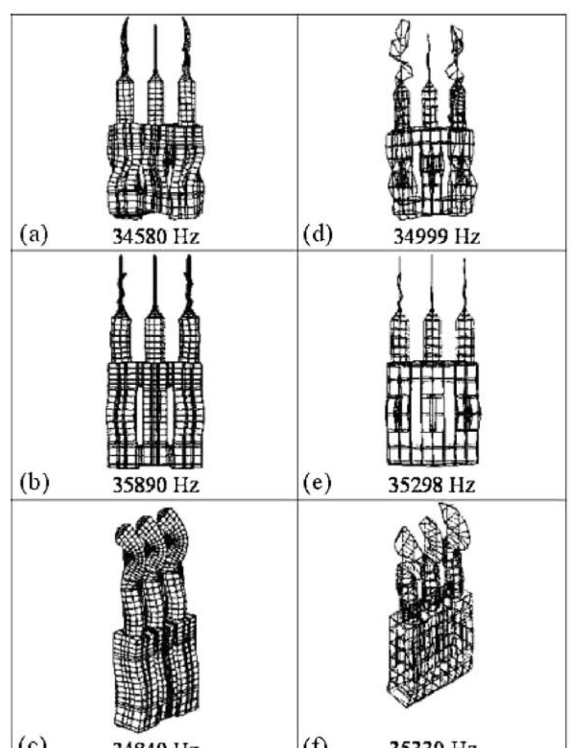

Fig. 5. FE modal data (a–c) and 3D LDV EMA data (d–f) for the torsional, longitudinal and bending mode of the blades.

Table 2
Cutting head modal frequencies in 30–42 kHz range

FEA (Hz)	EMA (Hz)	Error (%)
28 890	30 216	4.4
31 510	32 426	2.8
32 010	33 110	3.3
32 600	33 595	3.0
34 580	34 999 coupled	0.1
35 890	35 298 coupled	−1.7
34 840	35 340 coupled	1.4
36 370	36 382	0.0
36 920	36 954	0.0
37 330	37 333	0.0
38 380	37 976 coupled	−1.0
38 170	37 991 coupled	−0.5
39 770	38 629	−2.9
41 720	39 880	−4.4
40 180	41 358	2.8

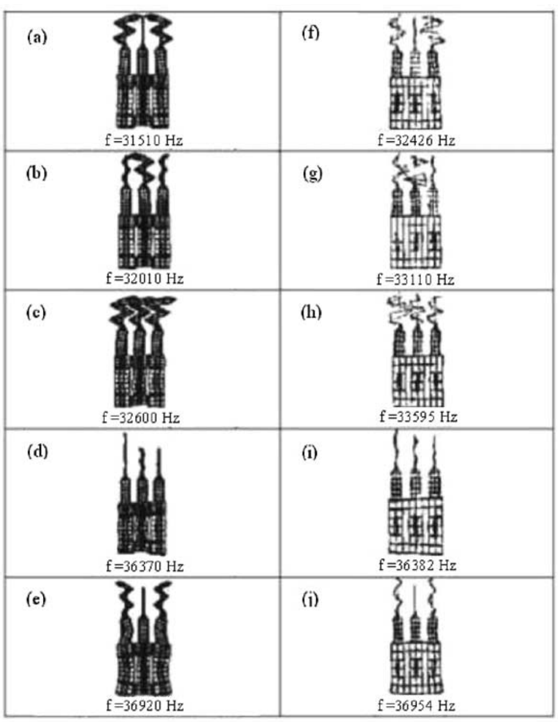

Fig. 6. Five in-plane modes determined from FE (a–e) and EMA data (f–j).

thickness. Both of the coupled modes belong to the latter group. Five of the in-plane modes in the range are presented in Fig. 6. Fig. 7 shows the FE predictions of mode sensitivities to horn thickness modifications, from which a 2.5 kHz isolation can be achieved.

3.2. Redesign of block horn to eliminate transverse flexural motion of the outer blades

It is clear that the method used to improve block amplitude uniformity is the cause of flexural responses in the outer blades. In fact the castellation of the horn

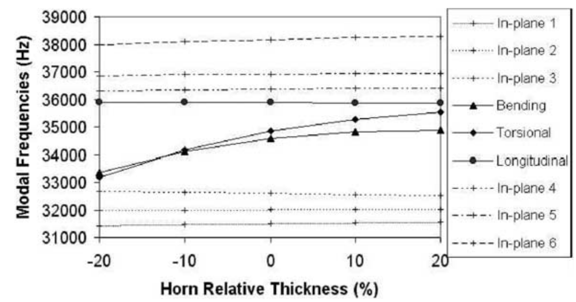

Fig. 7. Effect of horn thickness on modal frequencies.

input face produces high amplitude uniformity together with increased flexural motion in the outer columns and hence the outer blades. Subsequently, design alterations to constrain flexural motion of the block horn outer columns were based on modifications of the castellations. As shown in Fig. 8(a), a castellated block horn with a longer central column removes flexural motion from the longitudinal motion of the blades by tuning the block to the length of the outer columns. Another alternative block horn with a form of castellation of the outer columns is shown in Fig. 8(b). Again, the position and dimensions of the castellations were determined by a sensitivity analysis of outer column flexural displacement and frequency separation parameters, using FE models. The increased thickness of the outer columns increases the stiffness in flexure, restricting their lateral flexural motion in the longitudinal mode and resulting in parallel motion of all three blades, as evident in the figure. For both of these castellation design solutions, a further sensitivity analysis of block thickness variation has been investigated in order to improve frequency isolation of the longitudinal mode from close responsive modes. A 20% thickness reduction is predicted to offer

Fig. 8. Longitudinal mode for alternative block horn designs, (a) castellation of central column, (b) transverse castellation of outer columns.

the best frequency separation for both castellated blocks and maintains parallel motion of the three blades.

4. Conclusions

Two ultrasonic applications dominated by the behaviour of block horns have been presented in this paper: the first involving a block horn acting as a tuned working tool; the second a horn used to transmit vibration to other ultrasonic units. In both cases, careful component design must guarantee the required operation amplitude at the tuned frequency, avoiding modal coupling. Significant improvements in experimental validation of horn FE models have been achieved by the use of a 3D LDV, which allows modal analysis from both in-plane and out-of-plane measurements, which becomes crucial in validating the addition of fine slots to increase vibration amplitude of a double-slotted horn. For the cutting system, where the block horn acts as an intermediate tuned component, the block horn behaviour has a dominant influence on the vibration mode of the attached blades. Block horn design features must therefore be incorporated to ensure pure longitudinal motion of the blades. It has been shown that block horn castellations can provide an effective design solution.

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