M. Lucas*
Lecturer.

A. C. Smith
Research Associate.
Department of Mechanical Engineering,
Loughborough University of Technology,
Leicestershire
LE11 3TU
United Kingdom

Redesign of Ultrasonic Block Horns for Improved Vibration Performance

Ultrasonic block horns are prone to reliability problems associated with modal activity close to the tuned operating frequency. This paper presents an approach to block horn design, which relies on two laser based vibration measurement techniques, electronic speckle pattern interferometry (ESPI) and laser doppler velocimetry (LDV) modal analysis, to validate finite element (FE) models. Block horn vibration characteristics are interpreted from experimental and theoretical data such that successful horn redesign can be achieved from modifications to the FE models.

Introduction

Ultrasonic block horns are tuned components used to transmit vibration from a transducer to a work surface or to other tuned components in an ultrasonically aided manufacturing system. Typically, such block horns are a critical element in plastic welding devices (Shoh, 1976). A block horn is a customised ultrasonic tool having cross-sectional dimensions greater than one third of the material wavelength ($\lambda/3$). The two primary performance indicators for such a horn are amplitude and amplitude uniformity generated on the transmission face of the block at the nominal operating frequency. To aid frequency separation and amplitude uniformity during operation, block horns have a configuration of slots machined through the horn thickness. The exact configuration is determined from some established design guidelines, which have largely been determined empirically, and successful slotting still relies on a trial and error approach. Recent studies have shown that the dimensions and number of slots have a pronounced effect on horn performance (O'Shea, 1991) and it is clear that a more rigorous procedure for horn design is required. Problems associated with inherent modal activity arise in block horns due to flexural modes, occurring close to the tuned longitudinal mode frequency, which reduce the performance and reliability of the horn.

Ultrasonic systems are typically of high mechanical Q and amplitude transmission is highly dependent on maintaining resonance, often under varying load conditions. To compensate for system detuning, many ultrasonic generators offer a resonance locking/tracking capability. Although these systems maintain resonance, they can encourage mode hopping if several modal frequencies exist in close proximity. Alternatively, if modal coupling exists, more than one mode may be responsive at the operating frequency, leading to amplitude reduction and loss of uniformity on the transmission surface.

Finite element analysis (FEA) (Adachi et al., 1986), validated by electronic speckle pattern interferometry (ESPI) and experimental modal analysis (EMA) measurements, has proved to be an effective strategy for analysis and redesign of ultrasonic forming dies (Lucas and Chapman, 1989, 1993). These analysis techniques, along with laser doppler velocimetry (LDV), are applied to the study of ultrasonic block horns to improve performance through identification, classification and separation of flexural off-resonance vibration modes.

Measuring Block Horn Vibration

The measurement of vibration response in the low ultrasonic range is often not feasible using conventional sensors. High surface accelerations prohibit successful attachment of accelerometers and few non-contacting probes retain linearity at ultrasonic frequencies. Developments in laser technology have provided tools for vibration measurement such that mathematical models of ultrasonic manufacturing devices can be validated.

Measurement of block horn vibration relies on two laser based measurement techniques. Laser doppler velocimetry is used to measure in-situ vibration performance and as a laboratory instrument for modal analysis. Electronic speckle pattern interferometry provides a whole-field view of a vibrating surface, enabling in-plane and out-of-plane motion of the horn surfaces to be monitored in real time.

Block Horn Applications

The results from studies of two block horns, designed for two different ultrasonic operations and with distinct geometry requirements and constraints, are presented. The first (Figure 1*a*) is a wide-bodied welding horn, manufactured from titanium. The horn is rectangular in cross-section, with the aspect ratio of the welding face being 20:1. The drive end has a block geometry, with a stepped catenoidal profile producing the narrow welding surface. Four slots are machined through the horn to produce column widths of $\lambda/6$. The complex geometry and slender cross-section of this type of horn tend to excite flexural modes of vibration with highly profile dependent response shapes, close to the tuned longitudinal mode frequency.

The second (Fig. 1*b*) is a double-slotted block horn, manufactured from aluminium, which is required to transmit ultrasonic vibration amplitude to several stacks of tuned spacer horns mounted on the opposite face to the transducer. The slots are machined to produce a horn with equal column widths of $\lambda/4$. Equal and in-phase vibration amplitude must be transmitted to the sets of spacer horns from the block horn, which is remote from the work surface in this application.

Operating Vibration of Wide-Bodied Horn

An initial assessment of operational performance relied on measurements of normal-to-surface vibration by laser vibrometry, recorded at points along the base of the horn front face, which would provide the best indication of any amplitude non-uniformity conditions due to modal coupling during the welding

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* Currently with the Department of Mechanical Engineering, University of Glasgow, Glasgow G12 8QQ, UK.

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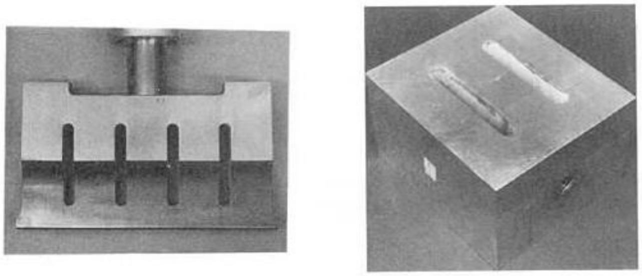
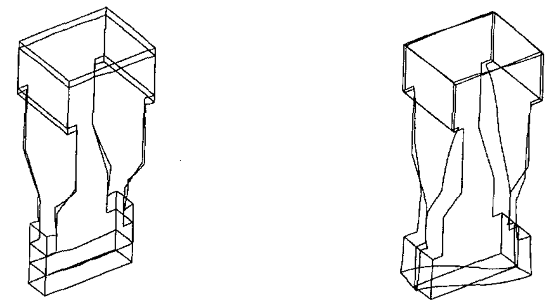
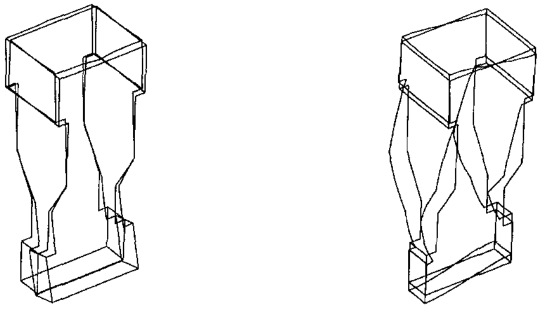


Wide bodied welding horn **Double-slotted block horn**

Fig. 1 Unltrasonic block horns



Longitudinal (L_y) **Torsional (T_y)**



Out-of-plane bending (B_z) **In-plane bending (B_x)**

Fig. 3 Mode classification by FE model of single column

process. The surface velocity signal was acquired by a FFT analyser to determine operating frequency vibration. The results are shown in Fig. 2.

For ideal horn performance, only a small amplitude variation consistent with Poisson's effect should be observed. The welding horn vibration variation in this case exhibits the characteristics of a flexural mode resonance condition and clearly indicates the excitation of coupled modal behaviour during operation. The weld quality during the experiment was poor, which would suggest that the flexural mode vibration was causing longitudinal mode amplitude nonuniformity on the welding surface. Although measurement of the existence of coupled modes assists identification of welding performance problems, classification of off-resonance and coupled modes is required if an appropriate redesign is to be determined.

Finite Element Modelling of Wide-Bodied Horn

The vibration behaviour of wide-bodied welding horns is complicated by the introduction of slots, which allows various mode families to be excited in the columns of the structure, with spatial phase variations between adjacent columns. It is useful therefore, to model one column of the horn initially, to gain an appreciation of the basic mode types from which the more complex full horn modes are derived, and on which a subsequent mode nomenclature could be based. The mode types from the FE model are presented in Fig. 3: longitudinal (L_y), torsional (T_y), out-of-plane bending or flexure (B_z) and in-plane bending (B_x). The mesh density of the single horn model was used to create a FE model of the full horn, or half-horn where the plane of symmetry allowed mode prediction.

The results of the FE modelling (Table 1 and Fig. 4) show how the basic mode types of the single column of the horn develop into the full horn modes, mostly exhibiting a sinusoidal feature along the welding face resulting from the column spatial phase combinations in the bending and torsional mode families. Modes are classified by the above descriptors preceded by the harmonic number. The existence of more than one mode of the same classification is due to the different possible spacial phase combinations of column response for each harmonic number. Coupling of flexural and longitudinal modes would be observed as a sinusoidal amplitude variation at the welding face. Some amplitude nonuniformity in wide-bodied horns already exists due to the positioning of the excitation injection point and therefore added loss of welding face performance due to modal coupling is clearly highly undesirable. Significantly, the FE model predicts the existence of a third order out-of-plane bending mode $3B_z$ at a close frequency to the tuned fundamental

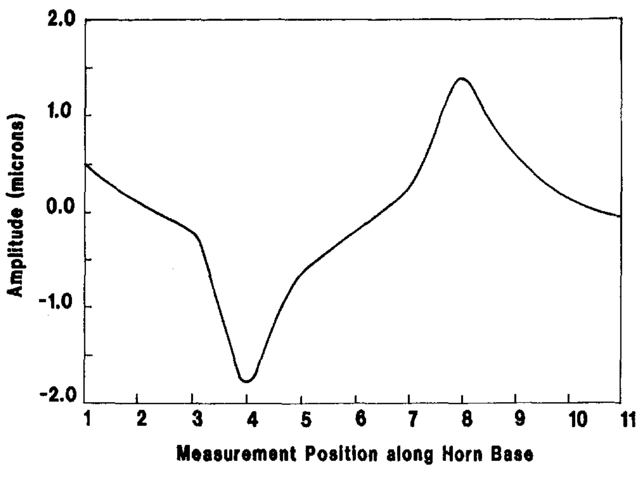
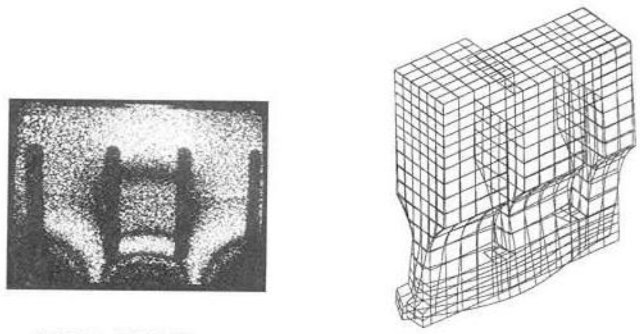


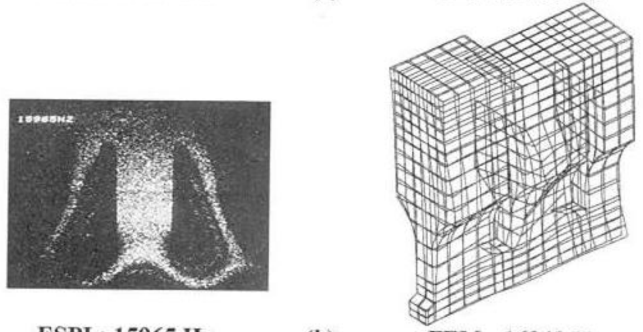
Fig. 2 Operating vibration response of wide-bodied horn

Table 1 Natural frequencies of wide-bodied welding horn

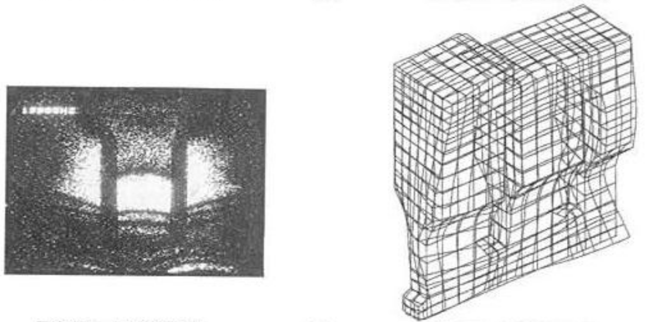
	Horn Natural Frequencies (Hz)		
Mode	Finite Element Analysis (FEM)	Electronic Speckle Pattern Interferometry (ESPI)	Error(%)
$1B_z$	6220	6520	-4.8
$1L_x$	7110	7153	0.6
$2B_x$	9300	9349	-0.5
$1B_z$	9730	9772	-0.4
$2T_y$	11590	11636	-0.4
$2B_x$	14980	14828	1.0
$2T_y$	16340	15965	2.3
$2B_y$	17200	16453	4.3
$3B_z$	18620 20290 21050	- 19985 -	- 1.5 -
$1L_y$	20006	19985	0.1



ESPI : 9772 Hz (a) FEM : 9730 Hz



ESPI : 15965 Hz (b) FEM : 16340 Hz



ESPI : 19985 Hz (c) FEM : 20290 Hz

Fig. 4 Comparison of modes determined by ESPI and FEA

longitudinal mode $1L_y$. These results must however be validated (and the FE model updated if necessary) before reliable redesign can be implemented.

Experimental Validation by ESPI

The mode shape at each horn natural frequency was obtained by measurement of the normal-to-surface and in-plane components of vibration of three of the horn surfaces: front face, side face and welding face. For the experiment, the horn was mounted via a threaded mounting stud to the transducer-booster stack, which was held at a nodal mounting flange. The modal frequencies were determined by swept-sine test in the 6-25 kHz frequency range. Each live mode shape was recorded on video in the form of a fringe pattern for subsequent fringe processing. Three of the modes detected by ESPI are presented in Figure 4 alongside the corresponding FE results. Figure 4(a) is a low order mode belonging to the B_z mode family, exhibiting out-of-plane sinusoidal variation along the base of the horn. Figure 4(b) at 15965 Hz is a torsional type measured to exist at several frequencies, the others being weak versions exciting low amplitude levels. The modes are of the same type but represent different column response spatial phase combinations. Figure 4(c) is the tuned operating mode, measured at 19965 Hz, clearly showing the bending mode participation in the longitudinal mode as a result of modal coupling. The coupled mode is confirmed as the $3B_z$ mode. Three modes of this type were predicted by the FE model but only one, which was dominated by motion of the central columns, was detected experimentally. A comparison of ESPI and FE mode estimations are presented in Table 1.

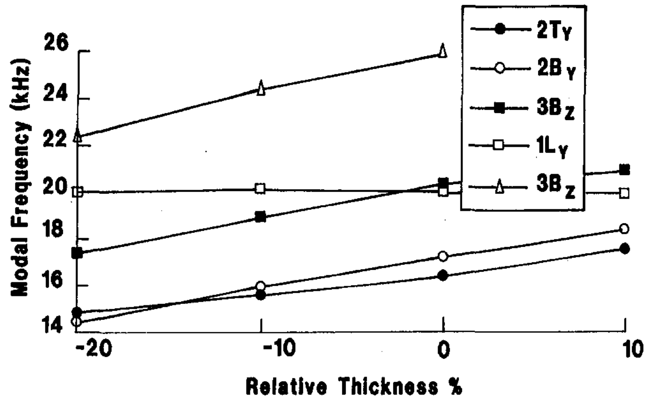


Fig. 5 Effect of horn thickness on natural frequencies

The FE modelling and model refinement procedure concentrated on achieving accurate prediction of the operating mode and any problematic close modes. The result is excellent correlation for the mode calculations which are most vital for anticipating modal coupling at the design stage. Having validated the FE model, design modifications can be incorporated to predict the horn geometry alterations required to achieve isolation of the tuned longitudinal mode.

Redesign of Welding Horn

To adjust the modal behaviour of the horn for longitudinal mode isolation, a horn dimension can be identified on which the problematic mode frequency is highly dependent and the longitudinal mode frequency is largely independent. The prerequisite for this redesign is the determination and classification of all close modes. Having identified the $3B_z$ mode as the main problem, its classification allows identification of the tool thickness in the z-axis as the appropriate dimension for alteration.

Figure 5 shows the FE predictions of mode sensitivities to alteration of the horn thickness dimension for several alternative thickness modifications of the original validated FE model. The aim was to estimate a horn thickness modification that resulted in longitudinal mode isolation by at least 1 kHz, which from measurements and previous empirical data, was deemed sufficient to remove the problems of modal coupling. A reduction in the modification parameter of 15 percent was estimated to

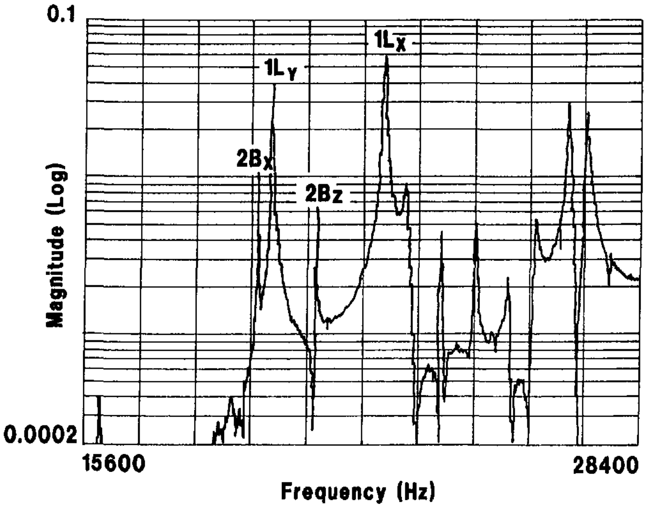


Fig. 6 LDV frequency response function measurement of block horn

Table 2 Natural frequencies of double-slotted block horn

	Horn Natural Frequencies (Hz)		
Mode	Finite Element Analysis (FEA)	ESPI/LDV Measurements	Error(%)
$1B_x$	9866	9820	0.47
$2B_x$	14666	14340	2.27
$1B_x$	16071	15960	0.70
$1L_y$	19725	19920	-0.98
$2B_x$	19879	19590	1.48
$2B_z$	20821	20910	-0.43
$1L_x$	22370	22480	-0.49
$2T_y$	25879	25990	-0.43

Table 3 Natural frequencies of redesigned block horn

	Horn Natural Frequencies (Hz)		
Mode	Finite Element Analysis (FEM)	ESPI/LDV Measurements	Error(%)
$1B_x$	9713	9570	1.49
$2B_x$	12029	12140	-0.91
$2B_x$	17035	16460	3.49
$1L_x$	18930	18890	0.21
$1L_y$	19319	19880	-3.26
$2B_z$	20600	20860	-1.25
$2T_y$	23075	21910	5.32

achieve satisfactory operating mode isolation and the longitudinal mode was predicted to maintain 20 kHz resonant frequency for such a modification.

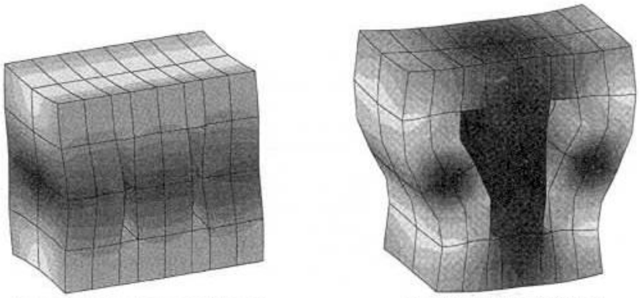
Operating Characteristics of Double-Slotted Block Horn

Frequency response measurements on the double-slotted block horn provided information of vibration performance at its vibration transmission surface. Figure 6 is a typical LDV frequency response function (FRF) measurement, depicting the problem of high modal density and features the response of the longitudinal operating mode and the participation of an off-resonance mode close to the tuned frequency. In operation the block horn was measured to exhibit an unacceptable amplitude variation and low amplitude levels on the transmission face and was therefore an inefficient vibration transmission component between the transducer and the spacer horn stacks.

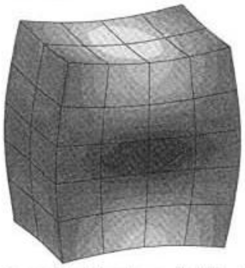
Finite Element Analysis of Block Horn

The double-slotted block horn was also modelled by FEA. The results and classification of the predicted modes are presented in Table 2. The half-wavelength tuned geometry was predicted to excite the longitudinal mode ($1L_y$) at 19725 Hz and a close flexural mode, estimated to be $2B_x$, was predicted at 19879 Hz. These two mode shapes, along with the FE prediction of the $1L_y$ mode for an identical block horn but without slots, are presented in Fig. 7. Comparison of the solid horn in longitudinal vibration with the double-slotted horn highlights the problem of amplitude variation due to Poisson's effect in the longitudinal mode, causing nonuniform vibration amplitude distribution, and the effectiveness of slotting in reducing or eliminating amplitude nonuniformity. The benefits of slotting are however, reliant on the longitudinal mode frequency being well isolated. In this case, the FE results also predict the existence of the $2B_x$ mode at a frequency close to the tuned operating frequency. Evidence indicates that slotting alone will not resolve the amplitude variation problem if close flexural modes participate in the response of the operating mode.

Again, validation of the FE predictions is required in order to investigate an effective redesign.



Longitudinal mode ($1L_y$) Flexural mode ($2B_x$)



Longitudinal mode ($1L_y$)

Fig. 7 Block horn mode predictions by FEA

Validating Block Horn Vibration Model by ESPI and LDV Measurements

Modal coupling between the longitudinal mode and the predicted close flexural mode ($2B_x$) was confirmed by LDV modal analysis and ESPI measurements on the block horn. FRFs from laser vibrometer normal-to-surface vibration measurements were downloaded to a pc equipped with modal analysis software, which produced animated mode shape predictions and allowed direct mode correlation with FE data. In-plane and normal-to-surface components of block vibration were measured using ESPI. The results of the experimental work are compared with the FE predictions in Table 2. Good correlation is achieved between the FE and measured data; being within 1 percent for operating frequency prediction and within 2.5 percent over the measurement range. ESPI measurements on the block horn surfaces further supported the LDV FRF data and demonstrated amplitude variation at the working surface of the block horn.

Having established the cause of poor vibration performance and classified the modes shapes, it is possible to identify horn profile alterations for which the coupled flexural mode is most sensitive and further predict the frequency shifts for all modes in the range of interest as a consequence of geometry modifications.

Redesign of Double-Slotted Block Horn

Because the natural frequencies of the family of in-plane bending modes is highly dependent on the column width introduced by slotting, frequency separation of B_x type modes from the operating mode can best be achieved by maintaining a double-slotted configuration and altering the horn (and conse-

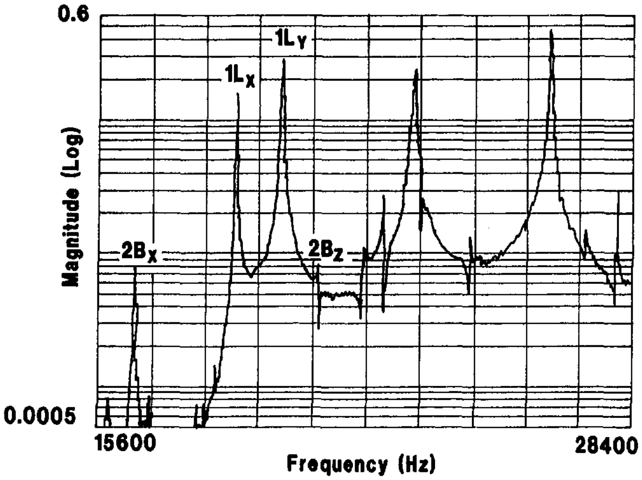


Fig. 8 LDV frequency response function measurement of modified block horn

quently the column) width. The appropriate width modification is determined by sensitivity analysis and is not intuitively obvious from the mode type. Determination of the mode in terms of column spatial phase characteristics is essential since two modes of the same family but differing column phase combinations will exhibit distinct sensitivities to the same geometry alteration. In this case, an increase in horn width was required to separate the coupled modes at the operating frequency and maintain the tuned longitudinal mode condition. It is also necessary to consider the effects of such a design alteration on the frequencies of the other flexural modes, in particular the bending and torsional modes occurring above the tuned frequency. The sensitivities to geometry modification parameters of the other flexural modes must be either large enough to reduce their frequencies to at least 1 kHz below the longitudinal mode or small enough to maintain their frequencies over 1 kHz above the longitudinal mode. In this case, the close coupled mode is reduced in frequency by 16 percent by altering the appropriate horn geometry parameters; block width and column width, and the results of the redesign (presented in Table 3) satisfy the mode separation requirement for the coupled modes. The $2B_z$ bending mode is largely insensitive to and therefore unaffected by alterations in the width parameters. The higher torsional mode is sensitive to the modification and its frequency is shifted to 21910 Hz, which still satisfies the requirement of being over 1 kHz separated from the operating frequency. The most sensitive mode to the modification is the $1L_x$ mode, which is reduced below the operating frequency. This particular mode is of little concern however, since its response is not detectable when the horn is excited in the y-direction in operation. Again this example illustrates the necessity of identifying and classifying all the horn modes around the tuned mode, for appropriate redesign. LDV FRF measurements (see Fig. 8) on the redesigned block horn clearly illustrated both successful isolation of the operating mode and the added benefit of considerably reduced modal density in the low ultrasonic range. Both problems due to modal coupling and those associated with mode hopping during operation were designed out by altering the correct geometry parameters.

Conclusions

Ultrasonic block horn design has tended to concentrate on slotting configuration as poor choice of slots will result in poor amplitude distribution. However, even carefully considered slotting cannot guarantee longitudinal mode isolation from flexural mode activity and therefore it is essential to implement a redesign procedure, involving horn geometry modifications, to eliminate modal coupling and close modes at the operating frequency, that can be adopted for the manufacture of block horns to improve vibration performance.

This study has concentrated on the identification and classification of horn modal behaviour as the pre-requisite for a redesign strategy which considers the sensitivities of horn flexural modes to geometry alterations in order to isolate the longitudinal mode at the nominal 20 kHz operating frequency. To achieve accurate mode classification, a rigorous approach to vibration analysis of the horn is adopted. It has been demonstrated that a combination of FEM for the prediction of horn behaviour, LDV for identification of problematic behaviour, and ESPI and LDV for model validation, provides a successful analysis capability in the redesign of ultrasonic block horns.

The two measurement techniques also produce information about the "strength" of the flexural modes. For slotted horns, FEM will predict the existence of several modes with similar characteristics, individualised only by the specific phase combination of adjacent columns of the block. Often, especially for wide-bodied horns, one of these modes will dominate the response and others will be undetectable. This information is vital for the redesign stage and allows unresponsive modes to be neglected in the sensitivity analysis stage.

The vibration performance of two distinct block horns has been the focus of this study but the proposed procedure is adaptable for block horn design generally.

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