KEFTOPICS
A technical bulletin covering aspects of development, design and use of loudspeakers
Volume 3 No 3

MAINTAINING QUALITY STANDARDS IN PRODUCTION

A great deal has been written about the development of new types of loudspeaker and the high standard of performance that can be achieved, but very little about all the checks and controls that are necessary to maintain this standard in commercial production. These processes must however be regarded as part of the overall system engineering strategy, since large production variations could render useless much of the effort put into the original design.

A modern high-quality loudspeaker, with its separate drive units covering different frequency bands, represents a system with many independent variables. The overall performance can be adversely affected by any mismatch between low-frequency, mid-range and high-frequency units, or by deviations of the component values in the crossover networks. To realise the full potentialities of such a system, a programme of rigorous production testing, covering all relevant parameters, is therefore necessary; each drive unit, for example, must be checked for conformity with the prototype on which the design was based, and matched, not only with other units in the same assembly, but with its opposite number in the other half of a stereo pair.

Some of these operations can now be carried out faster and more accurately by the application of digital techniques. A digital computer can derive the frequency response characteristics of a loudspeaker or drive unit from its impulse response, without the need for an anechoic environment*; it can also store the results from different tests and select or match units to within prescribed limits, all these processes being carried out within a time span short enough to satisfy the requirements of commercial production. Other tests likewise involve advanced instrumentation, and in general, meticulous attention to detail is necessary to ensure that the design concept is realised in every specimen of the final product. This issue of KEFTOPICS describes, as an example of modern practice, the various stages in the production test sequence of the KEF Model 105 loudspeaker.

*BERMAN, J. M. and FINCHAM, L. R.
(KEF Electronics Ltd.),
The Application of Digital Techniques to the Measurement of Loudspeakers,
Journal of the Audio Engineering Society, Vol. 25, No. 6, June 1977.

Drive Units

In the early days of large-scale loudspeaker manufacture, the mechanical properties of the diaphragm material were so variable that it was sometimes hard to find two drive units, even from the same batch, that sounded exactly alike. In more recent times, the situation has been ameliorated by the introduction of new materials, but close control is still necessary at all stages of production. In the Model 105, for example, the diaphragms of the low-frequency and mid-range units are vacuum-formed from Bextrene sheet, the mechanical properties of which have been measured, and coated with a visco-elastic damping material; they are then individually weighed, as shown in Figure 1, to check the thickness of the coating.

After assembly of the diaphragm with its voice coil — the resistance of which is kept to within ±5% of its nominal value — each drive unit is checked with a gliding tone for rattles or buzzes (an operation for which no satisfactory substitute for the human ear has yet been devised). The frequency of the fundamental resonance, i.e. that of the diaphragm moving as a whole on its suspension, is then measured on an "auto-resonator", illustrated in Figure 2. This device takes advantage of the fact that the mechanical resonance of the unit produces a corresponding "motional impedance" component at the electrical input; the effect is the same as if a resonant circuit, consisting of an inductor and capacitor in parallel, had been introduced in series with the voice coil. The unit under test is connected to an amplifier in such a way that the motional impedance forms part of a positive feedback loop; the whole system then oscillates at the resonance frequency of the diaphragm, which is read off directly on a frequency meter. To avoid external influences, the units are tested unmounted so that the acoustic load on the diaphragm is small; however, the allowable variation in the resonance frequency as measured in this condition is based on its known effect on the response of the complete loudspeaker.

Acoustic Tests

The higher the standard of performance attained in the loudspeaker design, the greater the accuracy required in production testing to ensure that this standard is maintained. To do justice to the best modern reproducers, the acoustic response needs to be measured to an accuracy that until recently could be achieved — if at all — only by time-consuming operations in the open air or in a large and expensive anechoic chamber. This situation has however been radically altered by the new impulse testing technique referred to earlier.

When a very short electrical impulse is applied to the input of a loudspeaker, the resulting transient sound output consists of a complex series of decaying oscillations from which it is possible, in principle, to calculate the response to any other kind of input signal. In the past, however, attempts to derive such information have been beset by practical difficulties — in particular by the poor signal-to-noise ratio at the "tail" of the transient — and only since the introduction of digital processing methods has it been possible to realise the full potentialities of this all-embracing technique.

***Fig. 1.** Weighing diaphragms to check the thickness of the visco-elastic damping layer; the balance is sensitive to changes of 10 milligrams.*

The application of the new method is briefly as follows. The loudspeaker under test and the measuring microphone are set up in a room which excludes external noise but need not be completely anechoic. An electrical impulse is applied to the loudspeaker, and the waveform of the transient response picked up by the microphone is sampled at regular time intervals, at a rate fast enough to allow all the fine detail to be accurately analysed; the amplitude of each sample is converted to a digital number, and the resulting series of numbers is stored in a computer. In theory, the analysis should go on for ever, but in practice there comes a

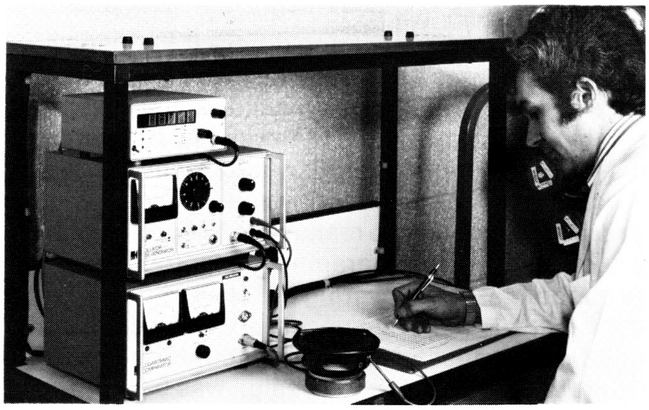

***Fig. 2.** Measuring the fundamental resonance of a drive unit; the "auto-resonator" makes the diaphragm vibrate at its natural frequency, which is displayed digitally.*

point at which the sound has died away so far that the measurement can be terminated without appreciable loss of accuracy; the dimensions of the room should therefore be sufficient to ensure that this point has been reached, and all the necessary information has been captured, before any reflections from the walls, floor or ceiling arrive at the microphone. Rooms of somewhat smaller dimensions can be used, but as the reflections then arrive earlier, the latter part of the impulse response must be truncated to avoid interference, and a correction made in the analysis for the resulting modification of the low-frequency response.

The effect of any random noise in the measuring system is reduced by repeating the test a number of times at intervals just long enough to allow the room reflections resulting from one impulse to die out before the arrival of the next; in practice, this means that the minimum interval between impulses must be about equal to the reverberation time of the room, i.e. the time required for the sound to decay by 60 dB. Each new set of digital numbers — which represent the amplitudes of both the wanted signal and the unwanted noise — is added to those already stored, and the total divided by the number of tests to give the average. The improvement in signal-to-noise ratio comes about because each successive test produces an identical set of signal amplitudes, the running total of which thus increases in proportion to the number of tests, whereas the corresponding noise amplitudes (which may be either positive or negative) add in random fashion, and their total therefore rises more slowly.

Fig. 3. Measuring the impulse response of a loudspeaker in a bare-walled test chamber; data required to compute the amplitude/frequency and phase/frequency response is picked up before first reflections arrive at the microphone.

Finally, the stored and averaged impulse response is subjected in the computer to a mathematical process known as the Fast Fourier Transform (FFT); this converts the original function of time to a function of frequency, giving the amplitude/frequency response — and, if required, the phase/frequency response — that would have been obtained by a gliding-tone measurement made under ideal conditions. Experience has shown that the response of high-quality drive units such as those used in the Model 105 loudspeaker is of the "minimum-phase-shift" type; this means that the phase shift between electrical input and acoustic output is no greater than that inherent in the shape of the amplitude/frequency response characteristic. For production testing, only the frequency response, which gives the amplitude of the output without the phase, needs to be considered.

Acoustic tests of the kind described above are carried out at various stages in the production of the Model 105. Figure 3 shows one of these loudspeakers set up in a large impulse test chamber, which is primarily intended for research and design purposes, but is used also for the calibration of selected drive units that serve as reference standards. The dimensions of this chamber, 7.6 m x 7.6 m x 7.6 m, are large enough to allow the effective free-field response of a loudspeaker at a distance of 2 m to be accurately determined for frequencies down to 50 Hz. With no added sound absorbent material other than the carpet, the mean reverberation time, and hence the minimum interval between impulses is 4 seconds.

Production Testing

Figure 4 shows the set-up for batch testing of drive units. The units, previously stored at room temperature (18° to 20°C) for 12 hours, are mounted in turn on a flat baffle which is set flush in a bare wall of the test chamber, thus providing an unobstructed hemispherical radiation space. The floor, ceiling and remaining walls of the chamber are covered with a small amount of sound absorbent material which reduces the reverberation time over the frequency range of interest to 0.2 second, so that the impulse tests can be repeated at the rate of 5 per second. A total measurement time of only 30 seconds is sufficient to determine the true free-field frequency response to an accuracy of 0.3 dB. The dimensions of the chamber, 2.5 m x 3.15 m x 3.66 m, allow the free-field response of the units at 1 m to be measured down to 100 Hz; measurements at lower frequencies are not required at this stage, since the response of bass units below 100 Hz is determined by the fundamental resonance and the flux density, which have already been measured.

The drive units are tested in batches of 94; as a check, a calibrated reference unit of the same type

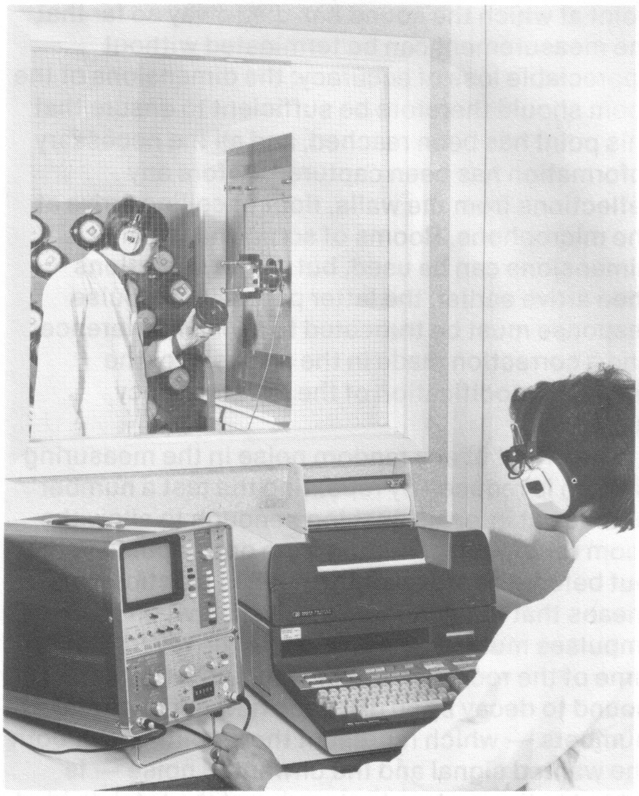

Fig. 4. Batch testing of drive units by impulse measurement.

is measured at the beginning and end of each set of tests. The impulse response of each unit is stored on magnetic disc; from this information, the computer calculates the corresponding frequency response and then carries out a matching programme for the batch, listing the sensitivity of each unit with respect to the reference unit together with the maximum deviation of the unit response — measured at eight frequencies per octave — with respect to the reference response. (If required, a printout can be produced showing, for each of these frequencies, the statistical distribution of the results.) The computer programme also matches the units into pairs, giving the mean sensitivity for the pair and the residual match error, if any; Figure 5 shows a typical computer printout of a matching routine together with the frequency response characteristics of two units paired by the computer with a match error of 0.5 dB. Finally, sets of six matched units are selected to make up pairs of matched loudspeaker systems; Figure 6 shows sets of selected units en route to the assembly area, illustrated in Figure 7. To facilitate after-sales service, test results for all drive units are recorded, so that in case of accidental damage, a pair of replacement units can be supplied which are matched, not only to each other, but to the other units in the system; the relevant information for each pair of loudspeakers is filed in the form of a ''customer printout'', an example of which is reproduced in Figure 8.

Crossover Networks

The crossover networks in the Model 105 loudspeaker are of an advanced type*, incorporating a total of 23 circuit elements; to ensure that the design objectives are realised in production, the values of these elements must be carefully controlled to avoid the danger of cumulative errors. To this end, all the network components — which, as received, are generally within ±5% tolerance limits — are measured and sorted into a number of groups, each covering an increment of 1% in deviation from the nominal value; in assembling the networks selection is made, on the basis of this grading, so that the deviations of different components have opposing rather than additive effects on the overall characteristics of the circuit. The networks are constructed in pairs, components from the same group being used in equivalent positions; for every network, the deviation of each component from its nominal value is recorded for reference, so that a similar replacement can be provided, if necessary, for after-sales servicing.

The response of the low-frequency, mid-range and high-frequency network assigned to each loudspeaker is checked against a corresponding reference network by a sensitive comparator, the maximum disparity allowed being $\pm\frac{1}{2}$ dB over the pass-band in each case, and ±1 dB in the cut-off region; the two corresponding networks of a

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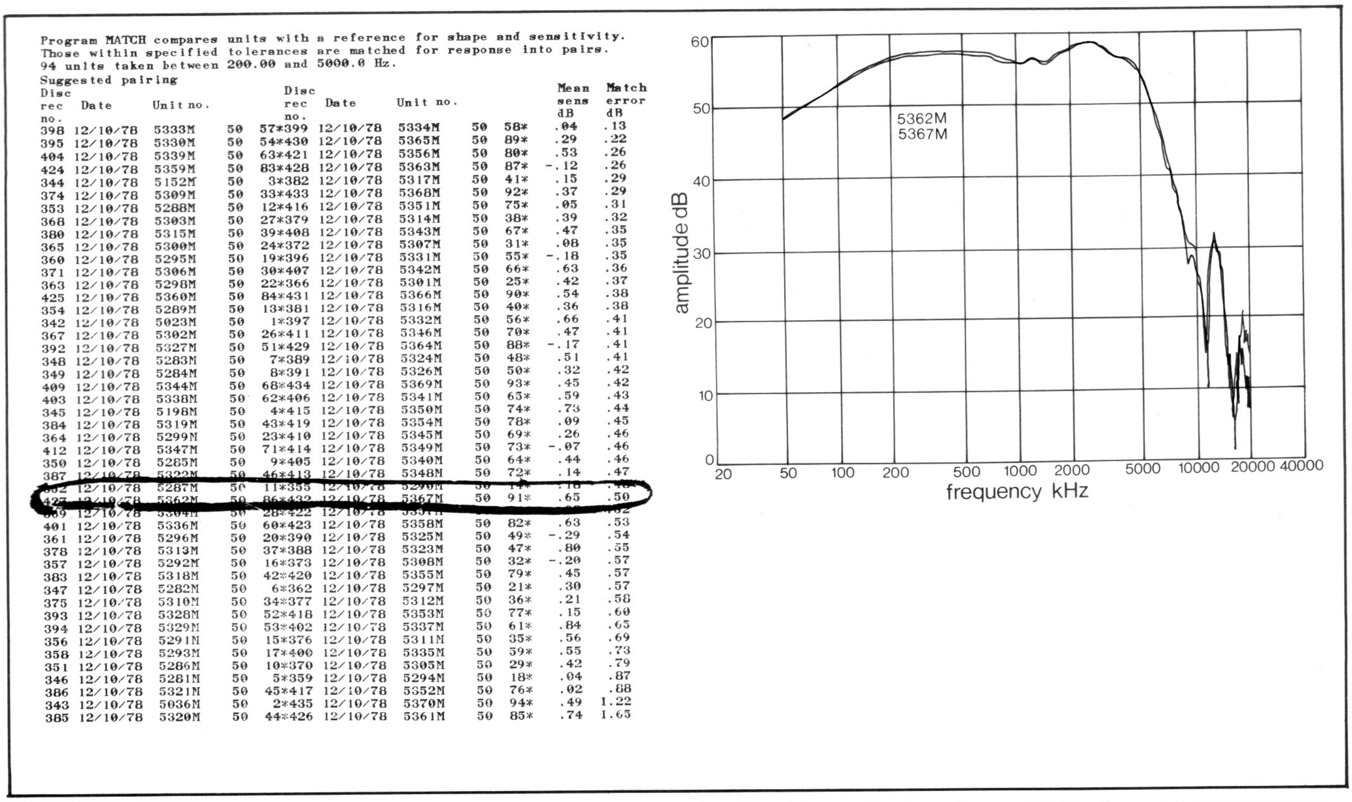

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Program MATCH compares units with a reference for shape and sensitivity.
Those within specified tolerances are matched for response into pairs.
94 units taken between 200.00 and 5000.0 Hz.
Suggested pairing
Disc                                 Disc                                 Mean  Match
rec  Date      Unit no.              rec  Date      Unit no.              sens  error
no.                                  no.                                  dB    dB
398 12/10/78  5333M     50  57*399 12/10/78  5334M     50  58*   .04   .13
395 12/10/78  5330M     50  54*430 12/10/78  5365M     50  89*   .29   .22
404 12/10/78  5339M     50  63*421 12/10/78  5356M     50  80*   .53   .26
424 12/10/78  5359M     50  83*428 12/10/78  5363M     50  87*  -.12   .26
344 12/10/78  5152M     50   3*382 12/10/78  5317M     50  41*   .15   .29
374 12/10/78  5309M     50  33*433 12/10/78  5368M     50  92*   .37   .29
353 12/10/78  5288M     50  12*416 12/10/78  5351M     50  75*   .05   .31
368 12/10/78  5303M     50  27*379 12/10/78  5314M     50  38*   .39   .32
380 12/10/78  5315M     50  39*408 12/10/78  5343M     50  67*   .47   .35
365 12/10/78  5300M     50  24*372 12/10/78  5307M     50  31*   .08   .35
360 12/10/78  5295M     50  19*396 12/10/78  5331M     50  55*  -.18   .35
371 12/10/78  5306M     50  30*407 12/10/78  5342M     50  66*   .63   .36
363 12/10/78  5298M     50  22*366 12/10/78  5301M     50  25*   .42   .37
425 12/10/78  5360M     50  84*431 12/10/78  5366M     50  90*   .54   .38
354 12/10/78  5289M     50  13*381 12/10/78  5316M     50  40*   .36   .38
342 12/10/78  5023M     50   1*397 12/10/78  5332M     50  56*   .66   .41
367 12/10/78  5302M     50  26*411 12/10/78  5346M     50  70*   .47   .41
392 12/10/78  5327M     50  51*429 12/10/78  5364M     50  88*  -.17   .41
348 12/10/78  5283M     50   7*389 12/10/78  5324M     50  48*   .51   .41
349 12/10/78  5284M     50   8*391 12/10/78  5326M     50  50*   .32   .42
409 12/10/78  5344M     50  68*434 12/10/78  5369M     50  93*   .45   .42
403 12/10/78  5338M     50  62*406 12/10/78  5341M     50  65*   .59   .43
345 12/10/78  5198M     50   4*415 12/10/78  5350M     50  74*   .73   .44
384 12/10/78  5319M     50  43*419 12/10/78  5354M     50  78*   .09   .45
364 12/10/78  5299M     50  23*410 12/10/78  5345M     50  69*   .26   .46
412 12/10/78  5347M     50  71*414 12/10/78  5349M     50  73*  -.07   .46
350 12/10/78  5285M     50   9*405 12/10/78  5340M     50  64*   .44   .46
387 12/10/78  5322M     50  46*413 12/10/78  5348M     50  72*   .14   .47
352 12/10/78  5287M     50  11*355 12/10/78  5290M     50  14*   .18   .48
427 12/10/78  5362M     50  86*432 12/10/78  5367M     50  91*   .65   .50
369 12/10/78  5304M     50  28*422 12/10/78  5357M     [illegible]   .62
401 12/10/78  5336M     50  60*423 12/10/78  5358M     50  82*   .63   .53
361 12/10/78  5296M     50  20*390 12/10/78  5325M     50  49*  -.29   .54
378 12/10/78  5313M     50  37*388 12/10/78  5323M     50  47*   .80   .55
357 12/10/78  5292M     50  16*373 12/10/78  5308M     50  32*  -.20   .57
383 12/10/78  5318M     50  42*420 12/10/78  5355M     50  79*   .45   .57
347 12/10/78  5282M     50   6*362 12/10/78  5297M     50  21*   .30   .57
375 12/10/78  5310M     50  34*377 12/10/78  5312M     50  36*   .21   .58
393 12/10/78  5328M     50  52*418 12/10/78  5353M     50  77*   .15   .60
394 12/10/78  5329M     50  53*402 12/10/78  5337M     50  61*   .84   .65
356 12/10/78  5291M     50  15*376 12/10/78  5311M     50  35*   .56   .69
358 12/10/78  5293M     50  17*400 12/10/78  5335M     50  59*   .55   .73
351 12/10/78  5286M     50  10*370 12/10/78  5305M     50  29*   .42   .79
346 12/10/78  5281M     50   5*359 12/10/78  5294M     50  18*   .04   .87
386 12/10/78  5321M     50  45*417 12/10/78  5352M     50  76*   .02   .88
343 12/10/78  5036M     50   2*435 12/10/78  5370M     50  94*   .49  1.22
385 12/10/78  5320M     50  44*426 12/10/78  5361M     50  85*   .74  1.65
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Fig. 5. *Computer printout from the matching routine for a batch of 94 drive units, together with the frequency response curves of a typical pair of matched units.*

loudspeaker pair are similarly checked against each other, and must not differ by more than 0.2 dB.

Head Assembly

In the Model 105 loudspeaker, the mid-range and high-frequency drive units, with their associated crossover networks, are housed in a separate head assembly mounted on top of the bass enclosure. The head assembly, which can be turned and tilted as required to give optimum sound distribution over the designated listening area, is provided with a light-emitting diode (LED), energised by the audio signal fed to the loudspeaker; this LED serves as a peak level indicator, but can also be switched temporarily to glow continuously at low signal level to enable the positioning of the head to be checked.

The bass enclosures are constructed in pairs with matching walnut veneer, and to avoid damage to the finish, they should be handled as little as possible. Before the complete loudspeaker is put together, therefore, the head assembly is tested separately while mounted temporarily on a dummy enclosure to simulate the final working condition. The gliding tone test for rattle and buzz, already carried out on the individual drive units, is repeated for each head assembly, and the operation of the LED is checked. The acoustic frequency response is then measured; each head assembly, mounted on its dummy bass enclosure, is carried on a roller conveyor into a system test chamber, illustrated in Figure 9, where a trolley driven by a linear induction motor brings it to the measuring position.

The dimensions of the system test chamber, 5.8 m x 4.8 m x 3.66 m, are large enough to allow measurements to be made on loudspeaker assemblies at the typical listening distance of 2 m. As before, sufficient sound absorbent material — distributed in this case over all six surfaces — is provided to reduce the reverberation time to 0.2 second, so that tests can be repeated at the rate of 5 impulses per second. The computer stores the characteristics of the two head assemblies designated as a stereo pair, and calculates the difference between them; both these characteristics and their difference — which must be less than 1 dB — are then drawn out on an X-Y plotter for inspection.

Overall Test

In the last stage of construction and objective testing of the Model 105, each head assembly is mounted on a bass enclosure fitted with the low-frequency drive unit already assigned to it, and the complete loudspeaker is given a further glide-tone check for rattle and buzz. The impedance/frequency curves for the two loudspeakers of a stereo pair are then traced, using an X-Y plotter coupled to an oscillator; the impedances must not fall below the specified minimum, or differ from one another by more than 0.5 ohm. Finally, each loudspeaker is returned to the system test chamber of Figure 9 where the impulse response is measured at 2 m on the design axis. The resulting data is stored on a magnetic disc for future reference, while the

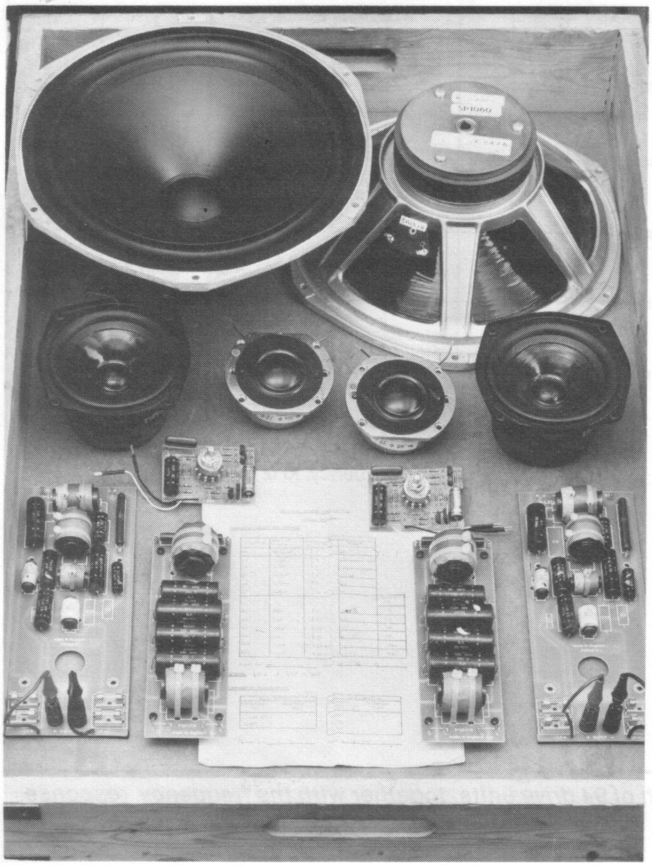


Fig. 6. *Drive units and crossover networks in matched sets ready for assembly.*

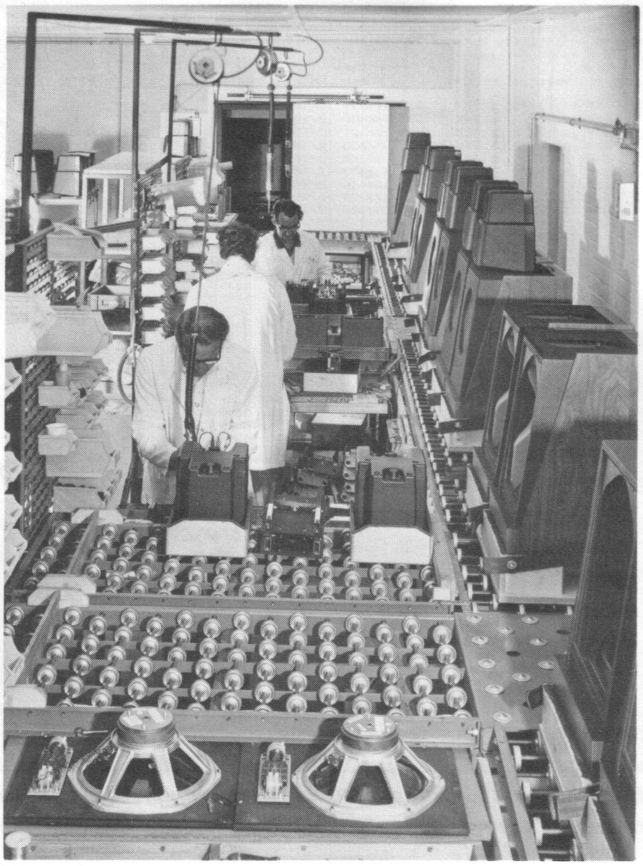
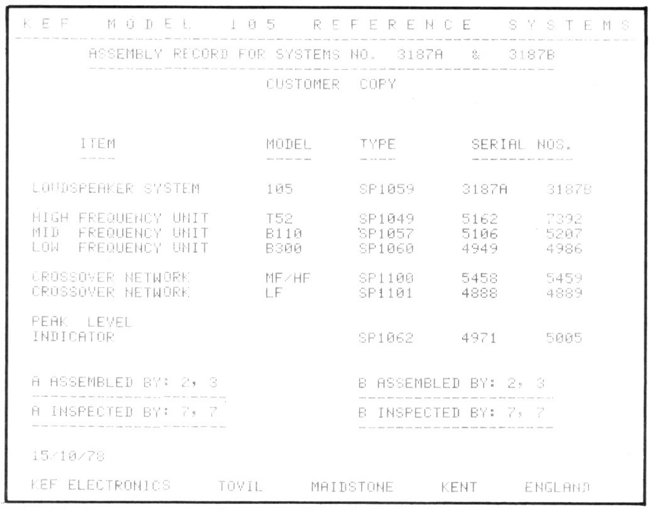


Fig. 7. *General view of assembly area for Model 105 loudspeakers.*

corresponding frequency response, from 50 Hz to 20 kHz, is plotted out; the difference between the two loudspeakers of a pair is also plotted, using a decibel scale magnified ten times so that even small disparities can be observed. The impulse response is truncated, as described earlier, to eliminate room reflections, and to obtain the true free-field characteristics below 150 Hz, a constant correction is made in the computer.

The tolerances applied to the overall frequency response are in practice more stringent than might be expected from the ±2 dB limits given in the loudspeaker specification. Those limits, if legalistically interpreted, would allow, for example, a continuously sloping characteristic with the top end 4 dB above the bass, or one that lies mainly on the lower boundary but has a number of 4 dB peaks. KEF, however, work on the principle that the frequency response of production models should be kept as close as possible to that of the prototype — which has already been shown to be acceptable — and that the most realistic criterion is therefore the deviation from the design centre curve. By rigorous testing and matching of components in the earlier stages of production, the spread in the axial frequency response of the Model 105 has been kept within the limits shown in Figure 10. The dashed curves are spaced by two standard deviations* above and below the design centre response; just over 95% of the characteristics measured on the production line lie between these curves, and thus fall well inside the ±2 dB specification. In addition, as a result of the selection of components, the frequency characteristics of any two loudspeakers designated as a stereo pair are closely matched, as illustrated by the typical example shown in Figure 10a.



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K E F   M O D E L   1 0 5   R E F E R E N C E   S Y S T E M S
-------------------------------------------------------------
      ASSEMBLY RECORD FOR SYSTEMS NO.  3187A  &  3187B
      ---------------------------------------------------
                       CUSTOMER  COPY


     ITEM                  MODEL     TYPE       SERIAL NOS.
     ----                  -----     ----       -----------

 LOUDSPEAKER SYSTEM        105       SP1059    3187A    3187B

 HIGH FREQUENCY UNIT       T52       SP1049    5162     7392
 MID  FREQUENCY UNIT       B110      SP1057    5106     5207
 LOW  FREQUENCY UNIT       B300      SP1060    4949     4986

 CROSSOVER NETWORK         MF/HF     SP1100    5458     5459
 CROSSOVER NETWORK         LF        SP1101    4888     4889

 PEAK  LEVEL
 INDICATOR                           SP1062    4971     5005


 A ASSEMBLED BY: 2, 3                B ASSEMBLED BY: 2, 3
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 A INSPECTED BY: 7, 7                B INSPECTED BY: 7, 7
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 KEF ELECTRONICS     TOVIL      MAIDSTONE      KENT      ENGLAND
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Fig. 8. *Customer printout showing serial numbers of drive units, crossover networks and peak level indicators fitted to one loudspeaker pair.*

**The standard deviation is a measure of variability; it is the root-mean-square value of the amounts by which the results for the individual specimens tested differ from the average.*

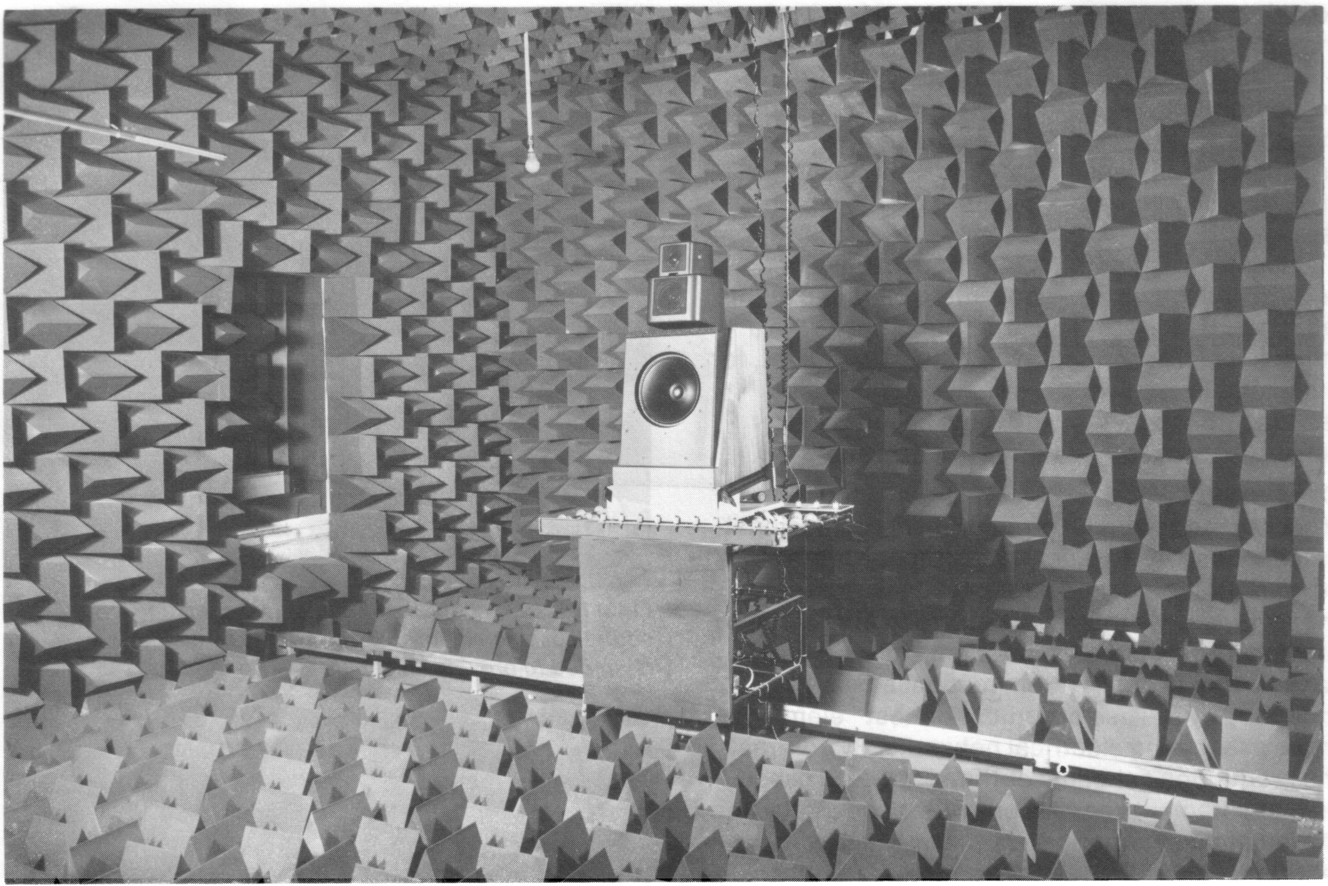

Fig. 9. *System test chamber for head assemblies and complete loudspeakers.*

Subjective Tests

After the comprehensive series of objective tests already applied to each loudspeaker, subjective assessment of performance might appear superfluous; experience shows, however, that a last-minute check of this kind is advisable, if only to detect faults arising, for example, from accidental damage or disconnection of units.

Each pair of loudspeakers is set up in the room illustrated in Figure 11, which is designed to provide ideal listening conditions in a room of typical domestic size, and has a mean reverberation time of 0.25 second. Initially, the two systems are placed side by side and fed with identical signals. The LEDs are checked for equal brightness, first in their low-level operating mode, using continuous pink noise, and then in their normal function as peak level indicators, using high-level pink noise pulsed to simulate programme.

The listening tests begin with pink noise, presented alternately on the left and right channels as a sensitive check on the tonal balance of the loudspeaker pair. This is followed by recorded speech, again alternating between the two loudspeakers; the voice is that of a male member of staff well known to the test engineer, and therefore constitutes a critical test for naturalness. Subjective assessments of this kind can give misleading results if the volume of the reproduced

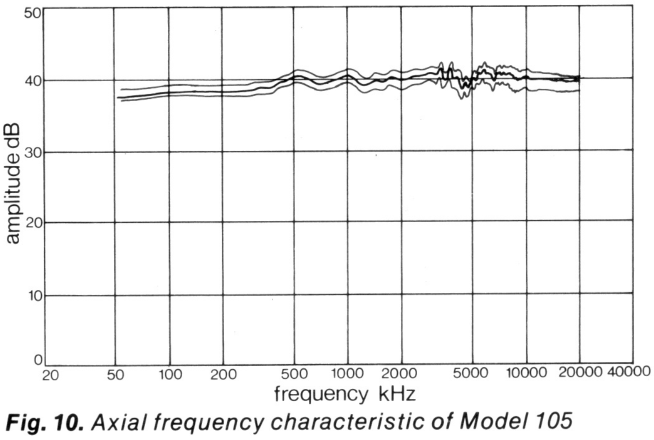

Fig. 10. *Axial frequency characteristic of Model 105 loudspeaker.*
—— design-centre response
production spread (± 2 x standard deviation)

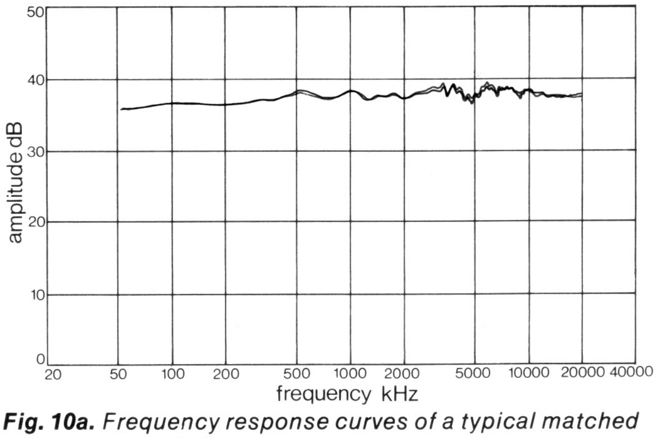

Fig. 10a. *Frequency response curves of a typical matched pair of Model 105 loudspeakers.*

sound is too high or too low; all signal levels are therefore accurately standardised.

Finally, the two loudspeakers are set up at the normal spacing for stereo reproduction, as shown in the figure, and recordings covering a broad cross-section of music, including strings, brass, piano and other percussion instruments are replayed.

Assuming that nothing untoward is observed — and it is indeed rare for any fault to be found at this late stage — the test schedule concludes with a minute visual examination, under a strong light, for finger marks or other blemishes that may have resulted from handling and must be removed before the packaging stage.


***Fig. 11.** Listening room for subjective checking. The sound absorption units on the walls and ceiling are designed to provide ideal listening conditions.*

Conclusion

Modern practice in the production of professional-grade loudspeakers such as the Model 105 is far in advance of the methods adopted a few years ago. In those days, drive units were selected on the basis of relatively coarse measurements, the grosser variations in overall system response being mitigated by the use of "adjust-on-test" elements in the associated electrical networks. By contrast, the production schedule outlined above is based on measurements carried out with an accuracy and thoroughness formerly possible only under laboratory conditions, combined with a comprehensive process of grading and matching; as a result, the performance of the end product can be held, without the need for adjustment, within limits close enough to satisfy the most stringent requirements — for example, those imposed on loudspeakers designed for monitoring purposes.

Although many of the operations described depend on computer technology, and in principle involve some advanced theoretical concepts, their practical application in a production routine is simple and straightforward. The cost of the necessary equipment has amply justified itself, not only by the improved performance of the product, but by the low fault rate that comes from stringent testing, plus the effective after-sales service made possible by the keeping of detailed records; as a result of the experience with the production of Model 105, it has been decided to apply the new methods to future KEF loudspeakers.

Because of the high degree of consistency obtainable by modern technology, it can now be claimed with confidence that the standard of performance achieved by the designer is not confined to the prototypes used in demonstrations and press reviews, but is realised in full for each and every purchaser.

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