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ABSTRACT

Several high load balance systems have been designed and manufactured in recent years. Some systems failed after intensive use. A review of the complete balance development chain, from specification to tunnel use has been performed, and influential factors have been identified. Better fatigue analysis is possible and necessary, based on a more accurate load specification. For balances which will endure a highly unpredictable load spectrum, a fatigue monitoring system is necessary.

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Abstract
Several high load balance systems have been designed and manufactured in recent years. Some systems failed after intensive use. A review of the complete balance development chain, from specification to tunnel use has been performed, and influential factors have been identified. Better fatigue analysis is possible and necessary, based on a more accurate load specification. For balances which will endure a highly unpredictable load spectrum, a fatigue monitoring system is necessary.

1 Introduction

In recent years the need for compact strain gauge balances with a high load capacity was apparent and several balances were designed and manufactured for this purpose. Not only in the form of universal sting balances but also as weighted parts i.e. model parts (e.g. flap, aileron) with measuring sections. Review of the general design approach of balances have been already performed (ref.[1]).

The requirements of smaller dimensions and higher load capacity complicated the design considerably. To cope with these complications finite element analyses were applied for optimising the design, ultra high strength steels were used, and in some cases the safety factors were relaxed.

However, some balance systems failed due to fatigue. In principle all the designs should have ensured an infinite life with respect to fatigue, so review of the complete process, i.e. specification, design, manufacturing, instrumentation, handling and use was necessary.

There already have been a number of studies (e.g. ref.[2]) regarding specific fatigue aspects with respect to strain gauge balances. Unfortunately, some articles are not to be referred to.

This article is intended to give an overview of fatigue related aspects in the complete process (from specification up to tunnel use).

2 Two examples of fatigue failure

Two examples of balance systems which failed are given here. Both systems were used in a severe dynamic environment for long periods of time. Their design was based on typical values of static and dynamic loads which were empirically determined during years of tunnel operation. Since available space was limited, relatively high material stresses were calculated and suitable balance materials were chosen (15-5PH H1025, and VEW W720).

Based on the safety factors for the static load and the expected dynamic allowance (30% of maximum static load), and analysed with a modified Goodman diagram, both designs were expected to have infinite fatigue life.

After intensive tunnel use a significant degradation of their behaviour occurred with various symptoms like altered bridge sensitivities, changed interaction terms, increased non-linearity, and significantly changed zero load bridge off-set values. In both cases no extreme hysteresis change had occurred. The first investigations were focused on an instrumentation problem. When this did not give appropriate answers further investigations were focused on the balance body itself. Though not apparent at first sight, fatigue cracks were detected in the balance body.

Weighted flap (secondary balance)

The model flap had simple beam sections for hinge moment and normal force measurement. See figure 1. Hinge moment signal was generated by torsion. The crack was only visible when loading the balance. See figure 2. The crack initiated from the radius of the beam and had grown to the strain gauge location.

The balance had endured at least $2{,}8 \cdot 10^8$ cycles.

Sting balance
This balance showed two cracks which were found using dye penetrant fluid. One crack was located in the model connection (threaded end), and the other crack was located on the back bone part of the central balance body (see figure 3). It was difficult to relate the position of the cracks to the observed strain gauge behaviours; potential cracks on the critical locations (see figure 4) would give a better explanation but to be able to investigate this the balance must be specially prepared (i.e. destroyed). After using this balance for some additional experimental load tests, this will probably be done in the near future.
The mere presence of fatigue cracks in the construction together with the degradation of the strain gauge signals was sufficient evidence that the balance had reached the end of its finite fatigue life.
It could be derived that the balance had endured at least $1{,}5 \cdot 10^8$ cycles.

3 Fatigue influential factors

Fatigue is a phenomenon that is well described in many excellent textbooks (ref.[3],[4]), and also the design aspects for machine elements are properly identified (ref.[5]). Some wind tunnel organisations specifically describe the fatigue requirements on a design for a part to be used in the tunnel (ref.[6],[7]). For strain gauge balances a different approach is principally not necessary but it is such a complex machine element which can be affected by a large number of phenomena, that identifying these influences especially for balances is worthwhile.

3.1 Specification of loads

In designing against fatigue the reliability of the expected load spectrum is of major importance. In most cases balances will be subjected to fluctuating loads (non-zero mean cyclic loads). The mean load, the alternating load amplitude, load frequency and the required life time are to be specified. It seems obvious to require an infinite fatigue life but for this the mean load and alternating load amplitude will have to be strictly limited and will probably yield to an unacceptable insensitive balance design.
In general strain gauge balances will be subject to two types of loads during testing : loads which are more or less expected results of the chosen conditions (model incidence, mach number etc.), and loads which have a random nature. For a balance the mean loads are usually predictable, and the alternating loads will be more random, although in some cases fluctuating loads are also to be expected (rotating systems) and therefore predictable.
Depending on the type of balance the prediction of the load spectrum can be more or less realistic.
For weighted parts the load spectrum could be well estimated from full scale values for the mean load and alternating load amplitudes. Also eigenfrequency calculations of the model part might give an idea about the expected life time. These types of balances will usually have a limited period of use, and can therefore be optimised for finite life.
For rotating balances (as a special type of a model part balance) the load spectrum can be well defined since rotational speeds and most load amplitudes are known. These balances have a dedicated design since they are normally intended for a specific model.
For universal balances (sting or external) the expected load spectrum will be essentially unpredictable since it will not be clear for which future tests the balance will be used. Each test with another wind tunnel model will have its own dynamic characteristics. Of course a classification of types of wind tunnel tests can be made with their own typical load spectra, but that requires a thorough dynamic analysis of a large number of tests. For normal capacity balances used in "normal" models and tunnel tests there was already a good specification available based on years of experience, but for high load balances this was not the case. The balances which failed were designed for an expected load spectrum for "normal" capacity balances. These high load balances were subject to quite a different load spectrum : instead of the assumed load amplitude of 25-30% of the maximum allowable mean load, amplitude values of more than 100% for specific components over longer periods were not uncommon. Figures 5 and 6 show the dynamic behaviour of the axial force signal and the main frequencies in this signal during a wind tunnel test with high dynamic loads. Furthermore, at the same time the mean measured loads were near or exceeded the maximum allowable mean load. Assessment of a reliable expected load spectrum for high load balances is necessary.

3.2 Design

For normal capacity balances a limited fatigue analysis is done by analysing the calculated

maximum loads and the expected dynamic load amplitude (max. 30% of maximum static load) using Master diagrams (if available) or constructed modified Goodman diagrams. Due to the relatively high safety factor (>3 on ultimate strength) on the maximum static loads and the limited load amplitudes for these balances, fatigue failure is unlikely.
After having established that high capacity balances will have to function in conditions which might lead to fatigue failure, the design procedure should account for this. There are many handbooks which offer good guidelines for doing this (ref.[5],[8]).
Some aspects are highlighted here.

Material fatigue properties

In many cases material fatigue properties are not or only limited available. For one of the most widely used balance materials (17-4PH/15-5PH) more details are available (ref.[9]), like a Master diagram. However, for high capacity balances maraging steels are used for which very little information is available. So for these materials modified Goodman diagrams for a given number of cycles have to be constructed, using sometimes estimated values for fatigue limits.
Moreover, fatigue data from manufacturers are based on fatigue tests on standardised test specimen which in most cases have no resemblance to the design of a balance. The manufacturer's data have to be corrected by applying so-called Marin factors which should represent the actual geometry and environment of the balance.

Fatigue correction factors

The corrected fatigue limit is the product of the given fatigue limit and a range of Marin factors :

$S_f = k_1 k_2 \ldots k_i \times S_{fg}$ with

S_f = corrected fatigue limit
$k_1(k_2 \ldots k_i)$ = Marin factor for specific situation
S_{fg} = given fatigue limit (manufacturer’s data)

This new corrected fatigue limit should be used in the fatigue analysis.

The most important factors are :
Surface finish : depending on the manufacturing technique a surface condition will be introduced which can affect the fatigue limit significantly. Polishing, grinding, machining, spark erosion etc. will result in different values of the Marin factor, depending on the tensile strength of the balance material. Grinding, machining and spark erosion are widely used techniques in balance manufacturing. Typical values will vary between k = 0.5 and k = 0.9. See for example references [2][5][10].
Size : a larger part will also have a larger probability of material imperfections. In the literature numerical approximations are given (ref.[8]) or typical values can be used (ref.[5]). For a balance the typical size is difficult to determine since the critical location will be part of the larger body. In fact the size of the critical region should be determined.
Type of load : many material fatigue limits are determined with specimen tested on rotating-bending machines. The critical region in a balance will probably be loaded in a different way, e.g. by torsion. For pure torsion the Marin factor is k = 0.577 (ref.[8]) which is a significant reduction.
However, this aspect is complicated by the fact that in many cases an equivalent stress (e.g. vonMises stress) will be computed due to the multi-axial stress state in the balance. The Marin factor for this can be k = 1.0, equivalent to bending.
Stress Concentration : especially for fatigue phenomena evaluation of stress concentration effects is important since the fatigue stress concentration factor is in fact a material property. The fatigue stress concentration factor K_f is related to the theoretical geometry stress concentration factor K_t via the notch sensitivity index q :

$$K_f = 1 + q(K_t - 1)$$

The theoretical stress concentration factors are widely used in many designs (ref.[11]) and the notch sensitivity index can be found in several handbooks (ref.[4],[11]). The factor should not be used to correct the fatigue limit but to correct the calculated stresses.
For ductile materials and nonzero mean loads the fatigue stress concentration factor should be applied to the alternating stress only, and not to the mean stress (ref.[5]).
When using finite element models in balance design stress concentration effects can be simulated and could already be included in the calculated maximum stress; for these situations no factor will have to be applied.

Finite element calculations

Over the past years the use of finite element methods has grown into a standard design tool in the balance design process. See reference [12] .A strain gauge balance is a very suitable construction for application of these methods since there always will be a good feedback of stress data from the realised product. For the "macro" behaviour of the balance this method will give very reliable results. However, in a detailed fatigue analysis local effects will have to be investigated. A FEM-model of the complete balance will not be adequate due to the inability to simulate in this model all small radii. Modelling only the critical parts of the balance should be done in order to be able to judge reliably stress concentration effects.

The above mentioned list of design factors is not complete and should not to be used without a detailed analysis of actual situation in the balance concept design. It is merely intended to point out the complexity of designing a high capacity or other fatigue sensitive balance.

3.3 Manufacturing

From paragraph 3.2 it is clear that the manufacturing process will influence the material fatigue properties. Choosing an adequate process will usually mean choosing a *technically* or *cost effective* adequate process, but for fatigue sensitive designs this requires special attention.
Also manufacturing imperfections (e.g. small grooves, notches) should be avoided near critical locations. Residual surface stresses due to machining or heat treatment also have an influence on the fatigue properties. Negative when tensile, positive when compressive.
There are surface treatments possible to compensate for the negative influence of the manufacturing process. Shot peening is an example of introducing compressive surface stresses in order to enhance the fatigue properties. When spark erosion has been used, the influenced layer can be removed by e.g. etching.

3.4 Instrumentation

Strain gauges have their own fatigue properties. When designing a balance the strain level for each strain gauge should be evaluated for fatigue. Normally the strain level will have an optimised measuring value which will be relatively low (400 - 800 microstrain).

Other instrumentation aspects are the choice of bonding, compensation resistances and coating. No fatigue problems related to these aspects have been reported, so failing due to these parts seems unlikely.
In determining the routing of bridge wiring, locations with possible large deflections are to be avoided.

3.5 Handling

During mounting and dismounting of models and balances, large handling forces and shock loads can occur. Although clearly to be avoided, especially the handling of heavy wind tunnel models could yield to momentary overloading the balance. This could cause local plastic deformation which may not be noticeable for a longer period. The general behaviour of the balance does not have to be deteriorated by this local deformation but it will influence the fatigue properties of the material. There will be a negative effect when it initiates new micro cracks which can grow in to large fatigue cracks.
Especially if tapered cone connections are used, a hazardous situation can occur when loosening the male taper from the female socket. Due to heavy loading during the wind tunnel test the cone connection will be firmly pressed. Loosening it can release large shock loads which easily can damage the balance.
Most wind tunnels will have special handling procedures to minimise the risks.

3.6 Tunnel use

When used in a wind tunnel test, balances normally can be on-line monitored using several systems.
The first system is an overload safe guard. By on-line computing the material stresses on critical locations in the balance body, this systems ensures that the mean static material stress will not exceed the allowable stress. However, it should be reminded that the critical locations have been determined by using a finite element model of the balance; although proven reliable, it will stay a theoretical model.
The second system is a signal check which ensures that the readings of the strain gauge bridges (static plus dynamic) will remain under a chosen maximum voltage. This maximum should account for the expected dynamic allowance.
Both systems are only intended as safe guarding during the wind tunnel test but can not be used as a fatigue monitoring system. Such a system will

be necessary if a balance will be used in a severe dynamic environment. The system should be able to record the load history with all relevant data. The advantage of using such systems will be that not only the balance history will be known, but it will give also the possibility to judge the remaining balance life. Based on cumulative damage assessment procedures and life prediction rules (ref.[4]) software routines can be written to form a dedicated system. However, automated fatigue monitoring systems are also commercially available; evaluation of their applicability for balance systems seems worthwhile.

4 Discussion

Using the terms "detailed fatigue analysis" implies an accurate performed analysis but caution must be taken since many of the available data needed for the analysis will be estimates (e.g. material properties) or theoretical approximations (e.g. FEM-results). Therefore accumulation of uncertainties cannot be avoided.

Reviewing the complete design chain, it is clear that there is no general optimal design routine for high load balance systems. Each new design will need its own detailed analysis in which the applicable fatigue aspects are dealt with.

Given the nature of the fatigue process, it should be pointed out that also normal capacity balances could fail due to fatigue if somewhere in their load history an overload has occurred. This overload could be either a load causing plastic deformation, or for a longer period an alternating load above the fatigue strength (which will have at that moment a value that depends on the number of already endured cycles). The overload can have initiated cracks which can grow into large fatigue cracks, even if the balance will further be used under "normal" load conditions. So, a fatigue monitoring system will also be useful for "normal" capacity balances.

A main problem is how to detect fatigue induced failing before the balance measurement behaviour is affected. Using a fatigue monitoring system can give a prediction of the remaining life under assumed future load spectra, but it will not give the exact failure point. Ideally, a fail safe mechanism should be present in the balance, i.e. failing of this part will not influence the measurement quality and not deteriorate the balance mechanical integrity; this part should be designed as the most fatigue sensitive part and should endure the exact same load spectrum as the complete balance. A special strain gauge with a relatively low fatigue limit, placed on a smart location could perhaps be such a mechanism.

5 Conclusions

A better fatigue analysis for high capacity balances and other fatigue sensitive balances can be done, based on more specific load spectra and a more detailed design approach.

Influential factors on fatigue properties are present in all phases of a balance life, and should be identified and accounted for.

If a balance will have to endure an unpredictable load spectrum an automated fatigue monitoring system is necessary.

The possibility of incorporating a fail safe system in the balance should be investigated.

6 Acknowledgement

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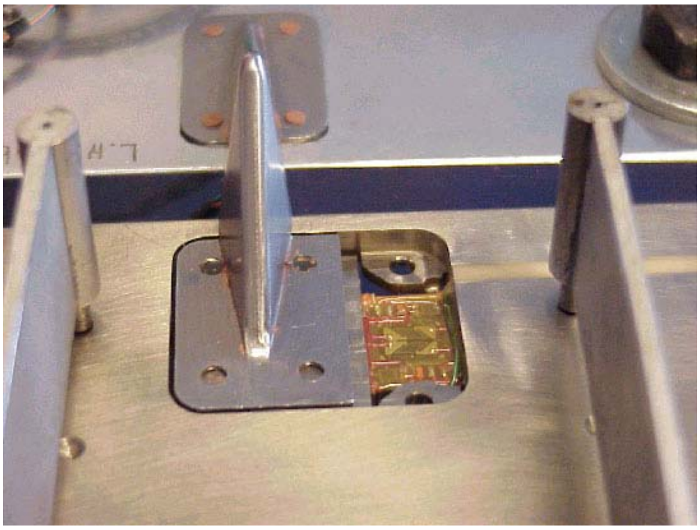
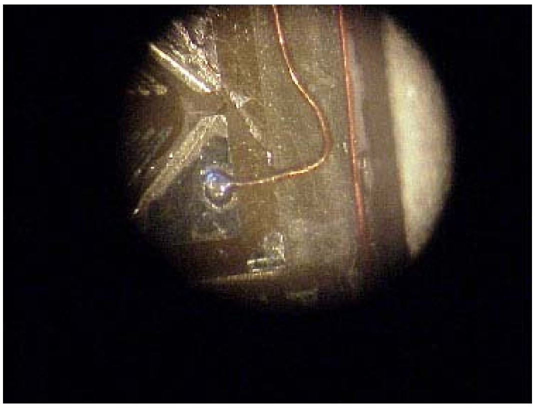


Figure 1 Measuring section on model flap



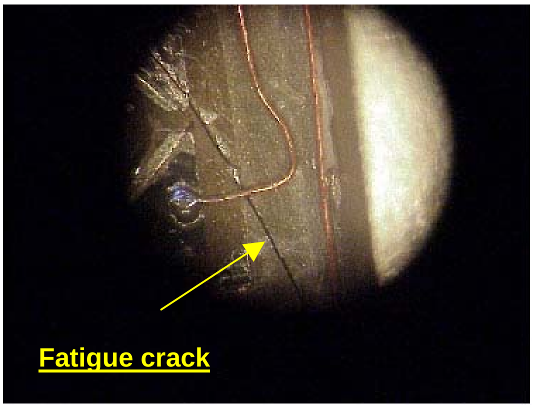


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Figure 2 Crack in measuring section

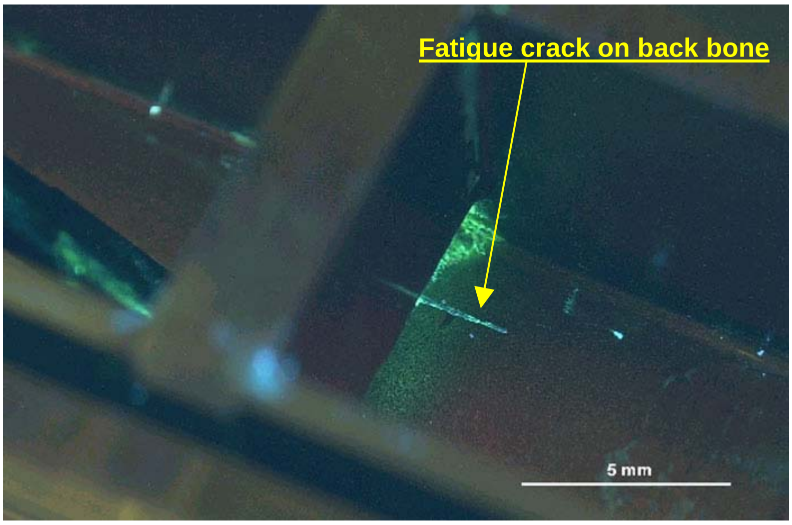

Figure 3 Crack in back bone of sting balance

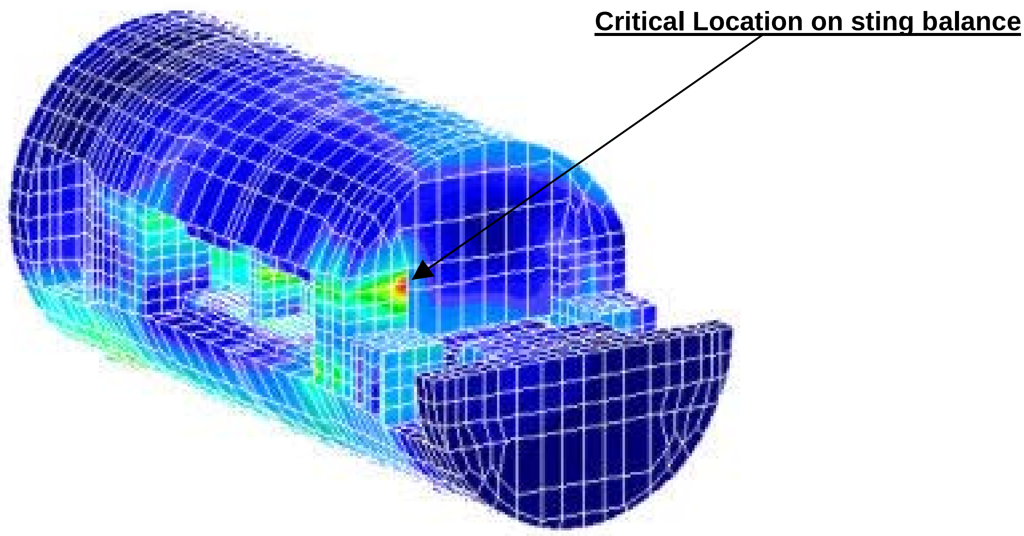

Figure 4 Section of FEM model of axial force element (subject to worst case load combination)

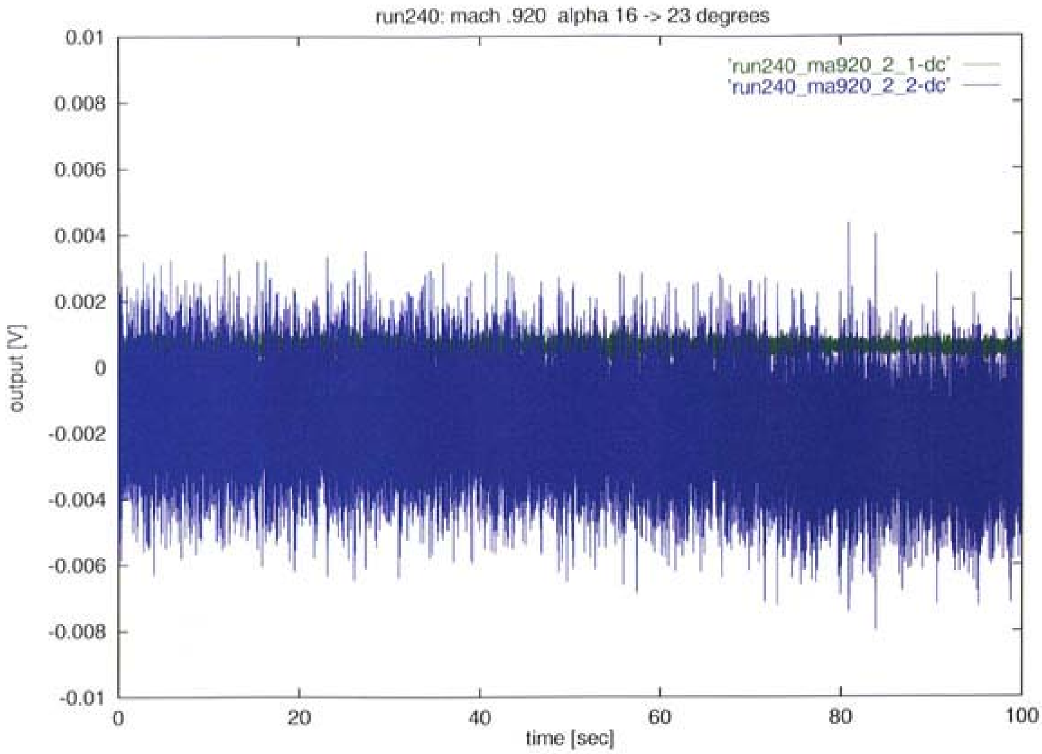

Figure 5 Example of dynamic behaviour of output signal

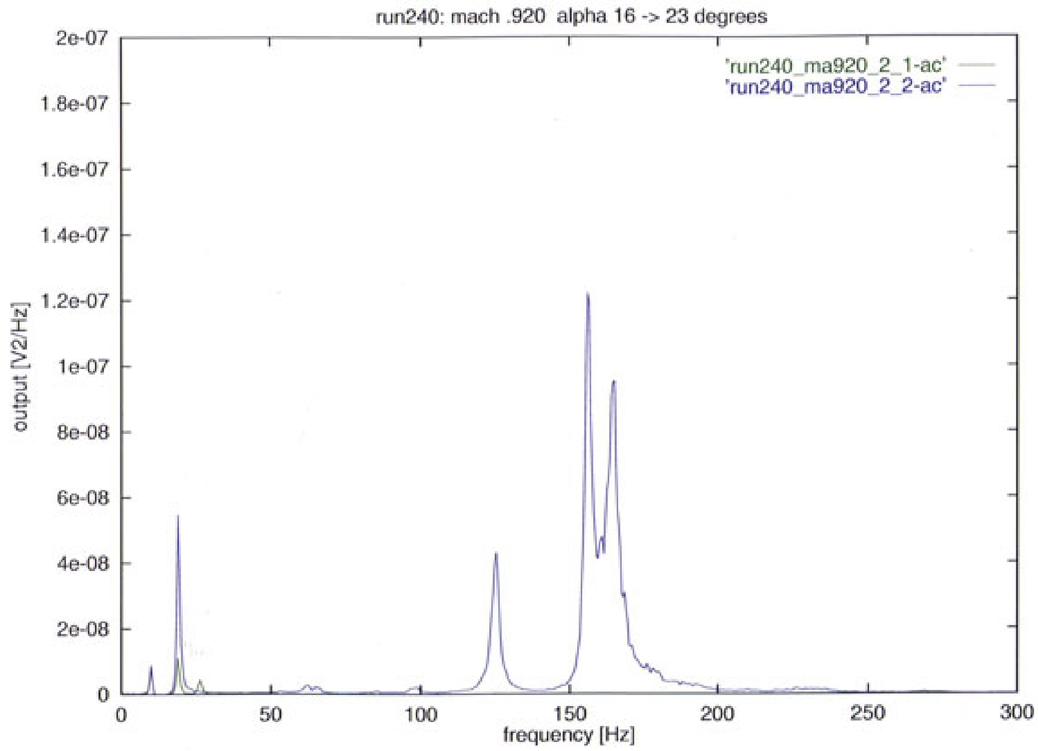

Figure 6 Main frequencies in output signal