PROCEEDINGS OF THE 16TH SYMPOSIUM
"AIRCRAFT INTEGRATED MONITORING SYSTEMS",
SEPT. 17-19, 1991 IN MÜNCHEN
H. HARDEGEN, DLR, SCIENTIFIC COORDINATOR

Modelling the Engine Temperature Distribution between Shut Down and Restart for Life Usage Monitoring

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Summary

The total life consumption during a flight depends on the initial temperature distribution in the engine. This definitely applies to helicopter systems, which often restart after a very short cooling time. An algorithm has been developed to model these temperatures as a function of the temperature distribution at shut down of the previous flight and the time elapsed. It is based on the same mathematical equations as the in-flight temperature calculation and satisfies the severe constraints due to processor speed and storage size. Furthermore parts of the algorithm can be used to calculate the temperature at shut down peaks. Examples show that the damage assessment can be significantly improved by using the modelled temperature distribution instead of ambient temperature, and by incorporating shut down peaks.

Modellierung der Temperaturverteilung im Triebwerk zwischen Abschalten und Neustart für die Lebensdauerüberwachung

Übersicht

Der Lebensdauerverbrauch einer Mission hängt von der Anfangstemperaturverteilung im Triebwerk ab. Diese Aussage trifft besonders für ein Hubschraubersystem zu, das häufig kurz nach dem Abschalten neu gestartet wird. Ein Algorithmus wurde entwickelt, der diese Temperaturen als eine Funktion der Temperaturverteilung beim Abschalten und der verstrichenen Zeit modelliert, dieselben mathematischen Gleichungen wie für die Echtzeitrechnung verwendet und die schweren Rechenzeit- und Speicherbedingungen erfüllt. Außerdem ermöglicht der Algorithmus die Berechnung der Temperaturverteilung in Abschaltspitzen. Beispiele zeigen, daß die Lebensdauervorhersage wesentlich besser wird, wenn man die modellierte Temperaturverteilung benutzt statt der Umgebungstemperatur, und die Abschaltspitzen berücksichtigt.

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List of Symbols and Abbreviations

$(TG)_n$, $TG(t)$	Vector containing all gas temperatures for a given step or at the corresponding time t
$(TF)_n$, $TF(t)$	Vector containing all leading temperatures for a given step or at the corresponding time t
$(T)_n$, $T(t)$	Vector containing all material temperatures for a given step or at the corresponding time t
$(TG_i)_n$, $TG_i(t)$	Components of $(TG)_n$ and $TG(t)$ respectively corresponding to the selected material point i
$(TF_i)_n$, $TF_i(t)$	Components of $(TF)_n$ and $TF(t)$ respectively corresponding to the selected material point i
$(T_i)_n$, $T_i(t)$	Components of $(T)_n$ and $T(t)$ respectively corresponding to the selected material point i
$N(t)$	Spool Speed
HU_i, HL_{ij}, HFV_i	Model coefficients for temperature point i
α, β, δ, S	Matrices
γ, ϵ, γ^*, ϵ^*	Vectors
Δt	Time step length
T_1	Ambient temperature
Π	Diagonal matrix
d_{ij}	given function

1. Motivation

In-flight monitoring systems determine the life consumption in critical areas based on the in-flight calculated temperature and stress histories. At the end of each flight the remaining life accounts are accessible to the maintenance personnel. The usual procedure is explained in Fig. 1.

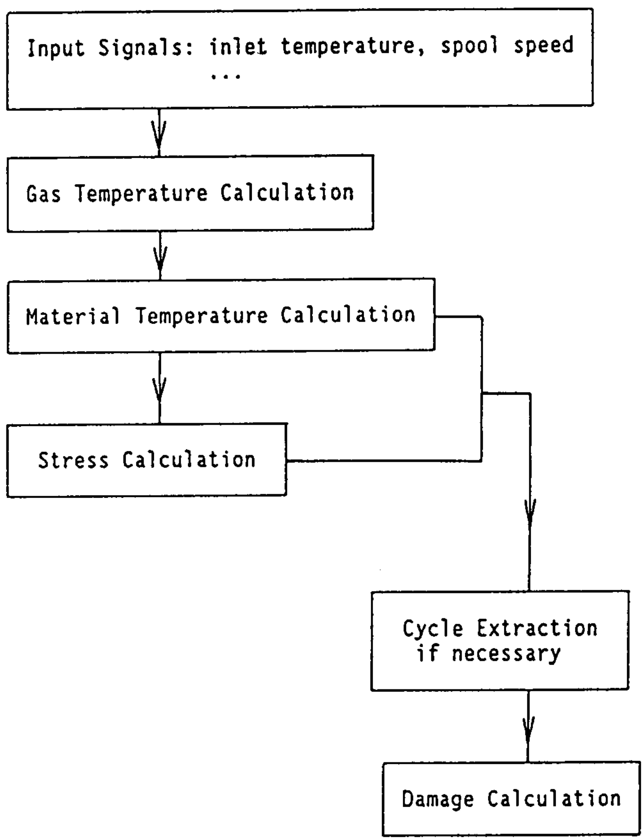

Fig. 1 Usual Calculations Procedure.

Based on the input signals (inlet temperature, spool speed ...) the gas temperature, material temperature and stresses are calculated. After cycle extraction (for LCF damage) the damage is calculated. A detailed description of the algorithms can be found in [1]. However, after turning off the engine the power supply is cut off and the in-flight algorithms cannot be used any more. This means that the in-flight algorithms do not give us any information about the temperature at stress peaks after shut down and the temperature distribution at the next start. However, both are very important.

Usually at least one stress peak per critical area occurs after shut down of the engine. It frequently leads to the biggest cycle of the complete mission. Omitting this peak leads to a severe distortion of the damage occurred.

In the same way an accurate calculation of the initial temperature distribution is very important, since it influences significantly the stress maxima at Take-off. Additionally it determines lower stress peaks at the start. If the engine has been shut down for a long time (in practice longer than 3 hours), one can assume that it has cooled down completely and take the ambient temperature as initial temperature. However, after a short shut down period the temperatures will still be high, and need to be calculated based on the temperature distribution at shut down and the time elapsed. In this case calculating with ambient temperature could lead to a severe error in the damage calculation.

Both phenomena indicate that a procedure has to be found to calculate both the temperature at stress peaks and the initial temperature distribution.

2. Description of the Model

The Material Temperature Model is based on an energy balance of the heat fluxes in the point under investigation (Fig. 2). The heat fluxes are governed by conduction inside the material and by convection, radiation and conduction from outside the material.

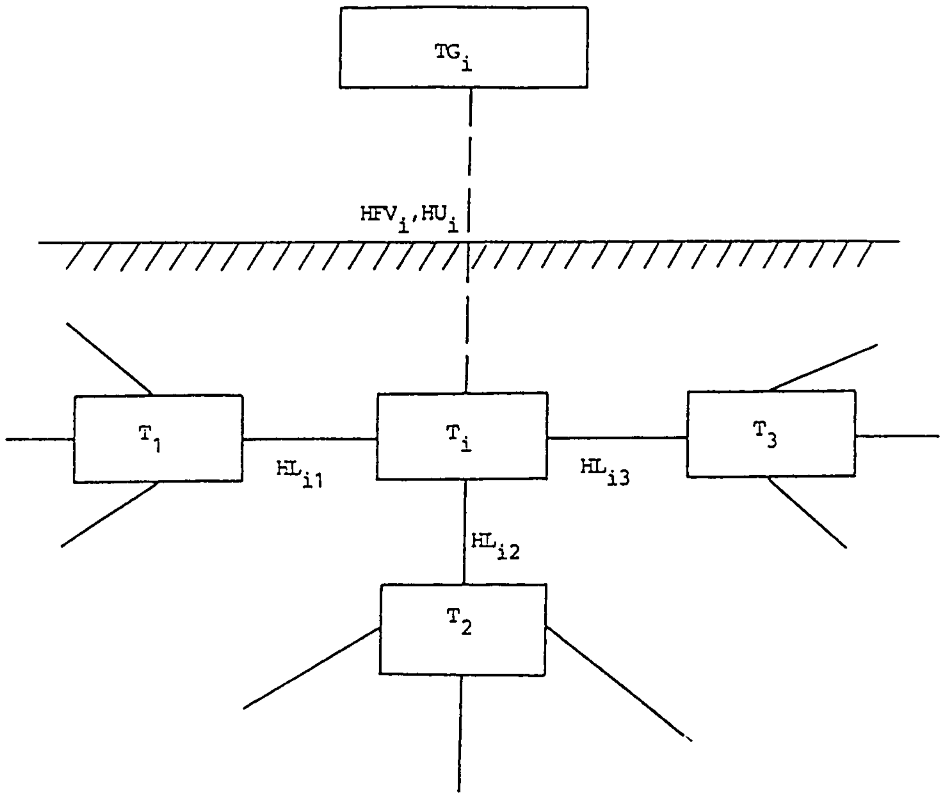

Fig. 2 Temperature Model.

For each material point i the finite difference equations are:

(1) $$(TF_i)_{n+1} = (TF_i)_n + HFV_i \cdot [(TG_i)_{n+1} - (TF_i)_n]$$

(2) $$(T_i)_{n+1} = (T_i)_n + \sum_{j \neq i} HL_{ij} \cdot [(T_j)_n - (T_i)_n] + HU_i \cdot [(TF_i)_{n+1} - (T_i)_n]$$

The heat conduction between material point i and the other points in the body is accounted for by the HL-term in (2). The HU-term in (2) and the HFV-term in (1) represent a delay of the 2nd order between T_i and the gas temperature TG_i. Further modifications can be introduced to improve the accuracy of the stationary temperatures or to discriminate between acceleration and deceleration. Indeed, experience has shown that the heat transfer between the gas and a rotating part often depends on the sign of the acceleration. All coefficients (HL_{ij}, HU_i ..) are a function of engine operating parameters (e.g. spool speed). The equations (1) and (2) allow us to calculate $(T_i)_{n+1}$ and $(TF_i)_{n+1}$, if $(T_j)_n$ (for all j), $(TF_i)_n$ and $(TG_i)_{n+1}$ are known.

The coefficients HFV_i, HU_i and HL_{ij} are determined by means of basic data (cf [1]).

3. Temperature Calculation after Shut Down

Equations (1) and (2) are used for the in-flight monitoring system where step by step calculation is applied. However, after shut down no step by step calculation is possible any more.

Therefore the following methods have been developed:

3.1. Temperature Calculation at Peaks

The basic data used for the development of the algorithms usually include a full mission with shut down, which enables us to locate the time of the stress peaks.

Now the assumption is made that for an arbitrary mission the stress peaks will occur at exactly the same time relative to the shut down time and that the gas temperatures in the time interval between shut down and the peaks depend in a linear way on the inlet temperature only. In general repeated use of equations (1) and (2) yields:

$$(3) \quad T(t) = \alpha(t)\, T(o) + \beta(t)\, TF(o) + \gamma\,(t, TG)$$

$$(4) \quad TF(t) = \delta(t)\, TF(o) + \epsilon\,(t, TG)$$

T and TF are vectors which contain the material temperatures T_i and leading temperatures TF_i respectively for all selected material points at the indicated time. O is the time at shut down. α, β and γ are time dependent matrices, γ and ϵ are vectors which depend on the time and the gas temperatures in the time interval (o, t). Because of the first assumption t is constant, e.g. t_p (p stands for peak, t_p can be different for each material point). Because of the second assumption γ and ϵ can be written as:

$$(5) \quad \gamma\,(t, TG) = \gamma^*(t) \cdot T_1$$
$$(6) \quad \epsilon\,(t, TG) = \epsilon^*(t) \cdot T_1$$

where T_1 is the inlet temperature.

Applying both assumptions yields:

$$(7) \quad T\,(t_p) = \alpha\,(t_p)\,T(o) + \beta\,(t_p)\,TF(o) + \gamma^*\,(t_p) \cdot T_1$$
$$(8) \quad TF\,(t_p) = \delta\,(t_p)\,TF(o) + \epsilon^*\,(t_p) \cdot T_1$$

which means that for each peak the storage of one row of α, β and δ and one number of γ^* and ϵ^* per critical point is sufficient to calculate the temperature at t_p for arbitrary values of T and TF at shut down.

3.2. Temperature Calculation at Restart

The approach of 3.1 cannot be used for restart, sinde the time between shut down and restart is variable. However, for constant spool speed and linearly varying gas temperatures equations (1) and (2) can be solved explicitly with the time as variable.

One gets:

$$(9) \quad T(t) = S \cdot \Pi^{(t/\Delta t)} \cdot S^{-1} \cdot T(o) + $$
$$+ S \cdot \left\{ \sum_{j=1}^{l} s_{ij}^{-1} \cdot HU_j \cdot d_{ij}\,(TG_j(o), TG_j\,(\Delta t), \frac{t}{\Delta t}) \right\}$$

S is a full matrix, Π is a diagonal matrix, Δt is the time step of the difference equations, and d_{ij} is a known function of the indicated arguments. For a partially linear gas temperature (9) can be applied repeatedly. Assuming that the gas temperatures are a linear function of T_1, $TG_j(o)$ and $TG_j(\Delta t)$ are known and equation (9) yields T(t) as a function of T(o), t and T_1. A similar formula can be derived for TF(t).

Since the spool speed is not immediately zero after shut down (cf. Fig. 3 for a representative spool speed history between shut down and start up), the previous method (called method B) has to be combined with the one of section 3.1 (called method A).

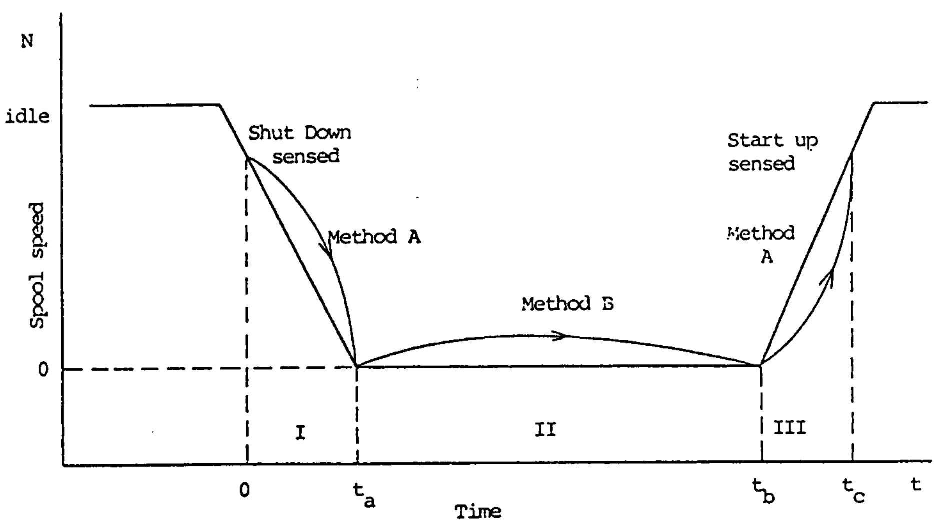

Fig. 3 Temperature Calculation from Shut Down to Restart.

Assuming that the time intervals t_a and $t_c - t_b$ are mission independent quantities method A can be used for section I and III, and method B for section II.

4. Example

As an example a combination of two flights consisting of synthetic data was chosen. Between these two flights the engine was switched off for 40 seconds. The first flight serves to generate a hot engine. The damage was only calculated for the second flight.

Four methods were used to calculate the damage of the critical areas:

1. Simple method

   The material temperatures are initialized with ambient temperature. Residual stresses are fed into the cycle extraction at the end of the flight.

2. Peak calculation

   The material temperatures are initialized with ambient temperature. Stress peaks are calculated and fed into the cycle extraction at the end of the flight.

3. Peak calculation and temperature initialization

   The material temperatures at the beginning of the flight are calculated. Stress peaks are calculated and fed into the cycle extraction at the end of the flight.

4. Reference calculation

   The calculation is made stepwise from some time before the mission until steady state.

Figures 4 and 5 show the material temperatures and stresses (without plastification) of 3 critical areas A, B and C calculated by method 4. The time period comprises both flights.

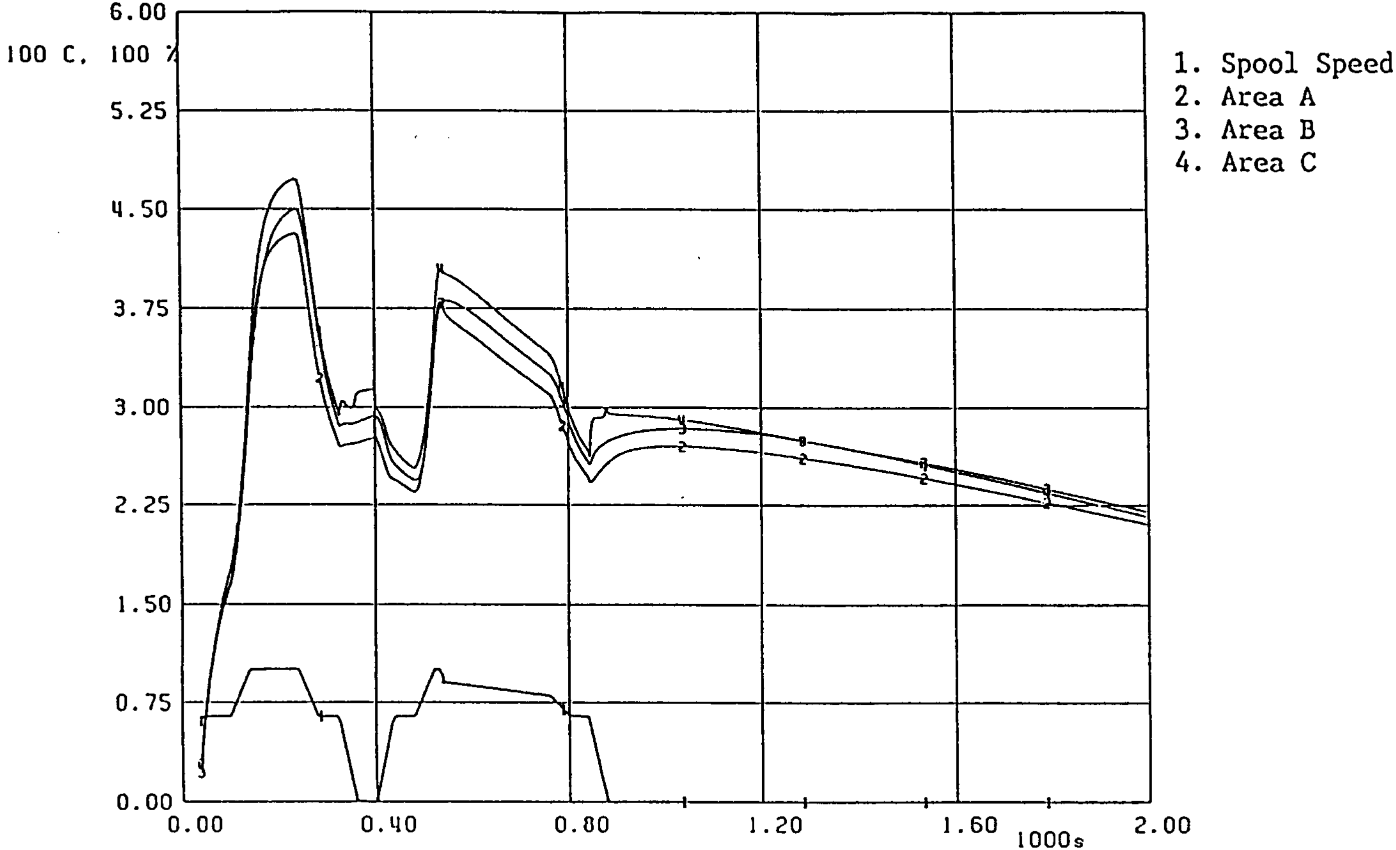

Fig. 4 Temperature by Method 4.

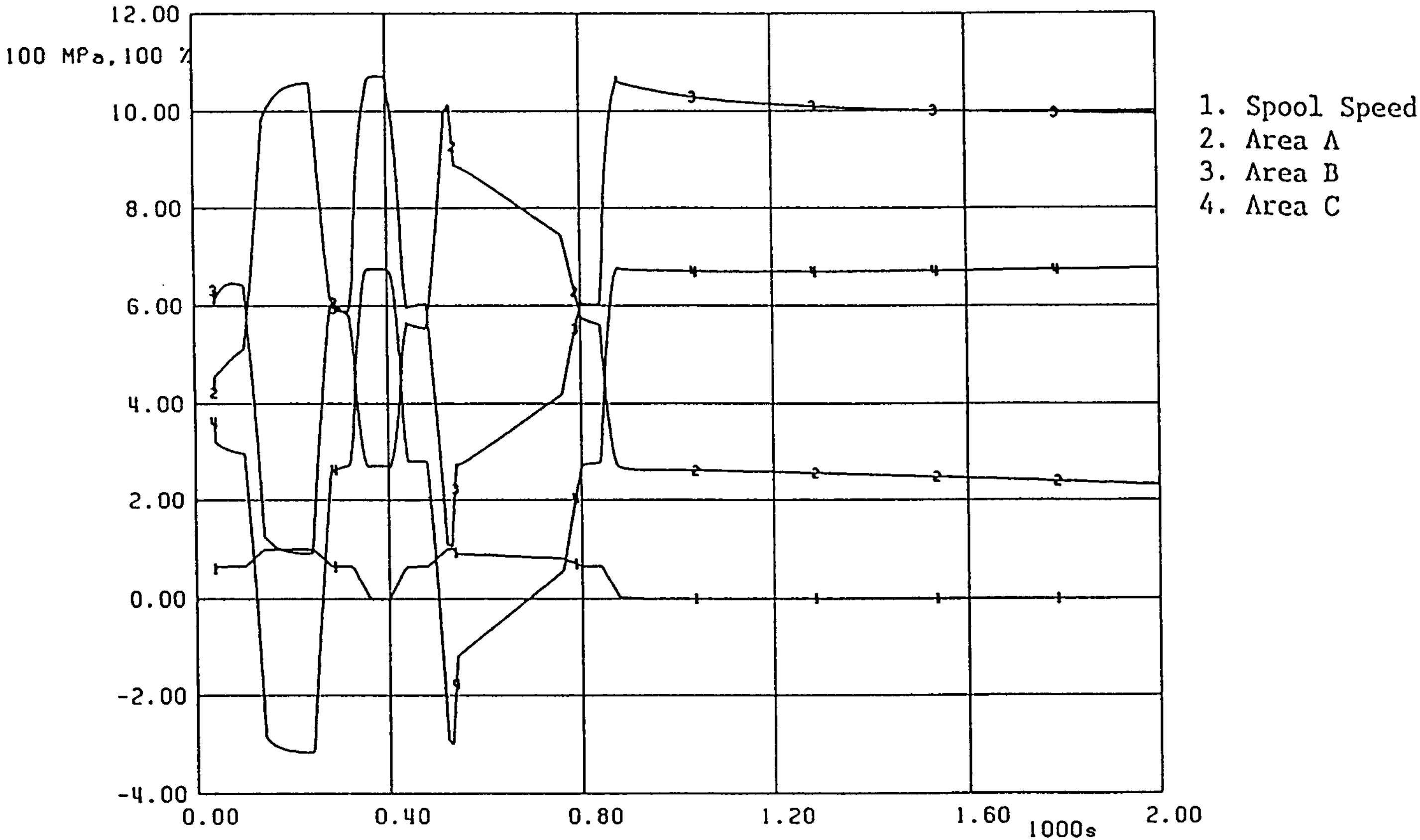

Fig. 5 Stresses by Method 4.

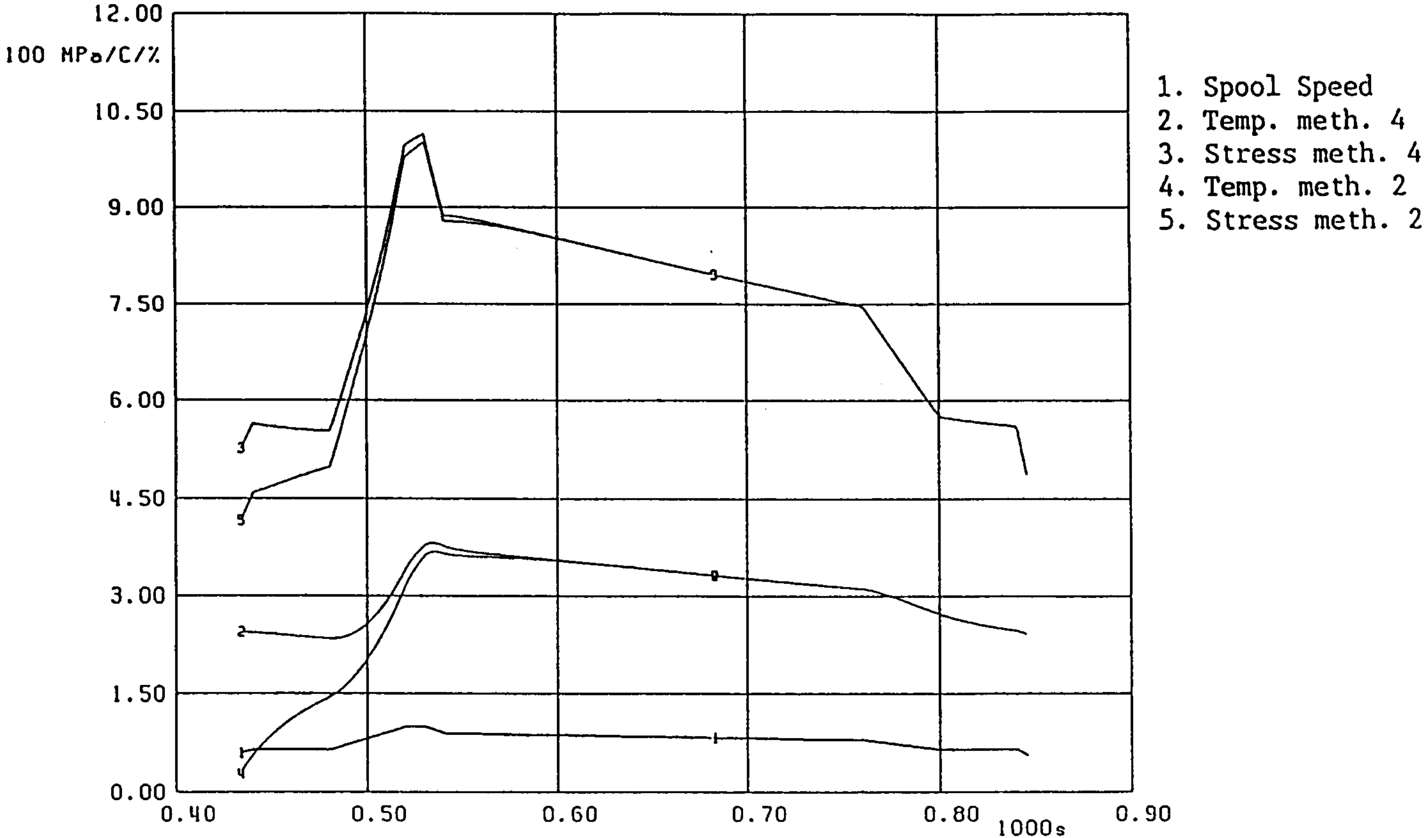

Fig. 6 Stresses and Temperatures by Methods 2 and 4.

Figure 6 shows the temperatures and stresses of area A calculated by the methods 2 and 4 for the time interval of the second flight where the main temperature calculation of method 2 is applied. In the beginning there is a considerable deviation of the temperature and the stress. Especially the peak values of the stress are not met correctly.

Additionally in each figure the spool speed is plotted.

The results of the different methods are shown in the following table. The stresses are given in MPa and plastification is taken into account. For the damage the results of method 4 are taken as reference.

		Area A	Area B	Area C
Method 1	min. stress	89	116	-295
	max. stress	942	941	620
	damage	0.839	0.740	0.476
Method 2	min. stress	89	116	-295
	max. stress	942	958	712
	damage	0.837	0.861	0.932
Method 3	min. stress	79	104	-300
	max. stress	944	958	712
	damage	0.998	1.020	0.999
Method 4	min. stress	79	104	-300
	max. stress	944	956	712
	damage	1.000	1.000	1.000

Table 1 Results of Different Methods.

The results of method 1 show an underestimation of the damage between 16 % and 52 %. The results are considerably improved by calculating the stress peaks, which is done by method 2. Here the maximum deviation is 16 %. Finally the additional calculation of initial values of the material temperatures (method 3) fulfills our requirements showing errors of at most 2 %.

In the case of area A the peak calculation has obviously no influence, whereas the material temperature initialization has a major effect. The reverse can be noticed in the case of area C.

5. Conclusion

The example has demonstrated that the methods developed to include stress peaks at shut down and the initial temperature distribution at the start lead to a significant improvement of the life damage calculation. Discarding these phenomena will lead to a severe distortion of the damage occurred.

6. List of References

[1] Broede, J.; Pfoertner, H. — Advanced Algorithms Design and Implementation in On-board Microprocessor Systems for Engine Life Usage Monitoring

Proceedings of the 15th Symposium on Aircraft Integrated Monitoring Systems, Sept. 12 - 14, 1989 in Aachen; DLR-Mitt. 90-04